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# Architecture and Design for Industry 4.0

## Theory and Practice

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ISSN 2195-4356 ISSN 2195-4364 (electronic)
Lecture Notes in Mechanical Engineering
ISBN 978-3-031-36921-6 ISBN 978-3-031-36922-3 (eBook)
https://doi.org/10.1007/978-3-031-36922-3



This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

# Preface

Ten years after the introduction of the concept of Industry 4.0 at the Hannover fair in 2011, the enabling technologies of the Fourth Industrial Revolution are gradually being implemented in various industrial sectors. Among these, the AEC sector has also begun to accept the challenges dictated by the 4.0 paradigm, continuing that path of hybridization with other disciplinary fields and industrial sectors (aerospace, naval, automotive, etc.) that characterized the first digital era. The 4.0 challenge leads industry operators to introduce a series of new paradigms that affect the entire supply chain, from first-level training courses to the creation of innovative companies, passing through the design and construction of digital and performative architectures.

The affirmation of computational design, the increasingly transversal and multidisciplinary flow of knowledge, and the democratization of machines open new possibilities in a historical moment where the combination of technological innovation and design can play an essential role in environmental sustainability and reduced consumption of resources. The development of CAD/CAM and robotics digital manufacturing technologies has helped to reduce the gap produced by the increase in computational power in the generation of the form compared to the materialization of the same. Through this process, architecture regains its own tectonic identity, and the architect can regain a material sensitivity which risks being dissolved in virtual space. The democratization of digital manufacturing tools and the ubiquity of computational design require a new material dimension and a new figure capable of controlling the entire process. In the post-digital era, where the essence of design lies in the control and information of the process that holistically involves all the aspects mentioned above, rather than in formal research, it is necessary to understand technologies and analyze the advantages that they can bring in terms of environmental sustainability and product innovation.

This book intends to systematize from a theoretical and practical point of view, the best contributions, and the best experiences in the professional and entrepreneurial, academic, and research fields of architecture and design based on this new design paradigm. The main purpose of the proposed systematization is to create a widespread awareness necessary to initiate technology transfer processes involving the public sector, universities and research centres, and the private sector consisting of innovative companies. The issues addressed in the book are central to the development of a total 4.0 awareness for architects, engineers and designers, and digital entrepreneurs: advanced and computational digital design, virtualization of the project and production and construction processes, use of cyber-physical systems, advanced and customized prefabrication, additive manufacturing, automated manufacturing and construction, artificial intelligence, as well as the story of significant experiences of public and private self-entrepreneurship.

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# Contents

# Theory

# The Big Vision: From Industry 4.0 to 5.0 for a New AEC Sector

**Micaela Colella, Maurizio Barberio, and Angelo Figliola**

**Abstract** The contribution offers an overview of the key concepts of Industry 4.0 and the application of enabling principles and technologies in the AEC sector. In this sense, the most promising possibilities offered by the fourth industrial revolution are analysed, hinging them inextricably around the theme of sustainability, in the broadest sense of the term. Furthermore, the chapter addresses the issue of the transition towards the emerging Industry 5.0, proposing a refocusing of technological advancement in a human-centred and planet-oriented key. Moreover, the foundations are laid for a broader discussion around the issue of training the professional figures who will be called upon to manage such complex, interrelated, and systemic processes. What is prefigured is a new professional figure capable of managing the entire design process with a systemic vision through which human sciences are merged with technological research, embedded into a holistic vision necessary for guaranteeing a future of prosperity and economic progress while ensuring a sustainable tomorrow for our planet.

**Keywords** Industry 4.0 · Architecture 4.0 · AEC 4.0 · Sustainable architecture · Industry 5.0

**United Nations' Sustainable Development Goals** 8. Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all · 9. Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation · 12. Ensure sustainable consumption and production patterns

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_1

## 1 Industry 4.0 Principles

The term Industry 4.0 (I4.0) was first mentioned in 2011, when H. Kagermann, W. Lukas and W. Wahlster presented their strategic proposal to strengthen the competitiveness of the German manufacturing industry at the Hanover Fair, which was subsequently adopted by the German federal government and entitled Industrie 4.0 [1]. However, although there is still no precise definition of what is meant by Industry 4.0, it tends to be generally understood as the set of new technologies and new factors of production and work organisation, which, in addition to changing the way production is carried out, will also profoundly alter relations between economic actors, including consumers, with significant effects on the labour market and social organisation itself [2]. To establish a more technical and in-depth definition of the founding principles of this new technological era, the literature review on I4.0 publications by Hermann et al. in 2015 [3] is very thorough and extensive. In this publication, the following are identified as key founding components of I4.0: Cyber-Physical Systems, the Internet of Things, the Internet of Services, and the Smart Factory.

**Cyber-physical systems** (CPS) are a fusion of physical and virtual space. It is a continuous cycle of data exchange, between physical processes and computer calculations, which makes it possible for the former to influence the latter and vice versa. Physical processes produce data that are collected, stored, and analysed by sensor-equipped and network-compatible systems. Thus, a physical process is followed by a computing process with a real-time associated response in the physical world. Cyber-physical systems are the elements behind the definition of the Internet of Things and the Internet of Services. Things, the objects incorporating technological devices that create an interface between the physical and digital worlds, can be understood as cyber-physical systems, whereby the **Internet of Things** (IoT) can be defined as a network in which cyber-physical systems interact and cooperate with each other according to pre-defined patterns [4]. The Internet of Things, a concept introduced by Kevin Ashton in 1999, thus refers to a new method of using the virtual network within physical space, i.e., the possibility of making parts of the physical world and objects interact with each other via the computer network.

With the **Internet of Services** (IoS), there is a leap in scale, in which cyber-physical systems no longer consist of individual objects, but of the individual activities of the enterprise value chain. Thus, the development of this technology enables a new mode of business management, characterised by a dynamic distribution of activities [5]. Based on the definitions already provided for the CPS and the IoT, the **Smart Factory** (SF) can be defined as a factory in which cyber-physical systems communicate through the IoT, to assist people and machines in performing their tasks [6]. CPS create a virtual copy of the physical world and its processes, so in the continuous connection and interaction between the physical and virtual worlds, between machines among themselves and with humans, within SFs, it is possible to make decisions remotely and reorganise processes in real-time. This creates the preconditions, for example, for flexible and 'intelligent' production, i.e., based on the real demand for a given product at a given time, in real-time. It can be argued, therefore, that the pivotal point of the current revolution is the entry of the virtual world into the real one, through the IoT and the IoS. We are witnessing the progressive fusion of the physical and cyber worlds, in a new concept of a cyber-physical system. Ultimately, it is the combination of these technologies that define the concept of I4.0. Thanks to the introduction of these new technologies, it is possible to gain an insight into the principles that characterise manufacturing in the new industrial era. As mentioned above, the topic is not historicised and the interpretations are multiple, with boundaries that are still very blurred, sometimes contradicting each other. In any case, given the need to make choices, for a clear systematisation of the topic, it was decided to distinguish between:

- the new technologies (CPS, IoT, IoS, SF)
- the new principles introduced into the world of production (Real-Time Capability, virtualisation, decentralisation, servitisation, interoperability, mass customisation)
- the new IT services underpinning the above innovations (big data, cloud computing, cognitive computing, artificial intelligence, machine learning).

As it is easy to deduce from the description of new technologies, they are based on the collection and analysis of an enormous amount of data. Data is often considered the essential asset of the new era. Therefore, fundamental elements for the establishment of 4.0 are big data and cloud computing, services for storing, processing, and transmitting data, without which, the production and collection of data become essentially useless. Recently, with cognitive computing, we have reached a new level of complexity in data processing, being able to substantially reproduce the functioning of the human brain, to make decisions in the face of a very high quantity and heterogeneity of data and variables. Several principles elevate the factory to '4.0', opening new and innovative scenarios. CPSs monitor physical processes by means of sensors and are at the same time able to analyse and compare the collected data with virtual simulation models. As a result, there is a constant check on the correctness of processes, and any errors or inconsistencies are reported in real-time (**Real-Time Capability**).

Interconnected plants can recalibrate the production plan, restart production on other machines and optimise processes. In this way, humans are supported by the machines themselves in their complex management and, whereas in the past, each change in the production chain required weeks of testing by highly skilled personnel, thanks to virtualisation, i.e., the use of simulation models, pre-production tests take place in the virtual world and the time during which machines are inactive is greatly reduced, resulting in enormous savings in economic terms, making them more sustainable [7].

SPCs are, therefore, able to make decisions and perform their tasks autonomously. Therefore, constant planning and control on site are no longer necessary, making decentralisation of production and decisions possible, which can be managed and controlled remotely. This, of course, means less effort and less time spent by workers on the factory floor, but at the same time more effort in the design of machines and processes. This will lead to a change in the way work is done, increasingly focused on highly skilled intellectual work and less and less on physical work (compensated by machine work). In Factory 4.0, robots and humans may work side by side, thanks to the use of intelligent human-machine interfaces. The use of these new generation robots, called smart robots, will encompass countless functions, from production to logistics to office management [8]. The constant connection between manufactured goods and the manufacturing company (again thanks to the installation of sensors) is leading towards a deep integration between physical goods and services. This process, known as the servitisation of manufacturing (service orientation), will favour entrepreneurial formulas that, in addition to selling a product, will offer constant support services. Customer service will be completely rethought, with an inversion of roles: it will be the company, in fact, that will remotely control the functionality of the product and intervene in the event of anomalies, failures, obsolescence or exhaustion of part of the products. In this way, we will increasingly move towards a market in which the purchase of goods will be replaced by the purchase of services, whereby the manufacturing company will remain the owner of the good and will guarantee its efficiency, maintenance, and eventual replacement. This type of market can only have positive consequences from the point of view of environmental sustainability, since, for example, the disposal of obsolete or end-of-life products will no longer be left to consumers but will hopefully be managed efficiently by the companies themselves. A factor of fundamental importance for the development of the 4.0 vision is interoperability, i.e., ensuring, through compliance with common standards, that all SPCs can communicate with each other, even if they belong to different manufacturers, to create an open network in which everyone speaks the same language [9]. The aforementioned principles describe a highly flexible production model, capable of modifying and reorganising production in a short time, thanks also to the high degree of modularity that will characterise its components. This, together with the ability to collect and process an enormous amount of data, including consumer needs and desires, in real-time, will make it possible to implement customised industrial production. Thus, the specific desires and needs of the individual consumer will once again occupy the central role they played in artisanal production. This scenario is referred to as mass customisation.

To summarise, besides the change in the role that humans will play in the production cycle, one of the most relevant consequences of the application of IoT and IoS to the industrial world is the profound change in production methods and volumes. Being able to know in real-time the demands and needs of consumers and having at the same time great flexibility of the factory, capable of varying for each production cycle the goods produced, the canonical serial productions with storage of large quantities of products lose their meaning, opening the way to customised and on-demand production, returning to a dimension of production volumes and customisation of the goods produced closer to the artisan world than to that of industrial seriality. Consequently, even if one considers only the changes related to the use of these technologies in industrial production, the benefits derived from them are manifold and of considerable magnitude; there is the possibility of a reduction in waste related to overproduction, the optimisation of energy and materials used, and a reduction in the need for built space for storing products. Unlike previous industrial revolutions, whose main outcome was the improvement of living conditions through increased productivity, this latest industrial revolution has the potential to significantly improve human (and probably planet Earth's) living conditions not through increased production, but through the optimisation of available resources for more conscious, targeted, and customised production. As with all previous technological revolutions involving a radical change in the way we live and relate to each other, but above all in the way we work and produce, its arrival is viewed by many with a mixture of scepticism about its true potential and fear that technology will eventually overwhelm man and replace him in his work, making him useless for productivity. However, this evolutionary process is already underway, and the question should be: how can this enormous potential be harnessed to solve cogent problems and ensure a prosperous future and widespread prosperity for mankind?

## 2 Industry 4.0 and Architecture

The new scenarios outlined by the advent of the fourth industrial revolution are producing a change in the way of thinking about society and the world of labour, with the definition, for example, of new professional figures; however, the most affected field by the change is the industry, with a rethinking of its management, production methods and the products themselves. Even though, in recent decades, it has been a field of phlegmatic with less technological progress, compared, for example, to the rapid evolution of the automotive industry, we believe that the construction sector and its related professionals are destined to become one of the main fields of application of I4.0 and, later, I5.0. There is no doubt that the most important innovation that has taken place in the last thirty years in the design sector is the spread of CAD (Computer Aided Design) systems first, and CAM (Computer Aided Manufacturing) later. Although several decades have passed, the still predominant use of CAD tools is simply a computerised version (computerisation [10]) of traditional drawing techniques. However, since the early 2000s, a new (perhaps fully digital) digital revolution has begun to take hold: from CAD design, we move to computational design. In fact, as Kostas Terzidis states, while the computerisation that has taken place in recent decades can be traced back to the digitisation of established, defined, and predetermined processes to improve their efficiency, precision, and workflow, in contrast, computational design concerns the algorithmic exploration of indeterminate processes [11]. Why is it important to emphasise this step from our point of view? This shift is necessary because computational design is the only one capable of fruitful dialogue with the virtualisation processes inherent to I4.0. In fact, truly computational creation involves the performance of an exploratory materialisation process, guided by cyber-physical responses, which extends the properties of the design rather than simply realising it [12]. Machines, therefore, are made 'intelligent' and become part of the computational design process, not only performing tasks according to predefined patterns but devising alternative responses to improve the efficiency of processes, consequently reorganising production.

Taking the technologies characterising I4.0 and imagining an application of their principles to the field of architectural design [13], it is possible to outline feasible scenarios that could configure the architecture of the 4.0 era. Starting from the principle of virtualisation, it is, therefore, possible to identify at least six levels of virtualisation:

1. **Virtualisation of conceptual genesis**, i.e., concept generation processes based on the use of artificial intelligence (AI) technologies, through the input of a textual description (prompt) to which correspond a series of outputs (and subsequent variants) expressed in the form of raster images or three-dimensional models or textual scripts [14, 15].
2. **Virtualisation of the design process**, i.e., forecasting processes that can address several factors simultaneously, thanks to the increasingly sophisticated development of three-dimensional and computational modelling programmes. To cite just a few examples, it is possible to virtualise the climatic behaviour of a building, simulating the position of the sun at a given time on a given day in a precise location on the globe and the resulting irradiation (under clear skies); or the phases of the construction process and the entire life cycle of a project, thanks to Building Information Modelling (BIM) software; or able to analyse the structural behaviour of buildings, and so on [16].
3. **Virtualisation of the CAD/CAM and robotic manufacturing process**, i.e., processes of prediction, control, and prior verification of Computer Aided Manufacturing phases, referring both to single machining and to several consequential machining operations [17].
4. **Virtualisation of the production process**, i.e., processes made possible by the advent of I4.0, in which the entire production process of the factory is foreseen and verified in the virtual world [18].
5. **Virtualisation of the maintenance process**, i.e., processes of prediction, control and preventive verification of the global and local behaviour of the building throughout its life [19].
6. **Virtualisation of the demolition process**, i.e., processes of analysis and design for the selective demolition of the building and the recycling or reduction of the impact on the environment of the building components that are no longer suitable for the purpose for which they were designed [20].

The affirmation of **integrated virtualisation** may therefore represent a possible way forward, given that designers are already accustomed to a working approach with an important virtualisation component, which would be a key element in the interaction between the design process and the industrial manufacturing process. In other words, the designer would be allowed to take part in the management of the industrial process, through an integrated design that would be able to contemplate manufacturing and industrial production methods right from the design stages. Vice versa, the computational design becomes the subject of work and 'critical' analysis by the intelligent machines involved in the various phases of the design and construction process, which can elaborate, and signal possible modifications aimed at optimising a process, concerning, example, the optimal use of a material according to its performance, or to reduce waste, etc.

This is an aspect that brings with it a series of critical issues, mainly related to the interchange of data between one process and another, hence the need to be able to work on common software platforms or those that can interface with each other. In a state of interconnection between design tools and manufacturing and construction tools, in a continuous exchange of data and control of physical processes, the entire process would become ‘informed’—and not simply computerised—enriched and guided by the ‘cloud of data’ processed in real time.

In this context, the role of the designer should not be seen as marginal. The ‘data cloud’ can be a tool of extraordinary potential for the architect who can be a good director of the design and construction process. Imagining the application of the technologies characterising I4.0 to the field of architectural design, the architect’s work would naturally be supported by the potential of the new tools, but it would at the same time become more arduous and burdensome in terms of responsibility, as the project becomes increasingly integrated, the result of a holistic conception that could no longer be evaded. It is enough to think of the possibility of designing with the support of a software tool that is always connected, capable of informing and consequently conditioning the project with data relating to the project site, the processes involved, e.g., environmental data (climatic data, seismic risk, presence of electromagnetic fields, etc.), and having to ensure that each condition is part of the project with an appropriate architectural response. At the same time, the designer’s work would not be limited to the production of drawings useful for the construction site, but could (and should) allow for the management of manufacturing and construction processes through simulation tools of the processes themselves, which would ultimately also allow for the optimisation of available resources, be they material, energy, economic, etc.

Beyond the design moment, the benefits of 4.0 technologies could be no less fundamental if applied to the actual construction. In fact, the construction resulting from a 4.0 production process can be equipped with sensors and technological devices that make it a smart product, connected to the web and capable of reacting, according to different configurations, to the processing of data received in real time. New technologies could become part of the new generation of buildings, not only through minor elements such as furniture and household appliances, but also through the installation of sensors in structural building components ensuring the monitoring of their performance, in plant components to monitor their integrity and energy efficiency, and likewise ensure the control of values related to health and living comfort. New constructions would thus take advantage of the servitisation principle, whereby there would be the possibility for the manufacturing company to remotely detect wear and tear, malfunctioning, or impending failure of a building component, allowing timely intervention with targeted and less invasive maintenance. The characteristics outlined so far, although probably not described exhaustively given the topicality of the subject, make us realise how fundamental the almost exclusive use of prefabricated dry-assembled components is. Indeed, among the various construction techniques currently available, it is best suited to dialogue with the enabling technologies of the 4.0 era. The use of prefabrication, although ‘advanced‘ and ‘augmented’ by 4.0 technologies, would be indispensable for the following reasons:

- Adequacy with respect to digital and computational design processes.
- Total adherence to digital or robotic fabrication processes, especially with respect to wet or mixed systems, which are known to be inaccurate and uncontrollable fabrication/construction processes.
- Greater accuracy in the fabrication of building components, made in a controlled environment and under consistently optimal conditions.
- Greater precision in the construction/assembly phase of building components.
- Greater adherence between design and actual structural and energy performance, thanks to the precision of all execution phases and the use of certified performance elements.
- Reduced production of waste and scrap material during manufacture and construction.
- Possibility, if appropriately foreseen in the design phase, of being able to replace parts that are no longer suitable for their intended function over time.

## 3 Advanced Prefabrication as a Tool for Sustainable 4.0 Architecture

Prefabrication, by its very nature, implies the concept of prediction. Envisioning the entire construction process during the design phase, and not a posteriori, means having to conceive the project through a method that cannot be based solely on formal considerations, but must constantly relate the whole and the individual parts, according to a coherent and synergic relationship. Prefabrication intrinsically entails a design methodology that cannot disregard considerations on the efficiency of the construction process, since it entails precise planning of the project, which naturally leads to a rationalisation of all the phases of the construction process, from optimisation of the use of materials to optimisation of construction times and costs, up to making forecasts on the discharge of the same with a view to a circular economy and reduction of the environmental impact at the end of the building’s useful life. Manufacturing construction components in a factory ensures greater efficiency in the use of materials, drastically reducing waste. The quality of these construction components is also improved, with certifiable technical characteristics and performance, because unlike traditional construction sites, they are produced in dedicated factories, by qualified personnel, in a controlled environment, under conditions always maintained optimal and with the appropriate technical instrumentation, like what happens in the industrial production of any technological product. Off-site production allows for energy efficiency in all stages of the construction process, as the production of components is carried out in the factory, according to the company’s energy-saving strategies, while the energy used at the construction site is significantly reduced, as the traditionally designed construction site is transformed into a rapid dry assembly operation of the constituent parts. The dry assembly of parts, typical of prefabricated buildings, also makes it possible to conceive of reversible buildings, which at the end of their useful life allow for the selective recovery of materials and their recycling or reuse, reducing or solving the problems generally associated with the disposal of construction materials.

Prefabrication, in short, is a means of producing buildings in a planned, fast, precise, efficient, and safe manner, as is the case for any other goods produced through an advanced industrial process.

To pursue the goal of building by the principles of sustainability through prefabrication practices, designers should be prepared to manage a more complex design process that is no longer consequential, but oriented towards integrated design. Integrated design is a holistic conception of design, in which all participants in the design process contribute simultaneously so that the design is the result of holistic thinking in which all parts are interdependent and contribute synergistically to the functioning of the entire architectural organism. For example, by ensuring that the building is energy efficient and sustainable, not only because highly efficient systems have been employed, but because environmental well-being is primarily pursued by passive strategies integrated into the building design itself. In this way, the final construction will not be the result of an addition of independent contributions and successive stages of project adaptation that, in most cases, distort the designers' original, albeit valid, conception.

Naturally, this new modus operandi entails a great propulsive thrust in the evolution of the architectural conception against a greater complexity and responsibility on the part of the designer, who with his design choices must succeed in synthesising all the contributing disciplines involved in the project itself. Traditional construction practices, slow and uneconomical, sometimes carried out by unqualified personnel according to an approximate execution, can defeat the effectiveness of design choices. They should therefore be mostly abandoned in favour of a largely industrialised process, even if this means profoundly changing the economic organisation of the construction sector. The affirmation of 4.0 prefabrication, however, in contrast to the widespread vision that imagines it as a means for the mass production of buildings that are all the same, to be reproduced indifferently in any climatic zone and sociocultural context, should be accompanied by important reflections on the design and technological solutions to be adopted, so that these are integrated and appropriate concerning those of the local architectural tradition. This step is important, not only as a means of visual integration, using materials and forms that belong to the local architectural tradition, but above all as a means of extrapolating from tradition the principles of passive architecture that respond to the place and its climatic characteristics. Combining an industrialised construction practice with architectural solutions linked to the context is not to be considered a forced objective, nor an unrealisable vision. New developments in technology are indeed moving towards total customisation of industrially manufactured products. In light of the considerations outlined so far, it is worth reflecting on one of the most relevant aspects that I4.0 could bring about and which, it is worth pointing out, could lead to overcoming the very limits of prefabrication processes as we have known them until now: mass customisation.

The application of I4.0 principles to architecture will necessarily pass through computational design and subsequent digitally controlled fabrication and construction. About the principles underlying these two technologies, it is possible to identify two possible construction processes that, not surprisingly, are becoming the focus of research and experimentation by academic and non-academic research centres, and of public and private funding and investment. We are talking about a new concept of prefabrication, customised digital prefabrication, and technology that is spreading relatively recently in additive manufacturing. These are the two scenarios within which, in our opinion, the construction of the near future will develop.

**Additive manufacturing** could play an important role in the transition to a more sustainable construction industry. Through additive manufacturing, it is possible to create elements with an optimised shape obtained through computational strategies, eliminating the waste of material, time and money required for subtractive manufacturing or the creation of necessary formworks and counter-moulds. It even becomes feasible and accessible to make complex shapes that would not even be conceivable using traditional manufacturing methods. Digital fabrication makes it possible of working extensively with non-standard products, conceived and create about a specific project or adapted to it, with the use of the materials most suited to the nature of the project or local availability. In addition, the possibility of manufacturing the building elements on the same site as the construction, transporting only the printers as a sort of mobile factory, or entrusting the manufacture of the components related to a given project to one of the digital manufacturing centres spread throughout the territory, would considerably reduce the energy consumption and pollution produced by the transport of all building components from the respective factories to the construction site. However, the centrality of the manufacturing companies in the transition from the general design to the executive project aimed at construction effectively excludes the designer from having a proactive role in the production part and from entering a relationship with the industry, except in more limited cases. Therefore, it is of fundamental importance that, in the affirmation and diffusion of customised digital prefabrication, as a means of moving towards a more sustainable construction process and life cycle of buildings, the irreplaceable work of the architect, who should assume a pivotal role in the transition to an architecture produced with mass production means but with the individuality of a handcrafted product, is not bypassed. The designer, through computational design, should be at the centre of the new design-production process enabled by the principles of I4.0 and digital fabrication. Thus, the construction of buildings with prefabricated I4.0 components lends itself perfectly to becoming a fully digitised process. The designer develops his or her own (computational) design, which is passed on to the digital fabrication machines, optimising the process for making the components to reduce waste of any kind. All components are manufactured and finally assembled to a precision only possible in an industrialised process, thus reflecting the high-quality standards of the design in the finished construction.

## 4 From 4.0 to 5.0: Towards a More Sustainable, Resilient, and Human-Centred AEC Industry

The 4.0 revolution introduced several cornerstones for the transformation of several leading industries in Western development models, among which we certainly find AEC. The pillars against which this transformation developed were centred on disruptive technological innovations and interconnected cyber-physical systems in which AI was the driving force for increasing the productivity and efficiency of the industrial system. The focus of this transformation centred on the optimisation of a business model is not entirely consistent with the European Union's Agenda 2030 for Sustainable Development or rather does not appear to be the correct framework for addressing emerging and complex challenges such as climate change, resource scarcity and increasingly acute social tensions. The evolution of such a development model must necessarily contemplate some emerging issues that require actions aimed at:

- Introduce a regenerative dimension, with the circular economy as a key element of the entire production cycle.
- Introducing a social and human-centred dimension, promoting technologies designed to assist the workers and not developed to replace them.
- Introducing an environmental and ecosystem dimension that goes from the exploitation of renewable energies and the restoration of biodiversity, as well as overcoming globalisation and the cultural flattening based on it, towards a new model capable of guaranteeing the preservation and evolution of identities and cultures.

Based on the above, it can be said that there is no need for a new industrial revolution, but rather for proper management of the transition from 4.0 to 5.0, which share the same operational tools, and some methodologies, but certainly not the same aims. From our point of view, it is necessary to distinguish between opportunities and goals. Opportunities should be understood as possible enablers of social and economic development and are essential to ensure prosperity and progress. However, it is not opportunities in themselves that generate progress and prosperity: they must necessarily be driven by a set of goals, which can only relate to the most pressing agendas facing humanity such as:

- Overcoming dependence on economic growth as the sole enabler for development and accelerating the development of effective policies and best practices aimed at the sustainable use of material resources.
- The great acceleration of biodiversity loss, climate change, pollution and loss of natural capital is closely linked to economic activities and economic growth.
- The increase in social and economic inequalities, both between industrialised and developing countries and within industrialised countries themselves, with clear differentiation between metropolitan areas and less urbanised territories.
- The fight against the scarcity of potable water by promoting better exploitation of water resources through the recovery and recycling of used rainwater and potable

water and through the development of technologically advanced and precision agriculture.
- Countering the phenomena of depopulation of entire territories and the consequent concentration of an increasing number of people in urban territories that are increasingly large, polluted, and close to collapse.
- The preservation of the cultural and historical identity of territories, and the activation of virtuous dynamics for their evolution thanks to technology; overcoming cultural globalisation.
- Managing migratory flows and eradicating the political, economic, and social causes that incentivise them, to enable the sustainable development of all territories, even those that currently appear most disadvantaged.

It is precisely the aims that represent the key turning point concerning I4.0: an industrial revolution that is not based solely on economic and technological aspects but rather on a multiplicity of factors that configure a vision of restorative and regenerative sustainable development with an inevitable shift of focus from the 'Internet of Things' to 'Digital for people-planet-prosperity'. This paradigm shift inevitably leads to a transition phase linked to the difficulty of clearly and systematically measuring the impact of this transformation on the social and environmental aspects as opposed to the economic and productivity aspects of the industrial system. Underlying this is the enabling technologies that affect virtually as well as physical space closely interrelated through human-machine interaction and the digital twins.

## 5 A Paradigm Shift in Education to Manage the Transition

Time after time, the act of designing and making objects has remained almost unchanged: the human mind comes up with a design, the hand sketches it out and, finally, the hand works to manually transform the concept into reality. Adding digital know-how to the process sets the basis for realising any mass-produced object. In this scenario, AI becomes a disruptive tool because it can assist the designer in the creative phase up to the materialisation of the digital form. While it is true that tools proliferate with disarming speed, what is lacking is an operational methodology capable of systematising the above and opening up new scenarios through which to respond effectively to the concrete problems of the contemporary era. The use of technology for 'educated' and 'creative' entertainment can unfortunately be configured yet another element of mass distraction concerning the concrete problems that humanity is called upon to face. This risk must be concretely stemmed from using solid technical education, which must now start as early as primary school and continue throughout people's lives. A key element of this process is the inter- and trans-disciplinary approach that must be reflected in the development of an operational methodology capable of providing the right know-how to meet the challenges of the current era governed by the exponential growth of 'disruptive technologies'. In this respect, the role of second-level training is crucial as it should foster the development of a holistic vision supported using tools and technologies that learners should at least be familiar with thanks to first-level training courses. Looking at Italy, for example, the Next Generation EU plan has paved the way for the adaptation of technological infrastructures in Italian secondary schools and the introduction of emerging technologies in education. The *'Scuola Digitale'* (Digital School) plan represents a driving force for this, even if what is currently lacking is a teaching methodology capable of integrating tools and technologies into the teaching programmes of the various disciplines, both humanistic and scientific. It is precisely this last aspect that represents a further transition from I4.0 to 5.0: the interdisciplinary approach, which is necessary to govern complex processes and transformations, must favour the inclusion of the humanities in technological research from the earliest stages of education. However, from the point of view of education, the continuous, rapid and relentless race for technological innovation is making it increasingly complex to update and bring up-to-date school and university curricula. Teachers and researchers are called upon to chase innovation and master it at once to be able to disseminate it seamlessly in the community of reference. This process, in any case, can be very difficult to put into practice since the acquisition of knowledge even by the teaching staff requires time and a necessary degree of theoretical and practical depth: it is not possible to teach something that one does not master effectively and that one does not govern morally and philosophically. Therefore, this perspective calls on universities and research centres to change their model and to open up more and more to the corporations that are the protagonists in the development of these technologies, to foster paths of open innovation and technology transfer. In particular, the theme of lifelong learning and the perpetual structuring of courses dedicated to the acquisition of new skills in the field of technological innovation will lead universities to become management hubs of knowledge transfer. No longer, therefore, almost exclusive holders of the highest peaks of knowledge, but actors capable of organising and facilitating the horizontal distribution of knowledge in partnership with technology companies and with institutions and governments. On the other hand, technological innovation can open up many as-yet-unexplored avenues that can foster self-entrepreneurship dynamics, especially among university students. In this sense, universities must play a fundamental role, systematically equipping themselves with business incubators and accelerators, which can provide fundamental support for all those students who are interested in developing their entrepreneurial idea through the launch of a start-up. Nevertheless, this dynamic should also be encouraged and facilitated among researchers, through incentives and career advancement for those who decide to open and run a spin-off company in parallel with their academic activities, perhaps creating new job opportunities for young graduates or PhDs. In this scenario, the university is called upon to become increasingly 'entrepreneurial', i.e., capable of incorporating into ordinary study courses one or more courses aimed at starting up and running a company or developing a business idea. Such a prospect has the potential to detonate the possibility, widely perceived, of an uncontrolled explosion of unemployment resulting from the endemic spread of technological innovations such as robotics and artificial intelligence. In fact, humanity has two roads ahead of it: the first is to stop the incessant development of such technologies because it is potentially too impactful from a social point of view, especially from the employment perspective; the second, making future workers ready, to be able to seize the opportunities that technological innovation can offer, in terms of creating new (albeit different) job profiles and positions or new business ideas. The key to harnessing the opportunities offered by I4.0 from a social point of view lies in how we manage to channel innovation from a socio-occupational point of view. Indeed, being able to utilise technology to significantly reduce repetitive and time-consuming jobs, while significantly increasing the number of creative and knowledge-intensive jobs, could be a hugely valuable achievement for all of humanity.

## 6 Conclusions

This contribution offered an overview of the key concepts of I4.0 and the application of enabling principles and technologies in the AEC sector. In this sense, the most promising possibilities offered by the fourth industrial revolution have been analysed, hinging them inextricably around the theme of sustainability, in the broadest sense of the term. Furthermore, the chapter addresses the issue of the transition towards the emerging I5.0, proposing a refocusing of technological advancement in a human-centred and planet-oriented key. Moreover, the foundations are laid for a broader discussion around the issue of training the professional figures who will be called upon to manage such complex, interrelated and systemic processes. What is prefigured is a new professional figure capable of managing the entire design process with a systemic vision through which human sciences are merged with technological research. The training process must therefore not only provide adequate knowledge of the enabling technologies but also deal with structuring an operational methodology to be developed concerning a holistic vision necessary for guaranteeing a future of prosperity and economic progress while ensuring a sustainable tomorrow for our planet.

**Acknowledgements** This chapter is the result of the combined work of three authors. The authors have revised all the paragraphs, and the paper structure and the research topics have been conceived together. However, the first part of the contribution was primarily written by Micaela Colella and reviewed and integrated by Maurizio Barberio and Angelo Figliola, while the second part (Sects. 4–6) was written by Maurizio Barberio and Angelo Figliola and reviewed by Micaela Colella.

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# Achieving SDGs in Industry 4.0. Between Performance-Oriented Digital Design and Circular Economy

**Alessandra Battisti and Livia Calcagni**

**Abstract** Design sits prominently at the heart of the circular economy and requires us to rethink everything: from products, to business models and cities. Since everything that surrounds us has been designed by someone—the clothes we wear, the buildings we live in, even the way we get our food—and mostly according to the linear model, almost everything needs to be redesigned in accordance with the principles of the circular economy. Circular design process comprises human-centred and performance-oriented approaches. Extending the life of a product allows it to remain in use for as long as possible, and may involve designing products to be physically durable or require innovative approaches that allow the product to adapt to a user's changing needs as time passes. Digital Design plays a crucial role in achieving quickly and efficiently, quality architectural projects both from the users' point of view and from a global perspective as it closes the loop of material flows.

**Keywords** Performance e oriented · Digital design · Circular economy · Architecture 4.0

**United Nations' Sustainable Development Goals** 11. Make cities inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns · 13. Take urgent action to combat climate change and its impacts

## 1 Introduction

The digital revolution has set many challenges and opportunities before the architecture, energy and construction sector. Indeed the adoption of Industry 4.0 (I4.0) technology in sustainable production and circular economy has deeply transformed

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_2

the system of project design, construction, building management and maintenance, and last but not least, the sharing of information. I4.0, digitization, smart building, augmented reality have become part of the evolved common vocabulary of design in the construction sector and in particular in all its different declinations related to circular economy. The very concept of circular economy is amplified by I4.0, that provides a strong support to the different project phases, thanks to the integrated approach that allows to evaluate in a virtual way—and in advance—all the information related to the entire life cycle of a project: from design, to construction, demolition and disposal. The concept of circular economy from the perspective of performance-oriented digital design has gained momentum among businesses, policy-makers and researchers due to its potential to contribute to sustainable development [1, 2] through a series of efficiency and productivity improvements, commonly known as circular strategies. The high value of digitally oriented design is also emphasized in some EU technical-analytical reports [3] that highlight how standardized information management can contribute to the prediction of environmental performances and thus improve decision-making concerning the future impact of a project. This is achieved by detailing the various activities and respective indicators that characterize the project from construction in terms of climate-altering emissions, resource consumption and waste production, to construction in terms of transport, construction site, realization, and eventually to operation in terms of operating energy consumption, heating/cooling, shading, ventilation, water and waste treatment, building life cycle, use and maintenance. Innovative technologies and paradigm shifts applied to digitized design contribute to extend the useful life of building artifacts, to reduce waste, to discretize performance and improve environmental impact, to identify opportunities to reuse building materials and/or components. The knowledge of physical-technical-performance characteristics, the availability of materials, and the configuration of optimized combinations of materials and components, as well as the use of a standardized language that ensures and/or increases interoperability between different technical formats, also contribute to better planning and organization of resources. In this sense, digital technologies play a crucial role in improving circular economy strategies and practices by overcoming environmental problems and fostering paradigmatic approaches towards the achievement of the SDGs.

## 2 Methodology

The authors carried out an analysis based on performance-oriented digital design and on 7 strategies of the circular economy—recover, recycle, reuse, regenerate, repurpose, reduce, rethink—to assess how and to what extent the achievement of the SDGs can be found in some projects and in particular goals 12 (Responsible Consumption and Production: Reversing current consumption trends and promoting a more sustainable future) and 13 (Climate Action: Regulating and reducing emissions and promoting renewable energy). At the very moment, recovery and recycling actions carried out in construction processes do not always necessarily promote a circular economy, even though they are among the most common applied strategies in the construction field to date. It is precisely in the medium- and long-term planning on recovery and recycling that I4.0 could enhance the circular economy and lead to the pursuit, albeit partial, of these two SDGs. In relation to these, the essay reviews experimental digital tools and practices, showing how they can reduce waste, increase energy and ecological efficiency, effectively and efficiently employ renewable energies, close production cycles and maximize the preservation of the economic value of materials and products. The proposed methodology follows that used by Bocken [4], which identifies three iterative steps for a practice and literature review: (1) identification of topics and categorizations by literature review, (2) synthesis through the development of an integrative framework, and (3) identification and mapping of practical examples to validate and further develop the framework. The logical framework is essential to extend the knowledge base by providing a detailed review of Industry 4.0 between sustainable production and circular economy by integrating three contemporary concepts in the context of supply chain management: Agile approach; IIoT stack and Technology ecosystems.

**Agile approach**. An approach that employs rapid iterations, fast failures and continuous learning. An approach whereby research teams work together extremely effectively by facilitating collaboration between different functions and turning use cases into self-learning examples that enable rapid innovation and renewal.

**IIoT stack**. Smart manufacturing system that enables seamless integration of legacy and new Industrial IoT infrastructures to build a stable and flexible technological backbone through intelligent use of existing systems with efficient integration within a new technological smart manufacturing process while limiting costs, consumption and waste.

**Technology ecosystems**. Technology ecosystems with access to vast datasets and co-innovation opportunities that enable collaboration between technology vendors, suppliers, customers and related industries to implement cutting-edge solutions and best practices.

## 3 Limitations and Implications of the Research

One must keep in mind that digital transformations are revolutionizing all aspects of production, affecting not only processes and productivity but also people. The right applications of performance-oriented digital design technologies can lead to more effective decision-making, new opportunities for upgrading, retraining and cross-functional collaboration.

In the construction field, the impacts can be identified especially in the reduction of production time, optimized process management with win-win benefits associated with reduced environmental impact, made possible by lower emissions and reduced waste, and more efficient consumption of energy, water and raw materials. Yet, evident risks remain: by pursuing digital transformation as a theoretical exercise, many research centers unwittingly create isolated and local operations which have little to do with future cycles of manufacturing excellence. They fail to access a broader network of production as they are more technology-driven rather than value-driven This results in a technology-first rollout where proposed solutions are deployed without a clear link to real value opportunities, business challenges or market capacity to absorb them. In fact, a large majority of the experiments deployed remain at the pilot project level, as they don't develop the full potential of transformation through performance-oriented digital design also in terms of return on investment.

With so much at stake, manufacturers are investing a lot of time and money in digital transformation. These investments are paying off for some, but most are unable to scale successful pilot programs or take full advantage of new tools and technology to see significant returns.

## 4 Case Studies

Given the emerging and widespread amount of applied and realized projects, our study investigated not only academic sources but also practice case study examples and grey literature [5]. As mentioned previously, the identified framework embraces circular economy (CE) and industry 4.0 (I4.0) paradigms, digital fabrication (DF) processes and digital technologies (DTs), and performance oriented design (POD), all with a view to sustainable environmental design. The integrative synthesis was followed by the identification and mapping of practical examples to validate and further develop the framework. Indeed, there are some paradigmatic European and international examples that provide evidence of how the integration of performance-oriented digital design and circular economy principles and strategies is increasingly implemented in the construction industry for the achievement of the SDGs, in particular goal 12 and 13. In analyzing these virtuous case studies we asked ourselves why they work, in which terms they contribute to achieving the 7 strategies of circular economy: recover, recycle, repurpose, re-use, regenerate, reduce, rethink; and eventually to what extent the three concepts of supply chain management occur in terms of agile approach, IoT stack and technology ecosystems.

More precisely the case study research method involved a cross-case analysis following the presentation of separate single-case studies [6]. The case studies have been selected according to their relevance to the criteria and topics mentioned above and have been analyzed on the base of the same indicators.

### *4.1 Maison Fibre*

Maison Fibre (Fig. 1), exhibited at La Biennale di Venezia 2021, is the result of research on robotically manufactured fibre composite structures carried out by the Institute for Computational Design and Construction and the Institute of Building

Structures and Structural Design at the University of Stuttgart. It is a full-scale inhabitable hybrid structure combining laminated veneer lumber with fibre-polymer composites (FPC). It is the first multi-storey building system fabricated with this novel technique [7]. In terms of tectonics the entire structure consists exclusively of so-called fibre rovings: bundles of endless, unidirectional fibres made of glass and carbon.

IIoT stack. The manufacturing process involves the use of a coreless robotic winding process, which allows for locally load-adapted design and alignment of the fibres. Coreless filament winding is a robotic fabrication technique in which conventional filament winding is modified to reduce the core material to its minimum, thus enabling an extraordinary lightweight construction [7]. This technological smart manufacturing process allows to limit costs, consumption and waste.

Technology ecosystems. This structure marks a turning point in the transition from pre-digital, material-intensive construction that makes use of heavy, isotropic building materials such as concrete, stone, and steel—which are often extracted in distant places, processed into building components, and carried over long distances—to genuinely DFTs with locally differentiated and locally manufactured structures made of highly anisotropic materials [8].

Agile approach. The extremely low material consumption combined with the very compact, robotic production unit allow to run the entire production on-site without a significant amount of noise or waste, both during the initial construction process, and during expansion or conversions.

Furthermore, this novel material culture in architecture brings about its entailed ecological (material and energy), economic (value chains and knowledge production), technical (digital technologies and robotics), and sociocultural matters.

### *4.2 Aguahoja I*

Oxman's study focused on water-based robotic fabrication as a design approach and on enabling technology for additive manufacturing (AM) of biodegradable hydrogel composites meant for manufacturing architectural-scale biodegradable systems [9].

Technology ecosystems. The research group aimed at applying material ecology (ME) research to the study and design of a new biocompatible material for architecture, characterized by a programmed life, therefore bound to be gradually reabsorbed into nature [10].

IIoT stack. The structure (Fig. 2) is digitally designed and robotically fabricated: 3D printed from biodegradable polymers. The construction process involves a robotically controlled arm and multi-chamber extrusion system designed to mix, process and deposit biodegradable-composite objects combining natural hydrogels (e.g. chitosan, sodium alginate) with other organic aggregates. More specifically, the architectural skin-and-shell is made of 5,740 fallen leaves, 6,500 apple skins and 3,135 shrimp shells, 3D printed by a robot, modelled by water and coloured with

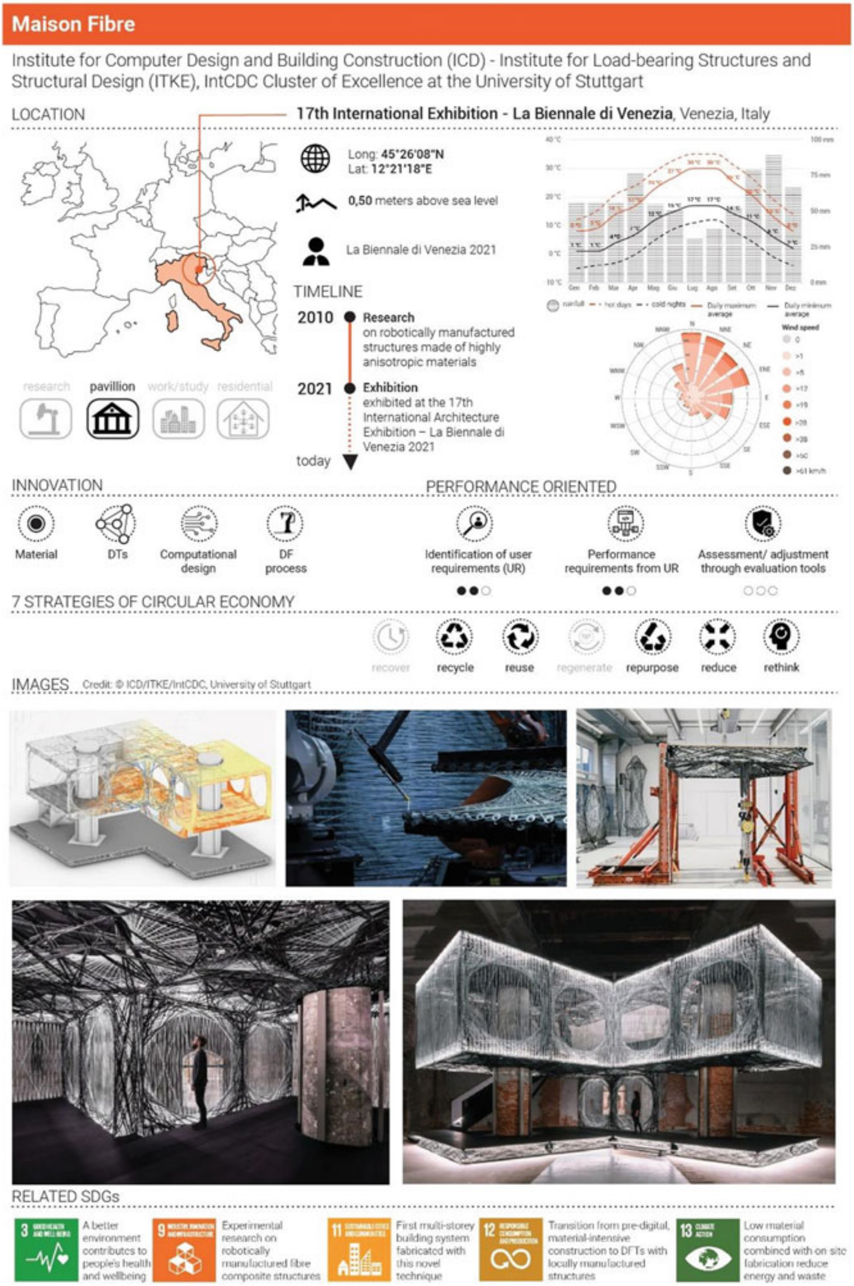


**Fig. 1** Maison fiber case study resume form

natural pigments. The result is an organism-matter that captures carbon dioxide, enhances pollination, increases soil microorganisms and provides nutrients.

Agile approach. These water shaped skin-like structures are designed and manufactured as if they were grown, therefore no assembly is required as well as no disposal issues occur.

Despite the urgent need for alternatives to fuel-based products and in spite of the exceptional mechanical properties, availability, and biodegradability associated with water-based natural polymers, AM of regenerated biomaterials is still in its early stage [9]. Moreover, these structures react to their environment, adapting their geometry, mechanical behaviour and colour in response to fluctuations in heat, humidity, and sunlight (time-based 'temporal' behaviour). This structure shows how ME presents new opportunities for design and construction that are inspired, informed, and engineered by, for, and with nature. An architecture capable of programmatically decomposing could introduce a new type of disposal in the construction sector that does not alter the ecosystem, and is perfectly in line with life cycle assessment principles oriented to the cradle to cradle design.

### *4.3 Harvard Science and Engineering Complex*

The new Harvard University complex (Fig. 3) is designed to inspire learning and scientific discovery while showcasing sustainability. Thus, special emphasis was set on effective façade design, efficient energy performance as well as occupant comfort. These are mainly addressed through the stainless-steel screen envelope which is designed according to parametric simulations and using a novel manufacturing method, hydroforming [11]. Hydroforming is an industrial cold forming process in which a metal blank is driven into a single mold with hydraulic pressure to form extremely thin parts with exceptional structural stiffness. It has been developed in the automotive and aerospace industries where weight to strength ratio has a compound effect on production cost, safety, performance, and energy consumption, but it has not been widely used for architectural applications yet [12].

IIoT stack. In this case hydroforming was applied in a sun shading system that leverages the advantages of this technology: lower tooling costs, precise geometric definition, and superior structural properties. Calibrated to the extreme seasonal variations of the local climate, the system is precisely designed and dimensioned to temper solar heat gain in the summer while maximizing daylight and solar energy in the winter, reducing cooling and heating loads [12]. The screen also reflects daylight towards the interior while maintaining large view apertures.

Agile approach. The use of parametric performance studies and simulations, including rapid prototypes, full-scale visual and performance mock-ups, and advanced industrial design and simulation software (like CATIA), allows to maximise structural, material and manufacturing efficiency and at the same time enables rapid iterations, fast failures and continuous learning.

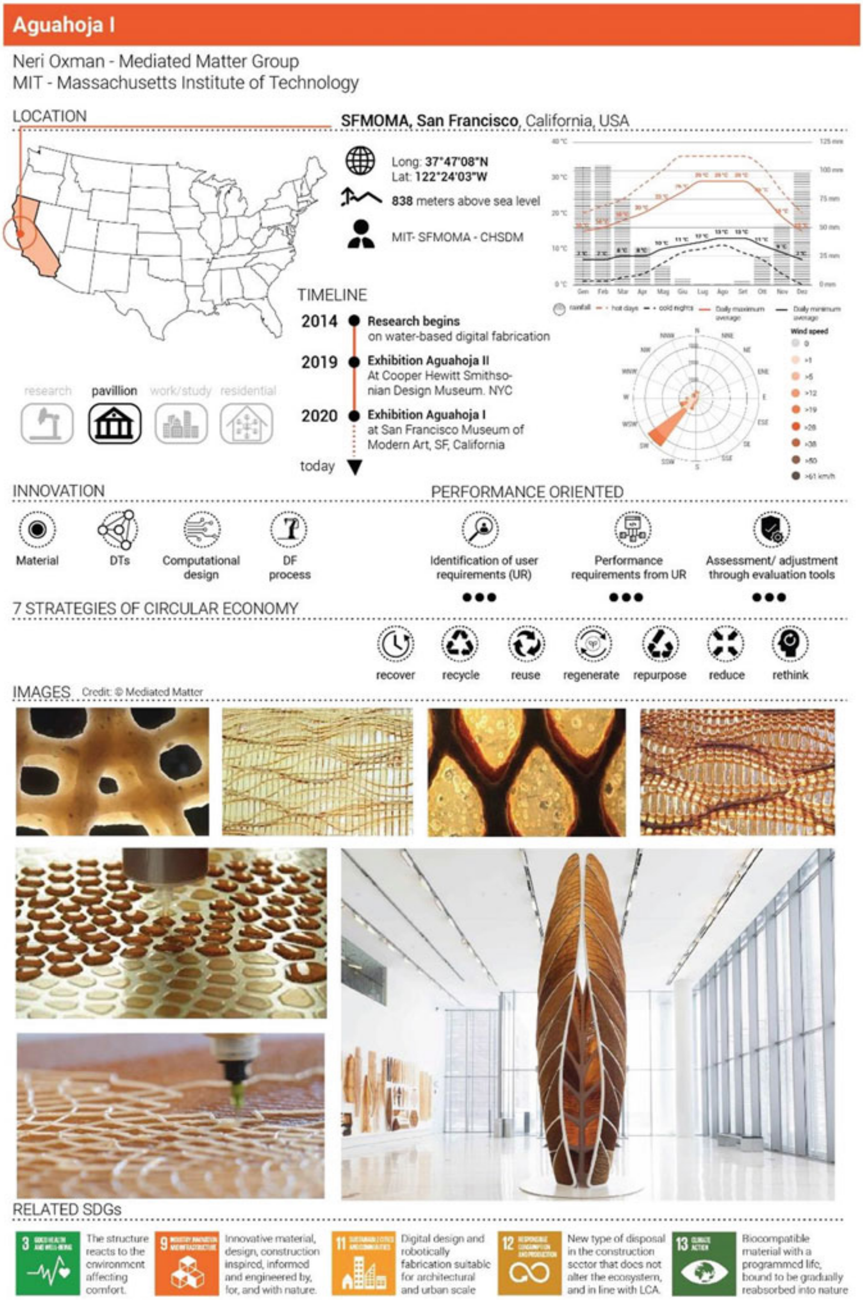


**Fig. 2** Aguahoja I case study resume form

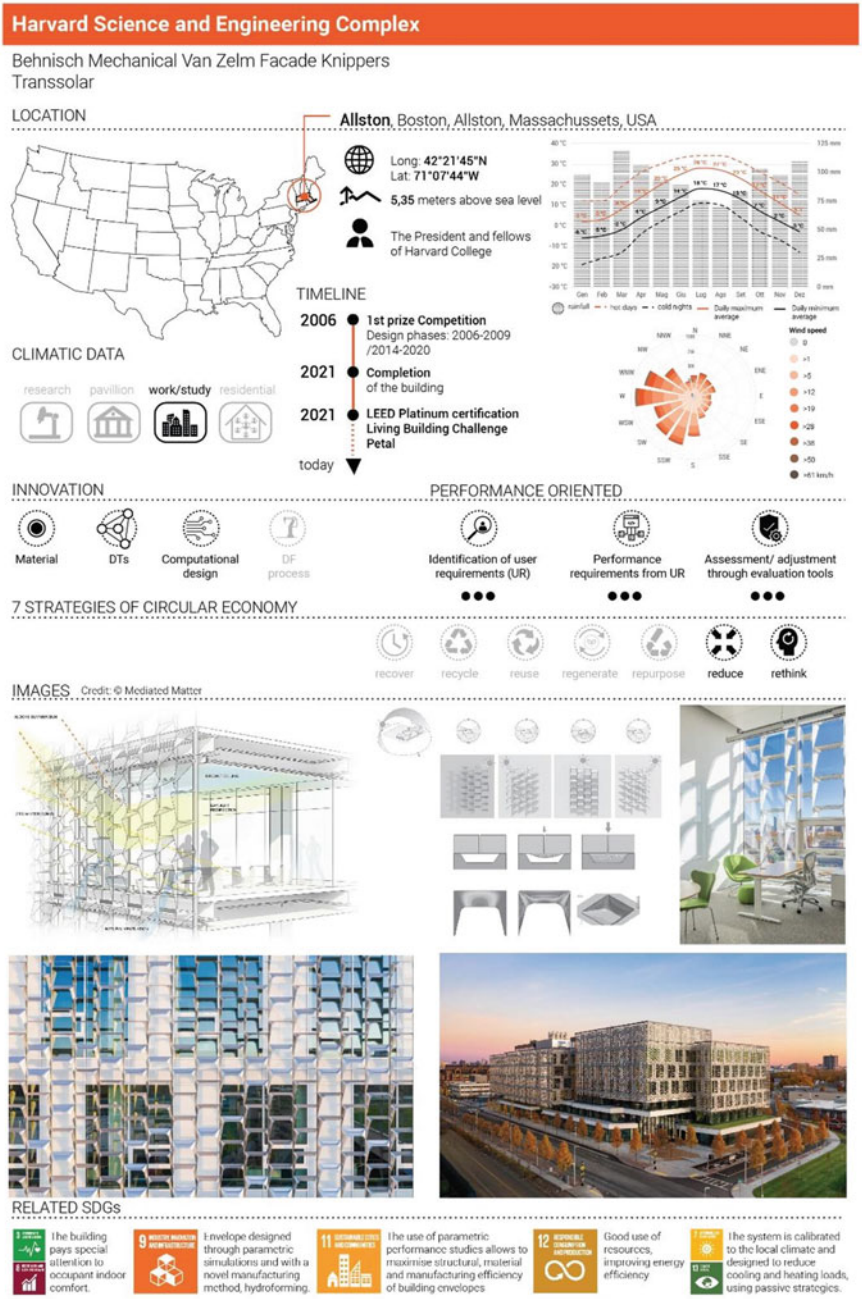


**Fig. 3** Harvard science and engineering complex case study resume form

Technology ecosystems. This project proves how a coherent and appropriate combination of environment, technology and architecture can achieve excellent aesthetic quality, a high-performance building envelope and energy efficiency.

### 4.4 J-Office

The project (Fig. 4) consists in the conversion of a dilapidated building from a warehouse into an architectural design studio located in an old industrial park in Shanghai, China [13].

The concept of the Silk Wall, the external wall that surrounds the warehouse, was developed starting from the manipulation of simple materials using up to date DF processes. In particular the wall consists of cement blocks, angled to create an interesting texture that varies the amounts of light into the building. These cinder blocks are used throughout China since they are so inexpensive, but they are extremely rigid in form and dimension. Thus, the exploration of the material limits led to the use of the blocks with a different bricklaying method by creating stacking algorithms.

IIoT stack. Parametric processes have been used to superimpose the patterns, the contours and definition of silk forms while allowing the wind to enter. To develop the design concept, an algorithm was designed to force a rotation of each cement block.

Agile approach. After an issue appeared during the construction phase, thanks to the advantages of parametric design, a series of alternative results were soon produced by adjusting the parameters, and, after a short calculation, a range of options was identified. This project shows the advantages of parametric design not only in the initial design phase but especially in the construction and management phase: by simply adjusting some parameters, a short calculation is able to offer a range of options and display a series of alternative results.

Technology ecosystems. Computational optimization in the design phase helps to adjust fabrication layouts according to known computer numerically controlled (CNC) technologies [14].

### 4.5 Living Places

The project (Fig. 5) suggests a new way of thinking focused on building a better living environment that benefits both people and the planet.

Technology ecosystems. Assuming that all phases of the project development must be taken into consideration, the project is meant as an open-source development model that takes into account its entire lifecycle, enabling a new holistic approach to sustainable construction. In fact, by using low impact materials and by considering all stages of the building's life cycle and understanding the implication of each design choice, it is possible to reduce emissions by up to 75% while meeting the demand for

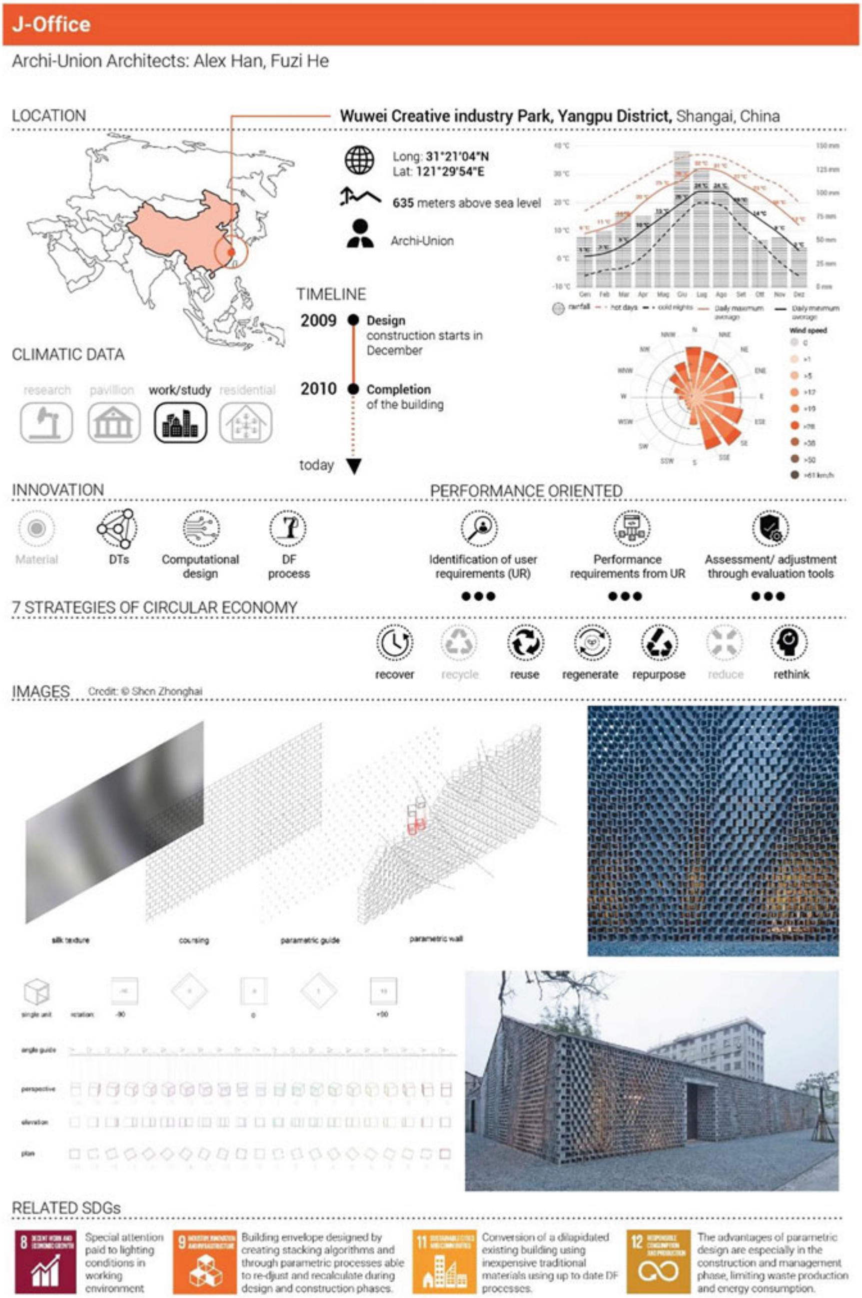


**Fig. 4** J-office case study resume form

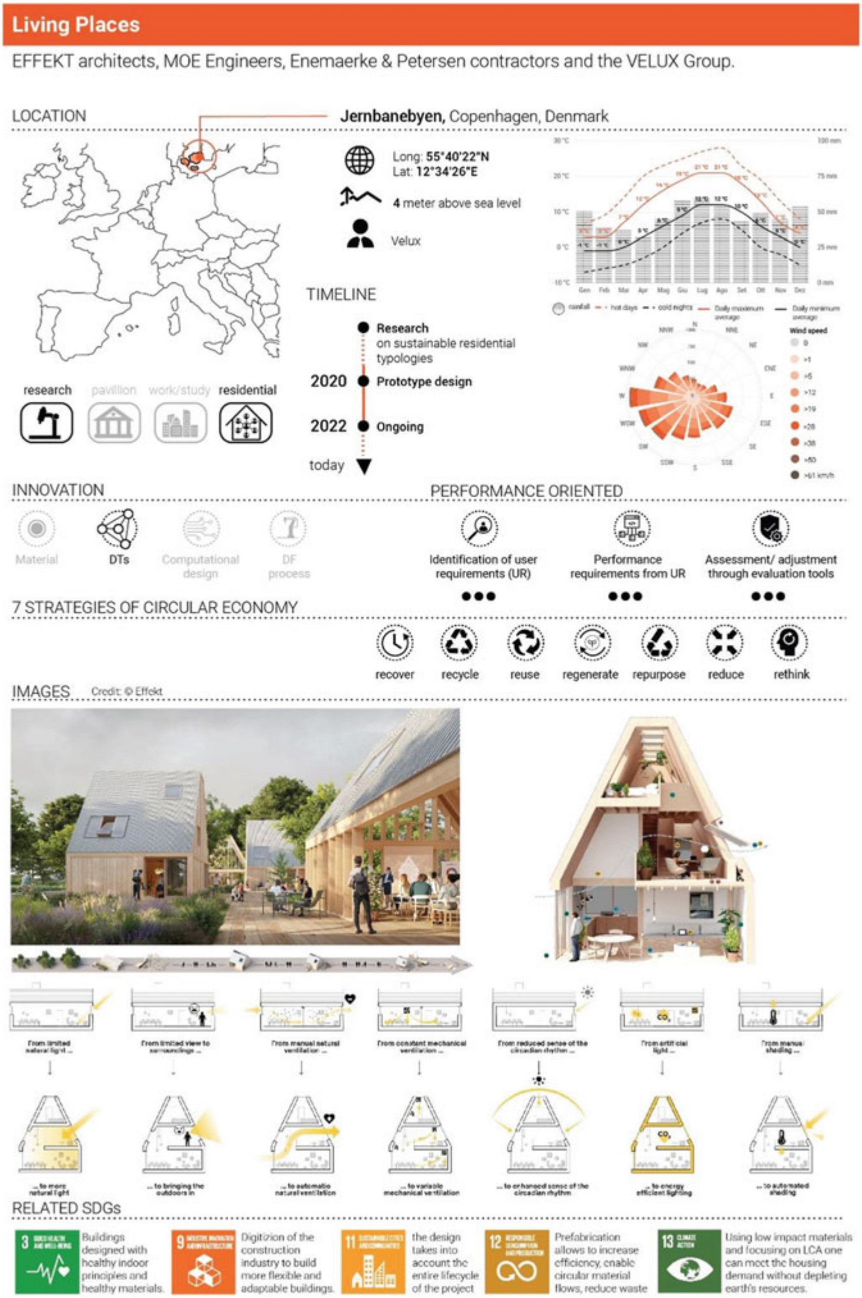


**Fig. 5** Living places residences case study resume form

increased housing without depleting the earth's resources. By separating technical systems and building systems the prototype uses circular economy as a means to extend the building's lifetime and reduce cost, labor and waste [15]. The Build for Life approach comprises seven strategic drivers (flexibility, quality, environment, health, community, local, affordability) making up the Compass Model, which is meant to guide the design and building process, providing stakeholders with a framework for reaching an outcome that is sustainable on multiple levels [16]. This solution offers a simple modular building system that requires little to no maintenance and can easily be disassembled and thus repaired or retrofitted during its lifespan.

Agile approach. Moreover, Living places is conceived as a toolbox of different housing typologies that are context-responsive and designed to constantly adapt as occupants' needs change over the day, the year, and the lifetime. The project stands out for its people oriented approach in the definition of the demand-performance framework aimed at acquiring an holistic and integrated understanding of the occupants' needs. In fact, special emphasis is paid to daylight, thermal comfort, air quality, acoustics and outdoor connection [17].

IIoT stack. Overall, digitizing the construction industry and through prefabrication one can increase efficiency and enable more sustainable development, reducing waste, and enable circular material flows.

## 5 Conclusions

These projects all reveal the strong need—within the construction practice—for innovative processes and technologies that recognize the importance of sustainable design and overcome the inefficiency and lack of interoperability present in the sector [18]. The role of technological culture, together with a performance-driven approach, interdisciplinary dialogue and the creation of a growing information content are essential to manage innovation in the context of digital eras [19]. At the same time, DTs, such as the Internet of Things (IoT), big data, and data analytics, are considered essential enablers of the circular economy (CE) [20]. In fact, the combined methods of computational design and robotic fabrication have demonstrated potential to expand architectural design. Above all, factors such as material use, energy demands, durability, GHG emissions and waste production must be recognized as the priorities over the entire life of any architectural project [18]. To this end, the potential of DTs, DF, and performance oriented design is remarkable for achieving sustainability according to the well-known broad definition (Brundtland Report 1987) of SD as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' [21].

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# Industry 4.0 for AEC Sector: Impacts on Productivity and Sustainability

**Ilaria Mancuso, Antonio Messeni Petruzzelli, and Umberto Panniello**

**Abstract** The Architecture, Engineering, and Construction (AEC) sector is experiencing an intense internal transformation, triggered by two topics that must be addressed for assuring a prosperous future of the industry. Specifically, on the one hand, the actors of the AEC sector need to commit themselves towards sustainability, in order to reduce the significant impacts that the industry causes on the environment in terms of pollutant emissions. On the other hand, work practices must be reviewed for improving their actual scant efficiency, which results for AEC sector in a very low productivity rate with respect to other industrial sectors. To ensure long-term business continuity based on the two pillars of productivity and sustainability, AEC actors are considering a deeper use of Industry 4.0 into their businesses. In fact, Industry 4.0 technologies are recognized to have positive impacts on both operational and sustainability performance in the AEC field, so much to determine the birth of the new Construction 4.0 paradigm, which is fascinating although scant adopted. In this context, the following chapter aims to analyze the changes that some of the most cutting edge and revolutionary technologies of Industry 4.0 bring in three phases of the construction life cycle. Specifically, the chapter explores how such technologies allow to address productivity and sustainability issues during the phases of architectural and design planning, works' execution, and support processes management, acting as levers for building more efficient and sustainable constructions.

**Keywords** Architecture · engineering and construction · Industry 4.0 paradigm · Technologies for sustainability · Technologies for productivity

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_3

**United Nations' Sustainable Development Goals** Goal 9: Industry, Innovation and Infrastructure. Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation · Goal 11: Sustainable Cities and Communities. Make cities and human settlements inclusive, safe, resilient, and sustainable · Goal 12: Responsible Consumption and Production. Ensure sustainable consumption and production patterns

**Suggested Topics** IoT and Cyber-Physical Systems in Architecture · Digital Twin · BIM and Interoperability · Virtual Reality and Augmented Reality · Digital and Robotic Fabrication · Additive Manufacturing and 3D Printing

## 1 AEC Sector and Industry 4.0

The Architecture, Engineering and Construction (AEC) sector is undergoing an intense internal transformation, which starts from two issues that must be unravel for the future of this industry. On the one hand, there is the challenge of sustainability. In fact, AEC sector is responsible for 36% of global final energy use and 39% of all carbon emissions in the world [18], using large amounts of materials and energy to develop, operate, and demolish buildings. On the other hand, the sector is currently characterized by a very low productivity rate. Indeed, the construction sector presents one of the highest productivity gaps among the other industrial businesses, with a yearly growth of 1% versus the average of 2.8% [10].

To respond to these issues and ensure both sustainable and profitable business continuity in the near future, AEC sector can seize large opportunities deriving from Industry 4.0 paradigm. In fact, innovation driven by new technologies in AEC businesses can lead to an increase in productivity, simultaneously reducing environmental impact [6]. Actually, Industry 4.0 has ample maneuver margin for augmenting sustainability and operational performances. In particular, on the operational front, Industry 4.0 in AEC sector reduces inefficiencies and waste with better, faster, and safer collaborations, communications, and procedures, while on the sustainability front it ensures prudent use of resources with significant reduction in energy usage and emissions [14].

The potential of Industry 4.0 to relaunch the AEC market is evident so much so that it led to the concept of Construction 4.0 [14]. The Construction 4.0 framework borrows typical Industry 4.0 technologies to be used in construction sites, also employing new digital technologies specifically designed for the AEC field. Examples of Construction 4.0 applications are the adoption of IoT sensors and platforms to manage workers and buildings, the use of robots on construction sites, the spread of 3D printing of homes, as well as the integrated management of all the aspects related to a project within the Building Information Modeling software. The benefits of these Industry 4.0 technologies applied in the AEC field are remarkable, including increases in performances and transparency throughout the entire built environment value chain, as well as reductions in resource consumption and $CO_2$ emissions, with the result of more efficient and sustainable construction [17].

Despite Industry 4.0 technologies are available and mature [12], their application to the AEC sector is not straightforward [17]. This is because the construction industry is one of the least digitalized in the world [2]. In fact, the sector, due to attitudinal, industrial, and institutional barriers, remains strongly anchored to traditional business models, proving to be averse to risk and change [16, 17] and missing in the exploitation of new technologies to innovate processes and services [12, 20].

In this contest of great fascination with the uses and challenges related to the implementation of Industry 4.0 in the AEC sector for increasing the sustainability and profitability of businesses, the following chapter offers a review of the technologies that AEC companies can adopt throughout the entire life cycle of construction to simultaneously solve sustainability and productivity issues (see Fig. 1). Specifically, the chapter covers areas ranging from architectural and design planning to works' execution on construction sites, up to the management of support processes. For each phase of the life cycle experienced by construction (i.e., planning, execution, and management), the chapter investigates how Industry 4.0 technologies positively influence both the improvement of operational performance (through increase in quality and work safety and reduction of project times and costs) and the achievement of sustainability goals (through reduction of the energy consumption).

With this result, the work aims to increase both scientific and practical knowledge on how the Industry 4.0 paradigm enables productivity and sustainability in the AEC sector, paving the way for an innovation strategy where these two pillars are equally embedded into all areas of business.

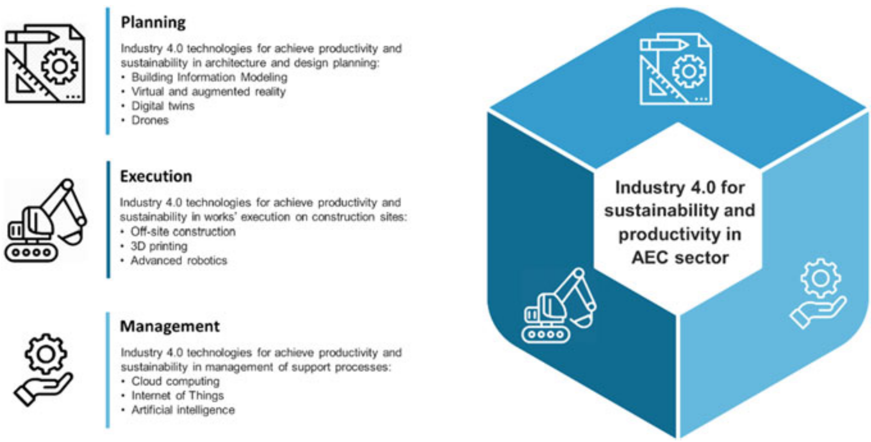


**Fig. 1** Industry 4.0 technologies for sustainability and productivity in construction life cycle

## 2 Industry 4.0 for Architectural and Design Planning

Architectural and design planning represents the first phase in constructions lifecycle, as well as is among the most expensive task for professionals and companies. In fact, planning activities require studying design choices, assessing the effectiveness and feasibility of possible architectural solutions, and coordinating the work of multiple intra-company stakeholders (e.g., designers, architects, administrators, accountants) for satisfying the needs of clients.

The management of this complicated but indispensable phase of constructions' projects life cycle can be facilitated by the use of various Industry 4.0 technologies. In this section, the potential brought by Building Information Modeling (i.e., information system containing all the information relating to a project), virtual and augmented reality (i.e., apps and viewers that overlay digital information on the real world and simulate different scenarios), digital twins (i.e., copies of structures that allow virtual management of physical buildings), and drones (i.e., controlled aircrafts that map and control work sites remotely) are presented.

### *2.1 Building Information Modeling (BIM)*

Building Information Modeling (BIM) is a software whose adoption has grown significantly in recent years in AEC industry [1]. BIM allows architects to design buildings by enclosing and linking, in addition to the drawings, all the information relating to the project that can be useful in different life cycle phases. For examples, as regards the phase of temporal and economic supervision of the project, thanks to the 4D and 5D dimensions of BIM, the model can be fully integrated with the Gantt diagram developed by the Microsoft Project software, used by almost all construction firms and professionals. Personnel benefits from this linkage because it can verify activities and times involved during a certain project phase, develop analysis scenarios for specific activities, and obtain a constantly updated overview of the work progresses and cost estimates. The 4D and 5D dimensions of BIM therefore optimize both the definition and updating phases of project releases (thanks to the possibility of quickly evaluating planned changes according to the clients' needs) as well as control ones (thanks to the possibility of analyzing and comparing the parameters of the work in real time to spot any deviation). In addition, the ability to use BIM models even on mobile applications allows supervisors to access the entire project, filtering the data of interest for coordination on the work site and viewing information that is always updated and updatable. The great interoperability offered by BIM is guaranteed by the open format IFC (i.e., Industry Foundation Classes), which assures the exchange of data between the various subjects involved in the life cycle of the commission (e.g., architects, engineers, designers, maintenance technicians) and between different software platforms. Thanks to this feature, the use of BIM generates a reduction in costs due to the zeroing of errors related to data fault or

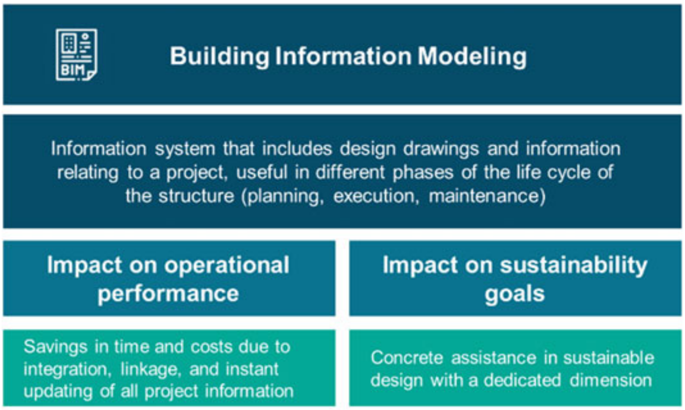


**Fig. 2** Building information modeling for sustainability and productivity in planning

redundancy. In fact, the maximum degree of interoperability offered by technology translates into the possibility for each of the members of the project team to work using the best software solutions for his/her specific discipline, without any risk of data incompatibility or loss. This leads to significant reduction of errors generated by a lack of coordination and/or updating, and determines a contraction of global construction times from the start to the completion of the works. Furthermore, the BIM technology effectively reduces energy consumption and greenhouse gas emissions. In fact, the 6D dimension of the software, which allows to carry out energy and sustainability analyzes for projects, assists the realization of Near Zero Energy Buildings (i.e., building with high energy performances thanks to the construction, typological, and plant characteristics), saving energy and reducing $CO_2$ emissions. Figure 2 resumes the main characteristics of BIM, as well as the impacts of this technology on the productivity and sustainability of the architectural and design planning phase.

## 2.2 *Virtual and Augmented Reality*

Virtual and augmented reality (VR and AR) tools such as applications on mobile devices, glasses, and helmets designed for the AEC sector facilitate design activities as regards stakeholder engagement, design and construction support, design review, operations, management assistance, and training [5]. In particular, the uses of VR and AR for the improvement in the collaborations between offices and work sites are extremely interesting for the impact on productivity and sustainability. In fact, the integration of VR and AR devices with the 3D models of construction sites, elaborated with BIM or with AutoCAD, allows designers and foremen to view the same plans in real time and verify the validity of the design choices, simulating their presence in the virtual models. The result is an instant identification and communication of design errors, as well as the receipt of immediate feedback on the design changes, to be attached in the form of annotations, links, and videos to the elements of the project. Indeed, VR and AR devices speed up instant changes and scenario analysis, by allowing to update models and immediately share them with everyone involved. Furthermore, VR and AR tools can help contract managers in the updating of budget releases, as they enable the modification, in a single environment, of the project Gantts and the 3D models. In this way, the evolution of construction sites can be simulated, facilitating the identification of works' interferences (e.g., space and/or time overlaps), thus highlighting the risks generated by the contingent situation. The easy access to schedules and operational details, combined with the devices' feature of on-site measurement and direct comparison with work plans, automates processes. Specifically, AR applications allow to digitally carry out the measurements and checks against the prescriptions, confirming the status of the activities (i.e., in execution, completed, or delayed) and specifying the errors found on the site. Also correction actions are accelerated, since workers can suggest with interactive post-it all the information necessary for the correct execution (e.g., regulatory standards, digital instructions) as well as collaborate with remote experts for the implementation of particularly complex procedures. As regards virtual reality devices, they can optimize operators training phases, by transferring them from classrooms to interactive scenarios developed directly from BIM models or from the real site situations. The training in virtual reality, as well as the opportunity to guide staff on sites by means of AR, helps to improve safety standards on site, reducing the margin of error and speeding up operations, thus resulting in times and costs reduction. In reference to sustainability aspects, the collaboration and fulfilment of work functions with different remote teams translates into a reduction in the number of trips to and from the sites, as control activities are entrusted to operators already present on the sites and in contact with the staff in the offices. This factor, added to the ability to virtually view models without the need for continuous printing, reduces energy consumption. In Fig. 3 a synthesis of benefits released by the adoption of VR and AR for planning activities in AEC sector is presented.

## 2.3 Digital Twin

Digital twins consist in virtual representations of buildings, infrastructures, and plants, obtained through incorporation of data from digital scans, CAD drawings, BIM models, and Geographic Information System (GIS) software, as well as from Internet of Things sensors. Digital twins contain all the information of real artifacts, from the parameters relating to operating conditions and health state of structures to any anomaly and potential risk situation. Therefore, since they serve as the real-time digital counterpart of systems, they empower virtualization and optimization of design, construction, and maintenance of buildings and infrastructures [13]. In fact, digital twins allow to design every aspect of assets and test the actual performances

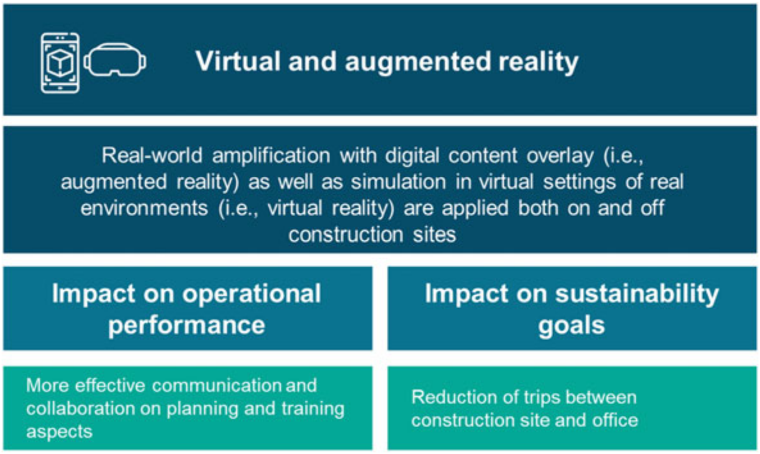


**Fig. 3** Virtual and augmented reality for sustainability and productivity in planning

that would be obtained in the real world through virtual simulations. The virtual verification of the effectiveness of different scenarios on digital twins increases the quality of work, while errors related to design or modifications are reduced. This aspect also translates into a reduction in the time and energy required for the development of cost-benefit analyzes related to system changes. It should also be noted that buildings simulations can be used to assess energy needs, quality of indoor environments, and $CO_2$ emissions throughout the entire life cycle of the assets. These analyzes allow to increase constructions and machine performances in design phases, leading to savings in energy costs by means of reduction of energy wastes. Furthermore, digital twins' dashboards are available in real time on PC, tablet, or mobile device, illustrating the most varied metrics, from costs to energy efficiency values, up to planning and inspections. In this way, facility management activities after design phases can be optimized. In particular, real-time data from buildings and machines can be used to perform predictive analyzes, in combination with series of historical data. The possibility to intervene with preventive actions with respect to problems that could cause accidents improves the quality of work and reduces management and maintenance costs. The potential of digital twins for planning phase in the AEC sector is shown in Fig. 4.

### *2.4 Drones*

The use of drones in construction sites is capable of effectively tracking and communicating the status of projects [15]. In particular, drones' adoption influences two critical AEC processes, that are place mapping and work packages monitoring. In

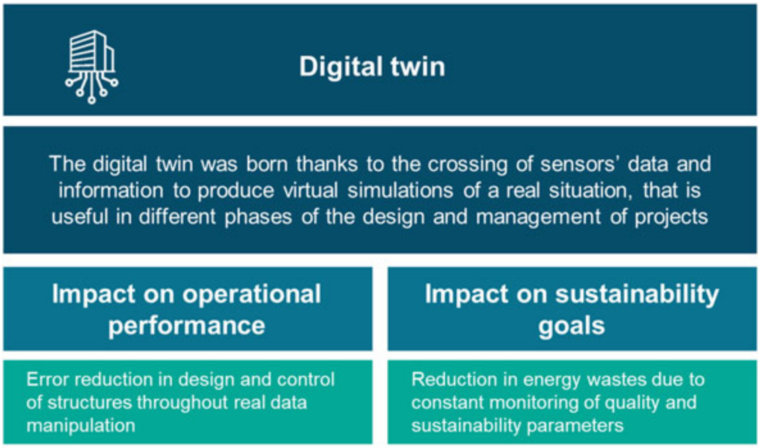


**Fig. 4** Digital twin for sustainability and productivity in planning

fact, drones controlled by mobile applications and empowered with remote measurement techniques (e.g., laser scanners, laser imaging detection and ranging) reduce data acquisition times, corresponding to a reduction in mapping costs. Moreover, data collections are not only faster and cheaper, but also more precise than manual measurements, an aspect that contributes to the increase in the quality of work. As a result, drones can be used to create highly accurate digital models, reproducing the reality of indoor and outdoor environments in a very fast and reliable way. Moreover, images collected from drones can simply be integrated within the main design tools such as AutoCAD and BIM. This feature empowers design activities of architectural renovations with the access to reliable real-world scans and simplifies the comparison between the project models and the scanned reality, promptly assessing any design error. Drones positively influence work quality also during on-site checking phases, keeping track of the times and methods of works. In fact, foremen can instantly and remotely monitor (on smartphone, tablet, or PC) all the operational phases of the work, through video-inspections in the sites carried out with the aid of drones equipped with Ultra HD cameras. This work monitoring method eliminates the need to send personnel to control construction sites and generates a rapid identification of inefficiencies, thus accelerating the implementation of corrective actions. Therefore, the remote monitoring of work progresses by means of drones increases on-site safety by limiting the risks associated with falls (the most common cause of an accident on site) due to the reaching of particularly dangerous areas for inspections or checks. In addition, the use of drones assumes particular importance in complex sites (e.g., sensitive sites from an environmental point of view or an historical interest), where the invasiveness of the intervention must be minimized. The operational advantages connected to the use of drones in work sites are combined with a high degree of energy consumption optimization, as the electrical power supply of aircrafts limits the environmental impact of the devices and avoids noise pollution, ensuring silence

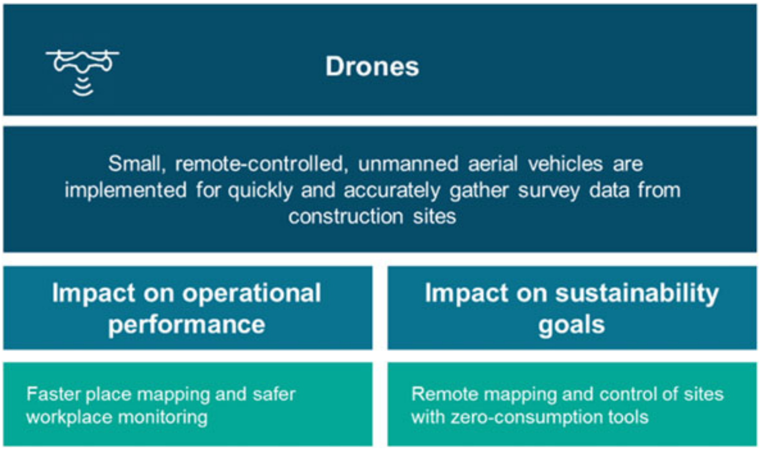


**Fig. 5** Drones for sustainability and productivity in planning

in flight operations. Figure 5 exemplifies the considerations on the role of drones in increasing the productivity and sustainability of the AEC sector.

## 3 Industry 4.0 for Works' Execution on Construction Sites

The execution phase of construction works represents a highly traditionalist activity, guided by well-established and poorly efficient construction techniques based on an intense use of manpower. Actually, novel methods of works' execution arise in AEC sector, borrowing different Industry 4.0 technologies from purely industrial and manufacturing scenarios to improve productivity and business sustainability.

The Industry 4.0 technologies featured in this section are off-site construction (i.e., transformation of the construction process into the assembly of prefabricated modules), 3D printing (i.e., use of mega-devices for the construction of buildings or parts of them) and advanced robotics (i.e., intelligent machines that support staff in carpentry operations).

### *3.1 Off-Site Construction*

Off-site construction involves the hybridization of construction with manufacturing. This method of works' execution consists in the production of modular components within an external manufacturing site and the erection of building structures throughout the modules' assembly on construction site [8]. The mechanism is particularly useful for carrying out building renovation activities, through components that are made in the factory and mounted directly on the old structure. Off-site construction requires an upstream 3D scanning activity of the building, followed by a design phase, then prefabrication, and finally assembly. In this way, complex structures are created safely and efficiently off-site, while the construction phase is limited to the installation of the components. As a result, off-site construction leads to paramount operational benefits, since it involves “just-in-time” philosophy, i.e., designing and building modular components only when necessary. This working method, combined with suppliers and operators of local origin, ensures shorter processing and delivery times, which in fact become independent from highly variable factors such as climate and weather conditions (i.e., one of the main causes of delivery delays in traditional projects). In addition, off-site construction, by transferring the performances of industrial processes to the construction sector, generates minimum stock levels and controlled waste. The result is a significantly improved quality of work as well as an overall cost decrease compared to traditional construction methods. The increase in the quality of work linked to off-site construction regards also not operational and procedural terms. Indeed, this technique affects the safety of workers who operate mainly in a closed and controlled environment, carrying out only the assembly of the modules on the working site. Concluding, the social impacts brought by off-site construction are added to the environmental ones. In fact, the production method optimizes energy consumption, guaranteeing energy savings thanks to a straightforward restoration and construction of structure without need of most heavy vehicles used in traditional construction sites. The influence of off-site construction on the productivity and sustainability of AEC businesses is summarized in Fig. 6.

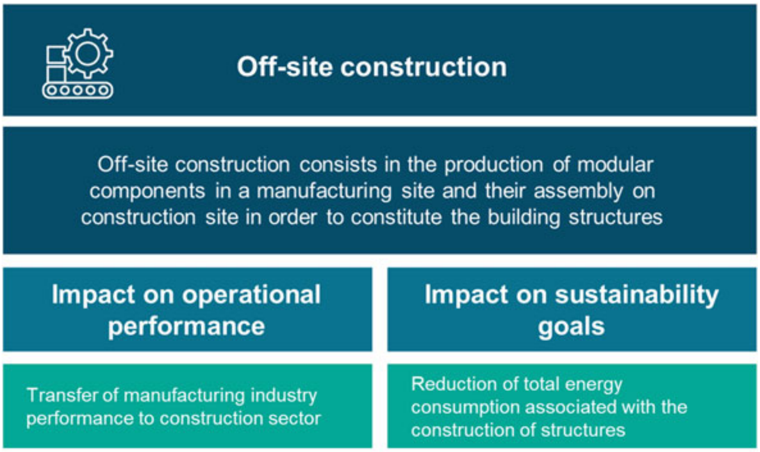


**Fig. 6** Off-site construction for sustainability and productivity in works’ execution

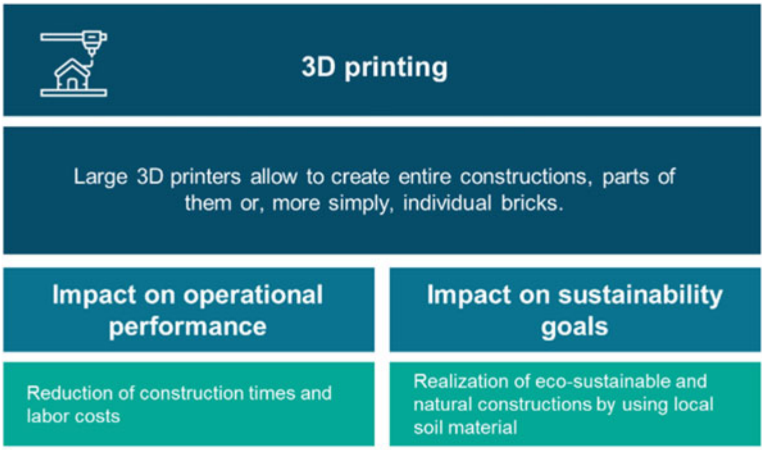


**Fig. 7** 3D printing for sustainability and productivity in works' execution

## *3.2 3D Printing*

Large 3D printers designed for AEC sector can create entire constructions, parts of them or, more simply, individual bricks. The main advantage of 3D printing is the ability to reduce the execution times of the works. Indeed, the production of buildings with mega-printers directly on site shortens construction times from weeks to hours. The impacts on construction costs are also interesting, especially for the creation of customized geometries and components [19]. The economic savings also derive in part from the reduced use of labor, which in some cases is almost entirely replaced by the printer. This aspect increases safety on site and allows to direct resources towards less harmful tasks, with improvements in the quality of work. In addition, 3D printing can reduce the carbon footprint of the construction sector, creating eco-sustainable and natural constructions with almost zero impact. This is unlocked by the use of natural materials from the surrounding area as a raw input for printers. Therefore, 3D printing can become the basis for a circular housing model, entirely created with poor, waste or recycled materials collected from local soil. Figure 7 reports how 3D printing can be applied to the AEC sector for a more productive and sustainable execution of works.

## *3.3 Advanced Robotics*

Advanced collaborative robots are used in the AEC sector supporting men in some of the most demanding phases of construction, such as, as reported by [11], site preparation (e.g., leveling), substructure works (e.g., foundations laying), and superstructure activities (e.g., load-bearing elements establishment). As regards foundation laying, in particular, machines are able to manage the loading, identification, cutting, rotation, and laying of all the bricks needed to complete the structures thanks to telescopic arms and according to a precise programmed logic and texture. The activities carried out can be controlled via mobile applications, which track operational parameters (e.g., laying times) and physical variables (e.g., bricks humidity), hence requiring minimal human intervention throughout the construction phase. In fact, human involvement can be planned to remotely control robots' works and refine activities, such as the recovery of cement in excess or the improvement of the walls' leveling. Moreover, workers can re-skill and up-skill towards less repetitive tasks. The added value of advanced collaborative robots in the AEC sector lies in the increase in on-site productivity and efficiency, in the reduction of wastes due to low-precision human activities, and in the decrease of the times and costs for carrying out the work. Furthermore, the role of advanced robots, whose arms are equipped with dynamic stabilization, is of great interest in the context of laying foundations for constructions in remote and difficult to access areas, where the safety of operators can be put at risk in traditional working methods. Finally, it has to be considered the benefits in terms of energy consumption associated with the use of advanced robots, given the possibility of using machines totally self-sufficient and ecological by virtue of the solar panel power supply established by some construction robots. The use of advanced robotics for the improvement of sustainability and productivity in AEC sector is well described in Fig. 8.

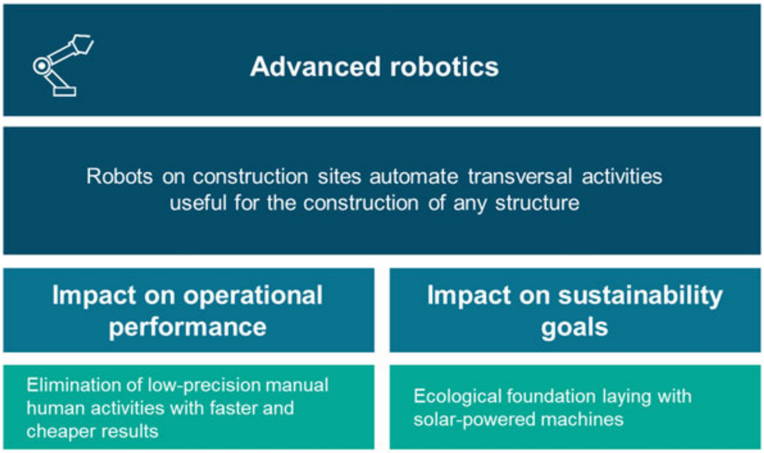


**Fig. 8** Advanced robotics for sustainability and productivity in works' execution

# 4 Industry 4.0 for Management of Support Processes

Design and execution of the works are activities that substantially contribute to the functioning of AEC businesses. Along with these primary activities, there are numerous support processes (e.g., drafting and updating of documents, work control, costing, procurement) that are equally indispensable for a successful business. On these processes, Industry 4.0 technologies have impressive possibilities of use, configuring as tools capable of transforming multiple points of potential inefficiency into value-added and competitive assets.

The technologies explored in this paragraph for the optimal management of support processes are could computing (i.e., services for managing databases and software on demand), Internet of Things (i.e., systems for monitoring structures and work sites in real time), and artificial intelligence (i.e., algorithms for automating various manual procedures).

## *4.1 Cloud Computing*

Cloud computing is one of the most significant technologies for the promotion of industries' digital transformation. In AEC sector, it allows the creation of databases automatically synchronized in real time, but also the shared access to software, calculation services, and on-demand applications from PC, smartphones, tablets, and other devices. Therefore, the adoption of this technology in AEC sector support coordination between people involved in different aspects of the projects, since it allows to speed up the transfer, updating, and sharing of information in real time [3]. In particular, the use of cloud computing platforms business ranges from shared design to control of works, up to reviews with customers. One of the most interesting applications consists in simplifying the communication between construction sites and headquarters, equipping foremen with mobile applications, accessible via tablets, to carry out instant reporting from sites. Open access to information optimizes the entire work, since it favors operations as well as the analysis of problems and possible solutions directly on site, with significant savings in times and resources. Furthermore, the possibility of using cloud management systems can improve the updates of budget releases and the evaluation of project changes requested by clients, being able to use a single environment to generate estimates, manage contract costs, plan and schedule interventions, and support the construction supervision. In addition, cloud computing solutions allow automatic backups and updates, by accessing all documents online on any device. This leads to a net decrease in project errors and conflicts between data, which are reported in a time-register form. In this way, it is possible to remotely control different versions and optimize coordination within the project team. Therefore, cloud computing contributes to increase the sustainability of operations in the AEC sector, reducing the need for travel and transfers for efficient project management. The advantages on operational and sustainability front

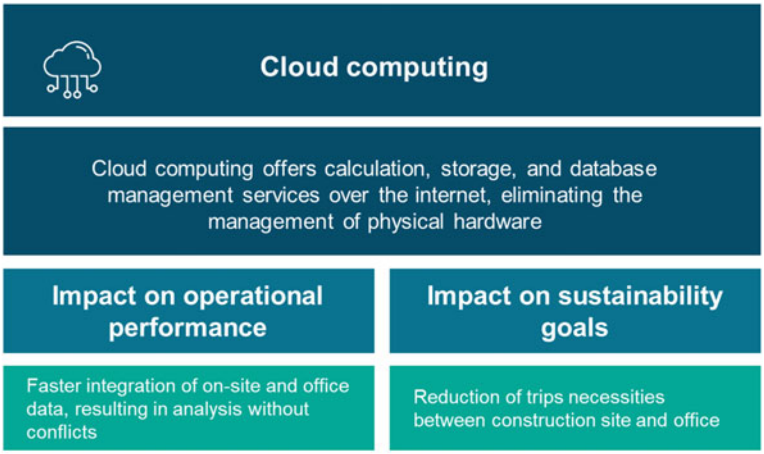


**Fig. 9** Cloud computing for sustainability and productivity in management

resulting from the adoption of cloud computing in managing AEC support processes are presented in Fig. 9.

## *4.2 Internet of Things*

Internet of Things in AEC industry simplifies both the analysis and the real-time monitoring of buildings and work sites, using sensors and a cloud platform for data storage and processing. Specifically, the technology finds ample space in the control of structural and environmental conditions of buildings and infrastructures [7], detecting any damage and foreseeing oscillations, subsidence, and structural variations. This is possible by integrating sensors directly inside the pillars, during the construction or restoration phases, to detect data regarding internal thermo-hygrometric characteristics, dynamic stresses, and construction variations. This information can be combined with environmental details gathered by sensors external to structures and relating to climatic data (e.g., temperature, quantity of rain, air quality, wind direction, intensity) but also machineries' performances (e.g., photovoltaic systems). All data, collected by a cloud computing service, can be processed to obtain precious insights, generating a net reduction in maintenance costs and times. In addition, Internet of Things sensors influence one of the most expensive aspects of building management, namely energy consumption. Indeed, the connection of the sensors with the air conditioning systems and with the entire building management system allows to check various parameters in real time (e.g., temperature, humidity, space occupation) and to optimize the environments accordingly. In addition to this, Internet of Things enable to control operational processes, thanks to the instantly collection of information on the construction site and on the work in progress. In fact,

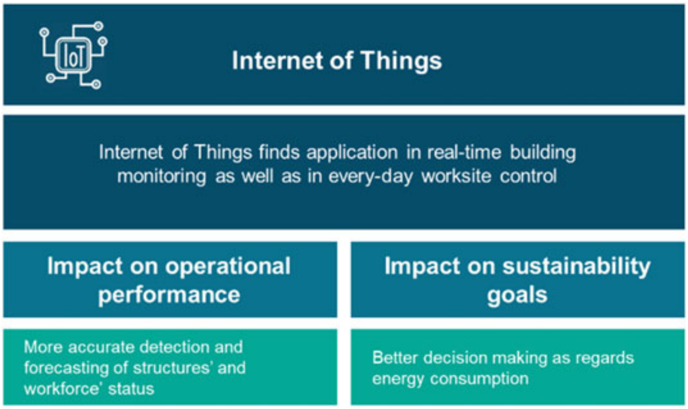


**Fig. 10** Internet of things for sustainability and productivity in management

sensors can check accesses and monitor workers' safety, by tracking the processes involving machines, materials, and personnel. In fact, sensors incorporated into tools worn by operators (e.g., bracelets, helmets) can send alerts regarding lack of safety equipment in specific risky areas or interference possibility with dangerous equipment or materials. In this way, the technology clearly contributes to the reduction of the percentage of accidents at work, ensuring both greater safety for operators and lower costs for the company. Similarly, procurement management also improves, since constant monitoring on materials' location generates notifications for low stock conditions. It is therefore evident that thanks to the use of Internet of Things sensors, traditional construction sites are transformed into digital construction sites, where the use of resources, the control of the progresses, and the work scheduling can take place also remotely through a web interface. Figure 10 resumes the beneficial impacts of Internet of Things for AEC businesses.

### *4.3 Artificial Intelligence*

Artificial intelligence algorithms can be applied in different ways by AEC actors, since they effectively respond to the industry's need to process huge amounts of heterogeneous data for extracting useful insights for decision making and tasks improvement [4]. A non-exhaustive overview of the uses of artificial intelligence in AEC ranges from the definition of the economic offer, to the revision of budgets and time schedules, up to the control of the construction site. For example, thanks to artificial intelligence software construction companies, technicians, and designers can use BIM files to automatically calculate project costs. In fact, the graphic entities of BIM models are used to define the bill of quantities, based on rules settable on the type of entity, processing, and measurement. The advantage of this technology consists in the connection of the output (i.e., the bill of quantities) to the input (i.e., the entities of the BIM model), which allows to automatically update the cost calculation with each modification of the original model. In this field, artificial intelligence aims to provide an integrated approach between the architectural design and the definition of bill of quantities, automating the operations of estimating and calculating project costs and reducing the time and margins of error in estimating and updating budgets. Furthermore, many artificial intelligence tools for defining economic offer exploit the set of data relating to previous orders to evaluate the existence of correlations and speed up the definition of the budget and time schedule on the basis of the most varied conditions, such as dimensions, costs, materials, structures and also sustainability-related constraints. Based on this information, the algorithms create thousands of solutions to the problem, analyzing the feasibility of each and eliminating the worst. The same mechanism can be used by the contract manager for the refinement of planning, automating the analysis of scenarios according to different factors (e.g., unexpected weather conditions, shortages of key resources including materials and manpower). In this way, the software can quantify the impact of changes on costs and schedules, simplifying the identification of the best strategies for managing the operations and responding to customer requests. In addition to being an excellent decision support tool, artificial intelligence algorithms simplify the management and monitoring of works' execution in various ways. By acquiring images directly from the construction site with a specific cadence (e.g., through the operators' tablet, drones or robot), it is possible to analyze materials, objects and structures, i.e., compare them with the planning given by the BIM models. This activity is useful, on the one hand, to determine the quality and progress of the work, immediately highlighting any anomalies to be corrected, and, on the other hand, to help project managers in identifying optimal work sequences to increase productivity and safety on sites. Figure 11 summarizes the main contribution of artificial intelligence for applications in AEC sector.

## 5 Conclusion

The present chapter explores how Industry 4.0 technologies can be applied in AEC sector to generate significant gains in productivity and sustainability. In fact, such technologies are recognized as capable of change construction processes, paving the way towards a new concept of Construction 4.0 [14], with significant advantages both in terms of performance and sustainability [9]. Specifically, the chapter analyzes the impacts of some of the most innovative technologies on three phases of the construction life cycle (i.e., architectural and design planning, works' execution, and management of support processes), illustrating how to use them for obtaining greater profitability and sustainability in the AEC sector. In this way, the chapter broadens the scientific knowledge relating to the concept of Construction 4.0, still in its infancy and still unaware of issues that go beyond the purely technical aspects

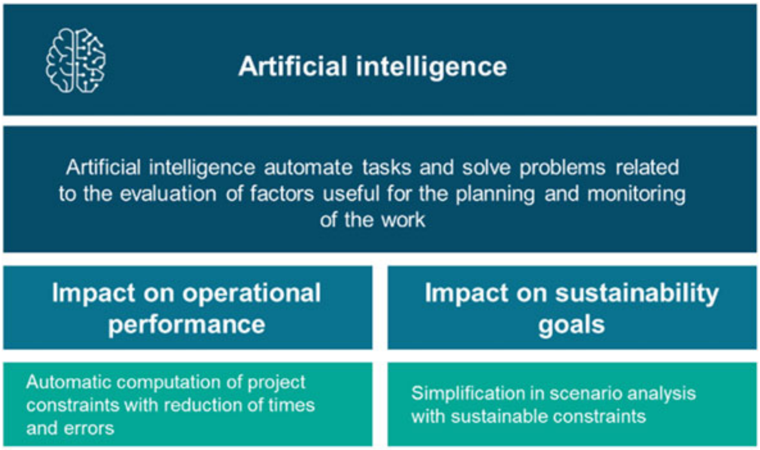


**Fig. 11** Artificial intelligence for sustainability and productivity in management

of applying technologies [9], such as those relating to the modification of operations and sustainability of AEC sector.

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# Programming Design Environments to Foster Human-Machine Experiences

**Giovanni Betti, Saqib Aziz, and Christoph Gengnagel**

**Abstract** The introduction of robotic construction methods in the building industry holds great promise to increase the stagnating productivity of the construction industry and reduce its current carbon footprint, in considerable part caused by waste and error in construction. A promising aspect is the implementation of integrated CAD/CAM processes where the design intent -expressed in CAD- is directly translated in machine instructions (CAM) without loss of information or need for intermediate translation and refactoring. As the introduction of robotics will hardly spell the disappearance of human workers, a key challenge will be orchestrating human-machine collaboration in and around the construction site or fabrication plant. Our contribution presents explorations in this field. Key to our approach is the investigation of the above-mentioned questions in conjunction with Mixed Reality (MR) interfaces to give access to both human and machine workers to the same dynamic CAD model and assembly instructions. This paper describes our work in this field through two artistic installations and ongoing research on additive manufacturing enabled construction. We probe principles for precise, customised, efficient, almost waste-free and just-in-time productions in the construction sector.

**Keywords** Human-machine-interface (HMI) · Human-machine-experience (HMX) · Computational design · Collaborative design · Mixed-reality · Robotic fabrication

**United Nations' Sustainable Development Goals** 8. Decent Work and Economic Growth · 9. Industry, Innovation and Infrastructure · 12. Responsible Consumption and Production

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_4

## 1 Introduction

Design technology and culture has significantly evolved in recent years in the Architecture, Engineering and Construction (AEC) industry. Among other technologies, Building Information Modelling (BIM), parametric and computational design, real time immersive visualisation are among the technologies that have become commonplace in many practices. These advances in CAD don't seem to have translated yet into increased efficiencies in the construction sector, which has been lagging in productivity compared to several other industries [1].

We postulate that this is at least in part due to the information loss that happens between the design and the construction phase. The reasons for the persistence of this information loss are many and complex. Some relate to the economic and societal environment of a fragmented AEC industry, which lacks vertical integration. Some factors are technological and cultural. Despite the advances mentioned above, the main tool to communicate design intent to contractors and fabricators still is 2D construction drawings. Although often automatically created by BIM software, the 2D representations thus created are but a static snapshot of the design. The act of issuing 2D drawings of a design creates a break in the digital information systems generated in the design phases that impedes feedback loops with the construction phase i.e., subsequent changes to the design are not automatically reflected and there is no clear mechanism to register and reflecting differences between the design intent and the built reality. Furthermore, 2D drawings are extremely useful for communicating with people, but are of little to no use in transferring information to robotic arms or other CAM systems. With this in mind, we started experimenting with systems that would create direct links between design intent and robotic fabrication. An important focus in those explorations is the inclusion of a Non-Expert Robotic Operator (NERO) in the loop. This step is crucial to any experiment that aims to advance digital construction and assumes that construction workers will interact in some way or form with robotic entities in the dynamic environment of a prefabrication plant or a construction site. To facilitate the communication and cooperation between the NERO and the robot, we devised a series of ad-hoc Human machine Interfaces (HMIs) that free the user from cumbersome interactions via mouse and keyboard. In the first installation described in this paper we used a sound-based control system, while in the second installation and in the ongoing research on 3D Concrete Printed Slabs (3DCPS) we resorted to an AR interface. The NERO needs to be able to intervene in various phases of the construction process, from influencing the design (i.e., to react to changing requirements or differences between CAD model and the reality of a construction site), to controlling the sequencing of operations of their robotic collaborator, to access contextual assembly instruction for their own manual assembly operations.

In essence, our strategy is to give simultaneous access to robotic systems and NEROs to the same, constantly evolving, representation of the design intent and of the current state of fabrication. We split tasks between the robotic system and the NERO to leverage the specific skills and strengths of each. To this effect we allocate tasks requiring human capabilities such as tacit knowledge, high mobility, dexterity, and situational adaptability to the human actors; tasks requiring repeated operations and high accuracy are allocated to robotic agents. By allowing the NERO and the robots equal access to the design system and creating a bidirectional flow of information between the design system and the construction process, part of the design process is explicitly transferred downstream.

The shift from static 3D models toward smart, parametric, dynamic 3D models is becoming common in the AEC industry [2]. This shift means that designers author design systems rather than specific design solutions. In this perspective, the built outcome represents one negotiated instance of the design space enabled by a computational model. The specific instance emerges through a collective and collaborative navigation and exploration of the design space performed by various project stakeholders. Therefore, the notion of authorship and ownership of the final design becomes diffuse, with many stakeholders able to claim parts of it [3].

In our investigations we explored how this approach may affect the transfer of knowledge and information throughout the various design stages, replacing the current linear design process with a more iterative and dynamic system, minimising costs associated with design changes and enabling integrated decision-making processes. A key strategy in the workflows and experiments presented in this chapter is the use of highly visual and intuitive human-machine interfaces enabled by various Mixed Reality (MR) strategies. MR is leveraged as a way of providing to the human actors highly contextual (both in time and space) information and enabling them, through natural interfaces, to materialise and modify the computationally encoded design logic and to control the robotic actors [4] (Fig. 1).

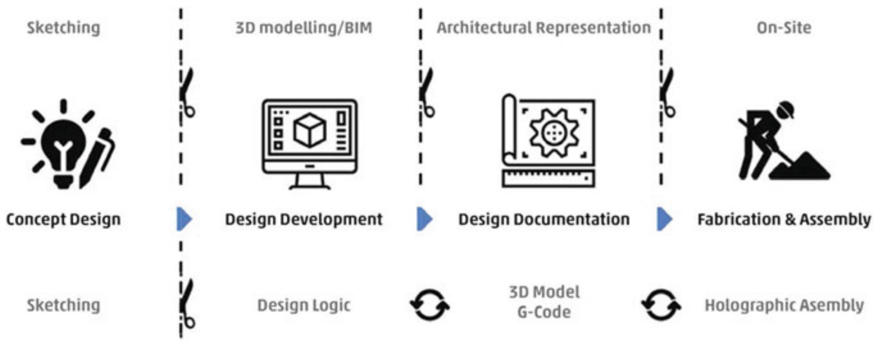


**Fig. 1** Conceptual diagram of the current fragmented processes in AEC and consequent loss of information across the project phases (top) and an ideal bidirectionally connected process (below)

## 2 Description of the Installations

In the following chapter two art installations and one ongoing research project investigating additive manufacturing of prefabricated building components illustrate the application of MR and robotic fabrication driven interfaces. Originating from an artistic and intellectual exercise, those explorations challenge current collaborative design processes and foreshadow practical applications of such design environments in the construction sector.

### *2.1 Communication Landscapes*

The participatory installation Communication Landscapes explores the epistemic potentials of emerging technologies related to Industry 4.0 and digital craft in the AEC industry and aims to foster an optimistic approach for future automation of mass-customizable production. The installation was conceptualised by the authors and others for the 2017 Seoul Biennale of Architecture and Urbanism, in the context of the exhibition Imminent Commons [5]. In the context of the exhibition theme, the installation explores how industry 4.0 can reintegrate manufacturing processes in urban contexts with advanced technologies and transition consumers to prosumers. The industrial revolution had far-reaching implications on society and urban planning. Production hubs started to grow and slowly migrate from the city centres to the suburbs. Consequently, craftsmanship and its peer-to-peer (P2P) model of production, trade, and consumption shifted into a business-to-consumer (B2C) relationship, restricting the artisan's access to new technological advancements in production and automation [6]. With the dawn of Industry 4.0 and the opportunities that the Internet of Things (IoT) brings, MR and robotic fabrication knowledge is being spread and democratised at an exponential rate. This can empower the artisan to explore and utilise new technologies that can also empower individual creativity in the production of mass-customised goods, distributed and co-designed throughout a wider population, promoting a new archetype: the prosumer—a producer and consumer of its own goods [7]. We devised an installation that could offer direct access to new modes of fabrication and digital crafting. To do so it is important to ensure that non-expert users can interact and use advanced equipment intuitively and with ease and playfulness. Natural and intuitive human-machine interfaces (HMI) are key to achieving this purpose. Research indicates that a well-designed interface enables users to intuitively navigate complex computer-aided design systems, bypassing the frustration and feeling of powerlessness of its users [8]. The disappearance of the classical computer model with its mouse-keyboard terminal might lead to more creative HMIs [9] derived by methods of gamification [10], which use new technologies, such as new mixed reality devices and applications [11]. Here, the entire body and/or sensory inputs such as voice-controlled interfaces can function as a bridge to control specific functions, such as the motion of robotic assemblies.

### 2.1.1 Installation Workflow

Based on these reflections, the installation, "Communication Landscapes", explores a future collaborative approach to distributed and participatory design. The installation consists of a microphone, a visual interface, and a robotic arm with an attached hot wire cutter. Over the course of five days, curious visitors were invited to engage in the installation by simply speaking into the microphone. This interaction triggers an algorithm to visualise the audio input and transform it in real time into a three-dimensional representation. By providing direct visual feedback of the created geometry, we were able to foster a fast and intuitive learning process, where users would learn to shape the virtual object by modulating their voice. Once the participants are satisfied with this design exploration, they can instruct the robotic arm to activate the production of the geometry. This automatically sets the robot arm in motion, and the hot wire cutter carves the design out of a block of foam, creating simultaneously a positive and negative instance of the designed object. Visitors are given the positive element as a gift, while the negative pieces are assembled into a sculptural wall. This sculptural wall represents a collective design featuring patterned surfaces, instantiated by the physical/digital translation of over 300 individual sound inputs collected over the duration of the installation. The position of each individual tile position is algorithmically determined based on their geometric similarities (Fig. 2).

In the design process of the installation, we made sure that we couldn't predict the exact form of the installation. Based on individual voices, each tile design is unique and unknown before it is created. As installation designers, we willingly relinquished control over the final product. Our role was to simply enable and only initialise the design system, with the specific intent of activating a collaborative process in which the "users" of the system could become co-creators of the final piece (Fig. 3).

We used the Grasshopper3D Firefly 3D plug-in to process the audio input in a suitable format for the design environment, allowing the pitch, volume, and frequency to be filtered in real time. The volume and frequency values of the input voices create two unique and opposing freeform curves that can be lofted to represent the recorded voice traces. The resulting ruled surface is allowed to rotate in the plane at a 90° angle, depending on the maximum peak frequency value of the sound input. The Grasshopper3D plug-ins Human and Human UI were used to create a custom user interface consisting of two main panels. The most prominent feature is the 3-D

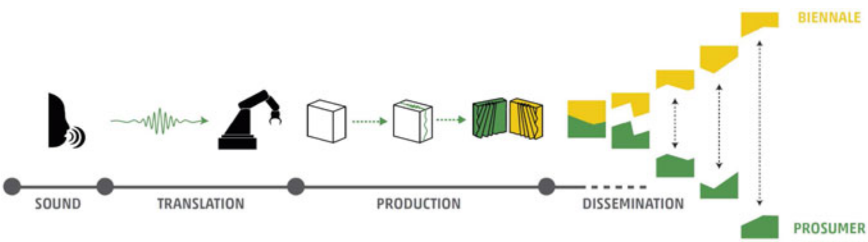


**Fig. 2** Communication landscapes installation workflow

**Fig. 3** From left to right: interface, interaction, and fabrication

representation of the foam block filling the entire left panel. In its rest state, the user can see a featureless box. As soon as a voice impulse is triggered, the shape starts to dynamically transform to represent the sound traces in real time, changing its colour and orientation to visualise the magnitude of volume and frequency. The right panel features three interactive infographics and two buttons: record and fabricate. The first infographic shows the custom placement map, indicating where the current design exploration would be placed in the sculptural wall, determined by its resemblance to previous design generations, allowing the participant to also play with the voice input to place the design at different locations. Beneath the placement map two scatterplots show the current magnitude of the frequency and volume. The record button allows recording the sound input, this act will determine the duration of the recorded sound and therefore the final traces that generate the shape. The fabricate button will translate the current design instance into g-code and trigger the robotic motion.

#### 2.1.2 Results

The installation was collectively realised over the course of five days together with the participation of the visitors. It was satisfying to observe the ease of interaction for most participants regardless of age and nationality. Due to safety guidelines the fabrication process had to be supervised which did not hinder the experience but rather allowed to engage with the visitors. It was also rewarding to see the immediate response of joy and amazement at seeing their voice translated into geometry that could be fabricated within. Perhaps the most notable interactions took place between children and the robotic installation (Fig. 4), providing anecdotal evidence of the large user group that can be reached with careful design of the HMI. The installation focused mainly on the creation of a unique artefact by “talking” to a robot. The less developed part of the workflow involved the manual aggregation of the pieces on the wall, for which only a simple placement map was developed. Even if relatively simple, this installation contained many of the elements referred to in the introduction. We successfully established a direct pipeline between a mutable design intent and a robotic fabrication process. We included hundreds of exhibition visitors in a collective design process, enabling people of various ages and backgrounds, with little to no instruction, to interact both with a complex parametric model and an industrial robot.

### 2.1.3 Pop-Up Factory

With the installation Pop-Up Factory, realised for the festival Make. City Berlin in 2018 [12], we aimed at creating a richer design and assembly experience. To allow for more complex and nuanced interactions between NEROs and robots, we decided to explore the use of Augmented Reality (AR) devices such as the Microsoft HoloLens. This wearable device can offer highly contextual and complex information to the worker enabling not only to illustrate 3d representations or instructions but also allowing access to a wide variety of technical and non-technical information [13]. Such devices offer hand-free access to planning information and enable the workers to execute tasks and have a dynamic communication bridge to the design teams, thus enabling feedback loops between design intent and built reality.

Based on the previous installation described in Sect. 2.1 the above-mentioned concepts were integrated into the research scope and resulted in a prototypical AR interface supporting construction processes. It is a first modest case-study to validate the potentials, limitations, and epistemic findings towards a fully AR supported design and construction environment. The methodology here allows non-professional participants to collaboratively create a human-scale structure that can be geometrically changed while being constructed, enabling it to conceptually include last minute adjustments on the simulated construction site. To this end an intuitive holographic interface was designed to empower non-experts to playfully access more complex 3D modelling, on-demand robotic fabrication and AR-guided assembly processes in real-time.

### 2.1.4 Installation Workflow

The technical hardware features a Microsoft HoloLens headset, a robotic arm (ABB IRB 1200) with a custom hot-wire assembly, a microphone, and computing desktops. The installation design was created using the CAD modelling software Rhinoceros 3D alongside Grasshopper and custom Python scripts. Commercial add-ins to Grasshopper, like Fologram and HAL Robotics were used to create an AR interface and to control the robotic equipment. A design system was programmed to iteratively and collaboratively design a 2 m high tower-like sculpture, giving the participants control of the design outcome. This design narrative was aimed to firstly initiate a discussion challenging the authorship and/or ownership of design in the architectural practice on an intellectual level and to secondly probe the practicality of such interactive and reciprocal AR construction environments for the deployment in the building sector. The installation would exist simultaneously in physical and virtual space. Without the headset the visitors would see the hardware components and the partially built structure. The AR headset would reveal a rich holographic scenery offering a variety of functionalities and information. The holographic interface (HI) was structured around two workflows: a design workflow and a fabrication and assembly workflow. The user was let free to switch between the two workflows iteratively and continue to change the design of the unbuilt portion of the installation.

All the computing units were hidden from the visitors making the AR head-googles the only required interface (Fig. 5).

### 2.1.5 AR Aided Design Modes

Over the course of three days the visitors would build the sculpture as seen in Fig. 5. In the custom AR aided design environment all actions/selections had to be controlled using "air tap" and "eye gaze navigation" [14] which represent an unfamiliar interaction paradigm for the general public. In comparison to the simple voice interface of the previous installation, introducing the visitors to a new interaction paradigm was a more challenging task, one that could be nonetheless completed in 5–10 min. While this might be a high time frame in the context of a public and participatory installation, it seems a relatively short time frame to train a non-expert in the use of a new system.

Inside the AR design workflow, the visitors could edit control points that would modify the overall shape of the target branching tower structure. The anchors determined the end points of 5 vertical free-form curves and could be adjusted to shape a resulting complex geometry, creating a sort of "branching tower". This geometry would then be dynamically discretized in individual custom brick elements (See

**Fig. 4** Installation interaction and results

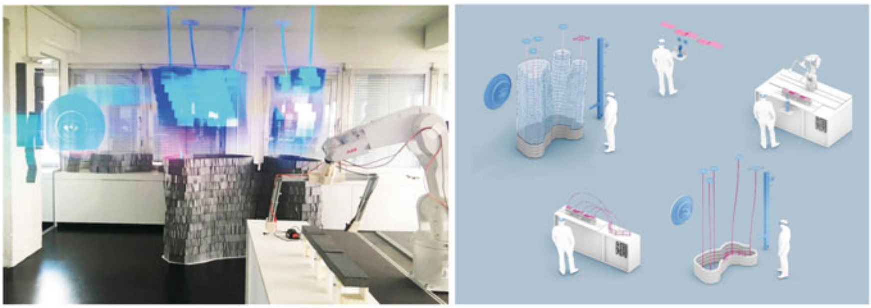

**Fig. 5** Pop-up factory, participatory mixed reality, and robotic fabrication installation

Fig. 6). When satisfied with the current design envelope the user could switch to the fabrication workflow. In this mode the user would then be able to access the fabrication and assembly instructions for the next modules. The system would constantly track the progress of the construction to offer the right sequence. The design workflow was conceived such that the built part would become no longer modifiable by the user, to ensure consistency in the conjoined design and fabrication process. Hence freedom to design what is not built would be preserved throughout the fabrication process.

The fabrication process would involve actions performed both by the human and the robot actors. Inspired by the first installation (see Sect. 2.1) a 3d surface texturing was enabled again using auditory impulses. The user could virtually tap a holographic 3d microphone to record the ambient acoustical noise in the room to texture the current set of brick-foams which would be integrated in the path generation of robotic fabrication sequence. Similarly, an air tap on a robot icon hologram would send the command to the robotic arm to start the fabrication process for the next set of custom blocks. The visitor would need to place a new stock of pre-cut foam material to be processed by the robotic hot-wire cutting. An algorithm would iteratively calculate the angles that are needed to assemble the foam bricks seamlessly to the new curvature "just in time". By virtue of the "just in time" nature of this process where only three to five custom bricks would be produced at any given time and then immediately assembly, labelling and inventory tracking could be kept to a minimum. After the robotic fabrication process each brick would need to be manually rotated and placed correctly relative to one another before this sub-assembly could be aggregated in the overall structure. Both the pre-assembly and the final aggregation steps would be augmented by holographic guides that would show the correct positioning and orientation of each element. In this process each actor -human and robotic- is used to the best of their skills: the hot wire cutting by the robot ensures submillimeter-scale accuracy and faithfulness to complex 3d information and the manual assembly process relies on the human dexterity in manipulating complex objects, mobility in an unstructured environment and higher positional tolerances.

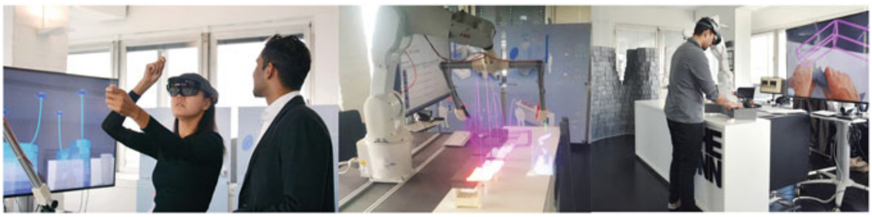

**Fig. 6** From left to right: AR-driven modulation, fabrication, and assembly

### 2.1.6 Results

The presented workflow uses AR to navigate through the design, fabrication, and assembly stage of a vicarious project in real-time, short-circuiting the digital information chain between the design phases aiming to minimise information loss. The installation is a first case-study evaluating AR-driven construction interfaces in controlled environments and would need to be developed further to be probed on a real construction site with e.g., safety requirements and construction regulations. There are also noteworthy technical shortcomings. For instance, the position accuracy and field of view of an overlaid holographic scene is still not as accurate as wished and spatially limited. Hologram visibility is dependent on the ambient brightness limiting the use in outdoor environments. The lack of a real inventory management system, even if reduced labelling labour for the installation, would be hard to easily scale to a more complex construction process, where various different materials and prefabricated elements would arrive at different times and located in less controlled settings. Furthermore, more work is required to explore more intuitive gesture-controlled metaphors and interface management to intuitively guide and structure the interactions with the AR environment for non-expert or skilled labour.

## *2.2 Large-Scale Additive Manufacturing and Mixed Reality Applications Towards a New Possible Construction Process*

Alongside robotic fabrication large-scale additive manufacturing with mineral materials such as three-dimensional concrete printing (3DCP) has made significant leaps over the last decade and offers a promising alternative to produce highly optimised prefabricated building elements for the construction sector [15]. Having in mind that about 60% of the buildings and 25% of the infrastructure that will exist on earth in 2060 still need to be built, making the decarbonization of the building sector the most critical aspect to success in meeting the 1.5° target defined in the Paris Climate Agreement, and that Cement production alone accounts for 6–8% of all global emissions [16], 3DCP could unlock unexplored potential of mineral materials, fostering more resourceful and material aware solutions resulting in massive material and grey energy savings and an overall better life-cycle performance. For the above ground structure of commercial buildings in reinforced concrete, the slab construction contains a fair amount of the material mass and thus most of the embodied $CO_2$ emissions. Conventional reinforced concrete flat slab constructions are considered an economical and adaptable solution. However, this assessment neglects the enormous material consumption of this construction method, the poor ratio of dead weight and load-bearing capacity, and its poor performance in terms of room acoustics and building physics. We are currently developing a workflow enabling us to combine algorithmic geometrical modelling capacity with optimization processes based on

Finite-Element-Analysis (FEA) for the generation and fabrication of multifunctional reinforced mineral construction elements as ceilings and walls [17]. The process enables high adaptability and multi-performance optimization of the manufactured components, supplemented by a semi-automated pre-fabrication of formwork and reinforcement elements assisted by an AR-interface for assembly processes on-site. Since 47% of the construction work (cost and time) is due to erecting and dismantling formwork and 20% can be allocated to reinforcement work, there is a great potential for automation and/or process optimization [18].

In principle, the methodology can be applied to a wide range of structural elements. The case-study presented here shows an application for a biaxial load-bearing beam grillage made of reinforced concrete, which allows for a variety of applications through the combination of additive prefabricated and durable semi-finished parts and in-situ concrete supplementation. The case-study reimagines the design of the Maison «Dom-Ino» by LeCorbousier using 3DCP and applies structural optimization principles inspired by the work of Pier Luigi Nervi, implementing isostatic lines following the principal bending moments and hereby creating an optimised rib structure [19]. To ensure a scalable construction method for such a design, 3DCP elements form the basic framework of the supporting structure and at the same time integrate acoustic properties programmatically tuned via geometric articulation [17].

### 2.2.1 AR-Assisted Additive Manufacturing

Based on the bespoke workflow a physical mock-up was to be fabricated and assembled using additive manufacturing and a prototypical MR Interface. To this end a smaller portion of the slab construction derived from the design Fig. 7 was used. An AR-driven interface was designed to allow the interdisciplinary team of researcher to navigate through the geometry generation of the form pieces, allowing to make modifications to the geometry, to evaluate the programmed mechanical and acoustical optimizations, to validate the printability, check for any system bound collisions, visualise the current hydration/curing state, get feedback on the material usage/overall weight, and to bidirectionally simulate through the print-path evolvement to understand the current additive manufacturing process and foresee any system or logic failures by the means of spatial aware holographic aids. The current development of such an interface proved to be a necessary tool since most of the collaborating researchers were not familiar with the algorithmic design environment used to program the robotic system and generate the g-code. Hence a more intuitive and representative interface was needed to visualise the complex fabrication process. The zero-waste formworks can be optimised for manufacturing purposes validating the printability and structural integrity of the 33 individual bodies in fresh and hardened states [20] (Fig. 8).

By simulating the printing process, including cement hydration/curing and autogenous shrinkage [21], the usage of CAD and CAM can address many of these problems and offer more complex design features. Moreover, previous research pointed out that printing speed optimization is crucial to find a balance between buildability

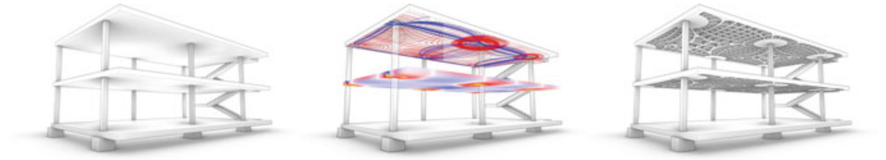

**Fig. 7** Case-study conceptual optimization

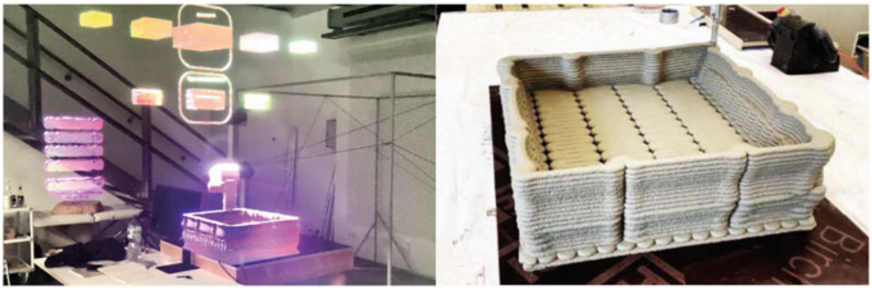

**Fig. 8** Experimental AR—assisted fabrication interface

and interlayer adhesion, both of which are strongly dependent on the "waiting time" of deposition of a layer upon the previous one [21]. Therefore, the AR interface enables situational control allowing to alter the current speed parameter and material flow rate during the manufacturing process. This could massively help workers on site to first detect any small deviations in the ongoing construction work and use the accessibility of the design features to locally alter the individual and manageable geometry enabling the overall element to fit more precisely in the actual environment. Alongside the AR-interface a custom algorithm was developed to generate the G-code with high degree of controllability for the described process. Fologram was used to instantiate a first working and AR-driven interface allowing to integrate the above-mentioned design and analysis features.

### 2.2.2 AR-Assisted Assembly

Due to their low weight the printed modules can be easily managed by one or two workers. To further streamline the montage sequence all formwork bodies were tagged with Aruco markers containing information such as the individual position of the piece in the final construction and their weight. Regardless of their current position, each formwork can thus be identified via the associated marker and accurately positioned through holographic instructions (Fig. 9).

The first prototype AR interface was developed using Fologram and the HoloLens2 headset. Due to the imperfections of the projected scene compared to the accuracy in the physical environment, a custom MR interface is currently being

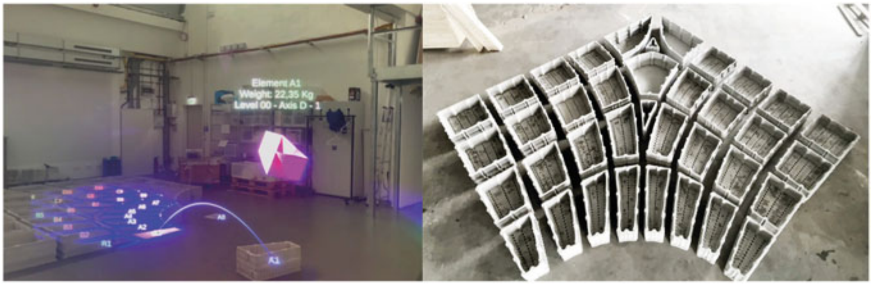


**Fig. 9** Experimental AR—assisted assembly workflow

tested that uses a direct connection between Grasshopper and Unity 3d and the use of the Oculus 2 MR headset. The advantage of the e.g., oculus MR headset is that they can seamlessly blend between physical and digital scenes using "Passthrough API" [22]. Here the physical reality is recorded and digitally projected in the MR environment enabling to overlay entirely controllable, adjustable, and precise digital overlays. Research is currently investigating such MR implementation and with them ways to address safety concerns [23]. In future, such approaches could be deployed on construction sites and mobile robotic production hubs. The fabrication of 3DCP elements could happen on-site, reducing costs and efforts associated with transport. This availability and accessibility to on-site production hubs in combination with intelligent MR interfaces could also further streamline construction adjustments empowered by dynamic scanning of the construction site. Any local construction deviations could be identified and adjusted in the sequential manufacturing process immediately.

## 3 Conclusion and Discussion

Technological advances that have been shaping the AEC industry haven't translated yet into increased construction efficiencies. On the contrary, the lack of integration in the digital tools and workflows seems the main culprit. We identify current standard practices of transmission of design intents as one of the critical bottlenecks in the industry and we advocate for a new paradigm where information can freely and continuously flow in a bidirectional fashion between design software and construction site. We identify MR and related technologies as crucial elements to provide the worker on site with information that is highly contextual, both in space and time, up to date and easy to understand. MR can, furthermore, enable the worker to bidirectionally update the design in real time by registering differences between design intent and realisation and by directly integrating in the design required changes. Giving the worker direct visibility and agency over the design model would also enable it to more easily collaborate, communicate and control advanced robotics, whether those are robotic arm, industrial 3D printers or other.

In this paper we present a small number of investigations that point in this direction at increasing levels of complexity: from artistic installations to 1:1 prototypes of innovative construction methods. Through those we demonstrate different methods and levels of connecting the workers with the design model and increasingly sophisticated methods for interacting with construction robotics, assemblies, and inventory management. Many open challenges remain before those concepts can be demonstrated or implemented in a reliable manner on a real construction site. Among those there is the need to develop reliable and robust communication protocols to ensure that information integrity is maintained, and information is delivered in a contextually appropriate manner. New interaction metaphors and interfaces need to be developed that enable intuitive and robust interaction with information, construction materials, robotics, colleagues, and the surrounding environment.

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# Designing with the Chain

**Stefano Converso and Lorenzo Pirone**

**Abstract** This paper will describe the case studies of Design-Build projects to discuss the use of digital and computational technologies as facilitators of a new role in AEC process, devoted to establishing the "missing chain" in the AEC sector, too often affected by fragmentation in several, conflicting actors. The "Design Mentality", by nature oriented at synthesis, and at bringing topics together can be the most effective "productivity boost" for the sector, but it needs a change in relationships and a different framework of responsibility. The architect needs to enjoy the management role, that means "make things happen", designing the context in a wider sense, including the selection of partners, of companies, packages, and solutions, and establishing the right "rules for form" that can keep the project identity. The "wireframe method" will be discussed as a geometrical method to manage the deployment and aggregation of parts in an adaptive process.

**Keywords** Off-site construction · File to factory · Wireframe coordination · Design management · Procurement · Design packages

**United Nations' Sustainable Development Goals** 9. Industry, Innovation and Infrastructure · 8. Decent Work and Economic Growth · 12. Responsible Consumption and Production

## 1 Introducing a Mechanical Approach into Architecture

The notion of introducing a "mechanical" industry approach to Architecture is not new in the discourse around digital innovation in our domain. US office Kieran Timberlake, for example, stated clearly already in 2003 that a method based

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_5

on assembly, prefabricated components and a custom manufacturing chain had to be applied more consistently, showing it in their work titled “Re-Fabricating Architecture” [1].

BIM software itself, in special projects of that pioneering time, turned out to be mechanical, when projects had to really deal with fabrication. Parts of the model were not just “representative” of the object, but identical to the final object geometry. The notion of “part and assembly”, typical of parametric modelling environments, turned out to be crucial in these projects. It was a time when BIM was, in fact, a sort of “younger brother” of these mature, complex environments. As opposed to the “representational” BIM models, these ones immediately suggested a sense of tectonics and materiality. While BIM insisted on classifications and taxonomy on top of objects, the mechanical environment pushed for geometry definition down to every little detail providing an almost tactile feeling. The only abstraction that can be found in these models lies suddenly in the set of relationships that is shown on the screen as a list on top of those “physical” objects. While 3D started in the world of animation and found in the simulation of dynamics and the relationship with movie industry its first start, and BIM somehow started from classifying, from trying to reduce objects to lists, here, in the mechanical models, the objects became somehow true to themselves, even independent, from their final assembly.

In other words, digital environments can provide different interpretations in relation to architecture and construction and therefore contrast the idea of a clear opposition between a physical and a purely digital environment and the related worry, well diffused in the 90s and never really abandoned, that Architecture would somehow dissolve in a virtual domain. Antoine Picon highlighted in his seminal book on the notion of Materiality in architecture more subtle possible interactions and influences that our current intense use of digital environments is providing with a material world that is being hybridized rather than becoming fully virtualized. So, in reply to a question if we are facing a “material turn” of architecture, after a “digital break” he argues that “(…) *This dimension was never forgotten, despite the concerns of theorists and historians like Kenneth Frampton, who assumed that digital tools would jeopardize the special relation between architecture and matter encapsulated in the notion of tectonics. It has simply become more present and, above all, is now interpreted in different terms than it was at other moments in the history of the discipline (…)*”.

So mechanical models in that sense, to recall Frampton’s studies, are not related to a textile, Semperian interpretation of tectonics but in general to the process of digitizing the material components, in every sense, being it formwork, steel structures, glazing, as well as more subtle still physical parts like material textures, real colours, and every kind of physical manifestation of reality into the design digital synthesis. The fact that these components, like in the manufacturing industries, are mainly prefabricated, is less relevant than it seems, in this context. It is more about the presence of digital objects that have a strict, often direct relationship with reality. A relationship that has changed as much as the tools themselves have changed, in a dynamic balance. As opposed to many approaches that looked for philosophical roots, here the investigation moves on to a more sudden, unspoken, almost instinctual, and direct inspiration.

## 2 Wireframe Aesthetics and Master Geometry

For many years, in the digital era of 3D modelling for Architecture, wireframe was the only way to go. Lynn argues very well how much this era should not be seen as an anticipation to something more complex to come, but as an era that produced projects that were inspired by the aesthetics, means and culture of that time. Lynn challenges through the exhibition the perception of digital instruments in architecture as something to be located sometime "in the future" and rather focuses on analysing projects. This design approach to software looks at how the features already present in programs at the time were translated by the architects into actual features in buildings and projects. He finally provided a key to link aspects like folds, surfaces, frames of these projects to forms found and explored through software, by breaking the "tool" approach and rather referring to the computer as an instrument, to something that enters the thinking process in the design as pure possible formal inspiration (Fig. 1).

The introduction of Solid modelling seems to have somehow erased that type of aesthetics. That clear, light, and dynamic structure made of "sticks and frames" became massive: objects attached on top of each other or even, more recently "pushed and pulled" out of a unique form. The notion of "bodies" came into the digital environment. Again, Lynn observed the evolution from simple to complex bodies,

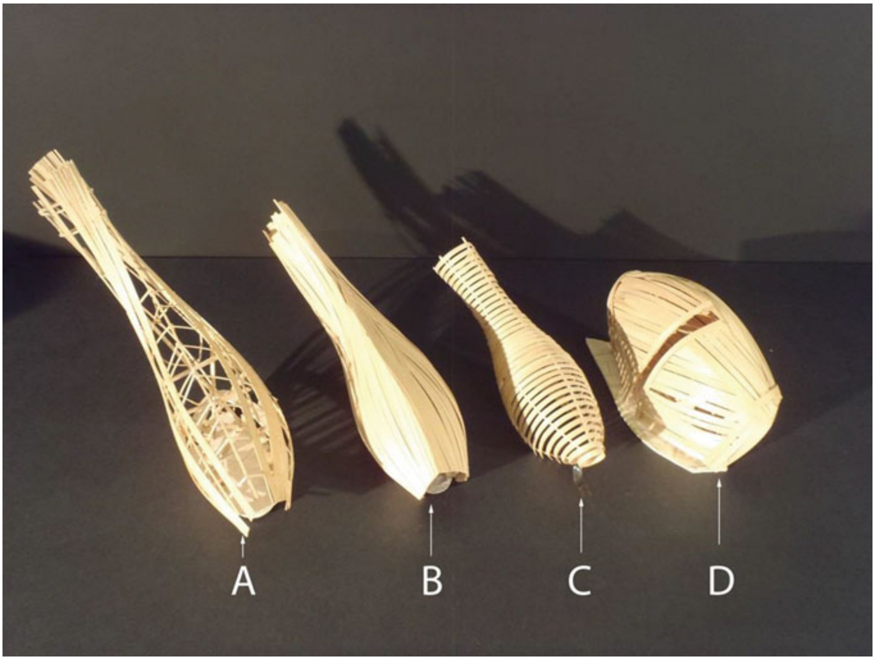


**Fig. 1** An image showing four studies for the Lewis Residence, by Frank Gehry from the exhibition "Archaeology of the Digital", held at CCA Montreal. Courtesy of Frank Gehry and Associates; taken from: https://project6rosemary.weebly.com/blog/archives/04-2015

controlled by subdivided mesh or Nurbs geometry [2]. Despite some attempts to recall the idea of structure (skeleton animation, for example) the attention shifted, somehow suddenly, to the "unique body". In general, what used to be a system turned into a single, "one" model. Wireframe remained, though, in the world of mechanical model, as "embedded sketch", hidden in almost every solid, and as "reference geometry": reference planes, axes, "traces" tell the story of the position of objects, of their underlying structure, of the sequence of actions that brought them where they are in the model. The introduction of solid modelling never fully replaced such an approach, since as already stated many parallel modelling techniques survived together.

In this parallel between modelling history and its influence on architecture, emerging tools matter, and two of them somehow broke the existing schema at the end of 90s: Generative Components by Bentley Systems, and a bit later, Grasshopper. Two examples of a way to establish a rule-based modelling technique, based on a sequence of steps and operation: a shift that broke the sense and idea of uniqueness, even though such a procedure was anyway ending with one single model. It's important to remember how the very beginning of Grasshopper, for example, lies in a tool called "Explicit History": a way to save the structure of a file, in the sense of the sequence of commands that defined its geometry generation. A tool that was born as a personal initiative of a young architect and software developer, David Rutten. This self-generation came to define a style, called "generative design". Instead of defining the final form, I define the rules for it. An almost "verbal" approach to design. One of the immediate formal effects of this approach was the emergence of the word "populating": there was a geometrical structure, and then something supposed to fill it with objects. There was a pure and sincere fascination with these procedures: the repetition with variation of a single component became the first attempt produced in these environments. Curvy triangulated and tessellated structures became widespread. In fact, this evolution brought back the idea of structure, and opened the discussion on the so called "Architectural Geometry" [3] discipline. that was raised in publications and in a series of conferences, from the "Smartgeometry to the AAG (Advances in Architectural Geometry) series. Wireframe was back, with a renewed identity of "active structure".

A completed project that could somehow be representative of this period is the Great Court of the British Museum, designed by Foster and Partners, where a clear mathematical model was developed by prof. Chris Williams according to the architectural intention to cover the entire span with a single surface, that was optimized and further optimized using the "relaxation" method [4] (Fig. 2).

At this point another important feature was also back, that is the link between wireframe and set of actual building components, numerically fabricated but as "variable parts". Single beams of variable length, and single nodes, with variable angles in different directions. A practice that fully embraced this approach as its primary identity was one of the pioneering offices of the digital era: the Swiss firm called "DesignToProduction". They worked with many architectural firms to help and finalize design geometry streamed to fabrication. Wireframe for them was the starting point of the process of clarification, rationalization, and full exploitation of the design geometry.

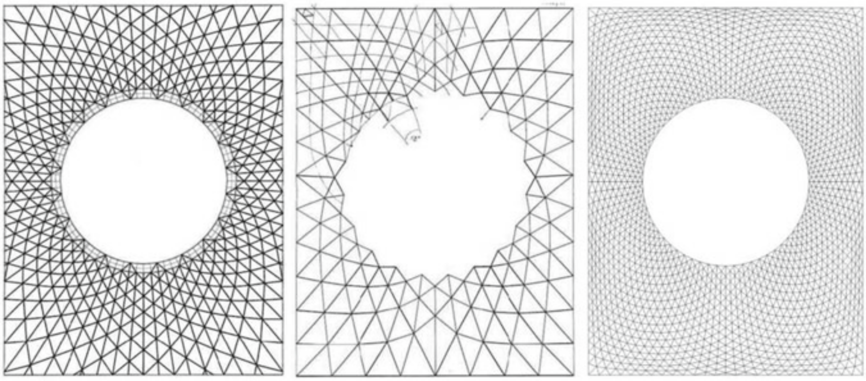

**Fig. 2** Sequence of geometrical grid optimization according to structural behaviour, provided by Professor Chris Williams for the British Museum courtyard design by Foster and Partners. Courtesy of Professor Chris Williams taken from the scientific paper: http://www.math.chalmers.se/Math/Grundutb/CTH/mve275/1314/Chris2.pdf

An important step in their strategy towards the definition of a "master geometry" is the case of the fabrication process engineering of the Mercedes Museum, by UN Studio. In that case, it was interesting not even how much the process was technically efficient (even if it was), but how much the story behind it was made explicit, described, embodied and put to the surface by the presence of Arnold Walz, the project "specialist in geometry", and one of the founding partners of the DesignToProduction office. It must be highlighted, again, how much this identity started with the design approach to the project by Van Berkel and Bos, who put the geometrical intertwining of ramps at the core of the space generation. A mentally focused design. Following that experience, wireframe light models managing parts detailed development were applied by DesignToProduction to all other projects, working with all materials, including concrete: the experience of custom CNC manufactured formwork, already tested in the German Museum reached a high scale in the massive production organized for SANAA's EPFL centre, again conceived as a surface, fully walkable.

Their Swiss origin makes evident how much their main material of reference is wood, and its tradition renewed by the possibility to be worked out through numerical machinery. It is not by chance that the works that more relevantly represent an architectural approach to these possibilities come from Japanese architects: the Pompidou Metz, by Shigeru Ban interesting melted the experimentation on a set of wooden net with the form finding design procedure used to generate a roof surface embracing the entire museum space. The construction and material-oriented approach of Ban helps in the tectonic feeling, often missing in many "experimental surfaces", maybe still structurally working, but less dramatically expressed (Fig. 3).

The result is an impressive "wooden tent" that lights up interior space and features a feeling of continuity, despite being composed of many different "variable" parts perfectly joined together. Fabian Scheurer, the second founding member of the Swiss

**Fig. 3** Interior of the “wooden tent” designed by Shigeru Ban for Pompidou Metz Museum. The whole structure was controlled and fabricated through a lightweight digital model prepared by designtoproduction. v1—Photo by Didier Boy de la Tour, taken from AREA Magazine online. v2—Courtesy of Jean De Gastines Architects

office, in several publications and public debates lamented later how much the rise of BIM took the lead towards manufacturing-oriented models [5], by somehow missing the full exploitation of the potential behind the detailed control over form definition of the parts. Even if perfectly defined, though, the parts they had to engineer for many projects were still “formally servant” to the whole. A further step in this formal exploration requires architects to explore a less strict relationship between parts and their “reference geometry”: the project itself becomes expressed as a kit of parts.

## 3 Project as a Kit of Parts

So, a shift can be imagined if the “model structure” can move towards becoming an architectural and aesthetical guide for a project, a building, or a pavilion.

In this case, the project can be seen as “expressed by its parts”: yes, the uniqueness and the quality of the whole is still there, but it comes from a tension with the individual parts. While some of the early exercises of the so called “parametric surfaces” always left the substantial aesthetical leadership to the whole (it’s full of examples), the parts became increasingly important, with their shape and in some cases materiality in many different projects over time. Examples of this logic can be found in the pavilions designed and built for the P.S. 1 original YAP competition in New York. Projects, despite many differences, featured very often an interesting tension between an overall shape and parts that were original, customized, and present in their shape and materiality somehow independently of the whole. Or, to better state it, that fully participates and contributes to the project identity (Fig. 4).

Of course, the best projects showed a balanced relationship between the perception of the whole and the emergence of parts, while somehow blurring the difference and the separation between the two. Examples of the most successful projects range from the first SHoP’s proposal to the Public Farm n.1, by Work. AC Ny based office. In both projects, but most prominently in the latter, the tension between a whole and

**Fig. 4** Two snapshots of the space generated by the installation called "Public Farm n.1", winning proposal of YAP competition in New York's MoMA Queens branch. Courtesy of Work.AC Architects

the parts became interesting: while the approach to the courtyard led as well to an urban approach, down to different scales of space (more monumental, intimated and shaded, open, and finally the roof), approaching the structure made also possible to appreciate the quality of the objects: tubular cardboard structures, sectioned in different manners and assemblies, hosting plants, lights, or just empty shaders. The possibility of having objects emerge with their singularity is helped in this case a lot by the typology of pavilions and of open shelters, where there is no need to achieve certain performance issues, such as the thermal envelope, just to mention the most constraining one. An interesting approach came thanks to the research of Kengo Kuma, who paid since its first projects an attention towards the balanced composition of parts, and over time shifted the attention towards a formal prominence to the part, and its aggregation logic, in a balance with the whole that evolved and still changed from project to project over time. Kuma's move to wood helped this path and reached an interesting point for this text with the cake shop SunnyHills in Tokyo where the notion of envelope was challenged formally by the stacked wood mountain that apparently took to formal leadership on the building behind it (Fig. 5).

In this project interiors are quite rough; Kuma was still exploring the expressive potential of such a tectonic mechanism, but he avoided the effect of "surfacing" by bringing the tectonic wood assembly to participate in the structural behaviour of the building. So, a three-dimensional effect is perceived and adds a layer of complexity and mystery to the building's overall perception that remains urban. Kuma's provocative approach in the cake shop is part of a strategy of investigation of the aggregation logic, which in this case is rooted in a search for a return to Japanese tradition. Wood is taken seriously as construction material for a contemporary architecture closer to nature, and the research moves on from the construction logic, based on local

**Fig. 5** Exterior view of Kengo Kuma's SunnyHills cake shop in Tokyo, Japan, 2013. Courtesy of Design Gallerist, Blog section https://www.designgallerist.com/blog/sunny-hills-kengo-kuma/

studies on component shapes and connections, that are investigated Stacked components provide a sense of freedom: they are free enough to allow for some formal uncertainty, even if they are precisely joined and prepared exactly like they were in traditional construction. The key is in the balance between the identity of the part and the whole, in its "controlled fracture", that comes from the rebellion to a strict established relationship between a building and its components.

At a different scale, the will to break up" the established relationship between parts and a whole in a context like housing has been the target of the approach of the first projects by the Danish office of the former OMA lead architect Bjarke Ingels. In that sense BIG's design approach can be seen under the logic of the tension between "prominent" shapes and cellular aggregation, where the whole takes the lead. But the starting move has been regaining to the part, in this case the residential cell, an autonomy, a sort of formal independence. The project approach shares the attempt

**Fig. 6** Exterior view of the dwelling complex called "The Mountain", designed by Bjarke Ingels Group (BIG) office, with JDS Architects, 2008. Courtesy of City of Copenhagen, photo by Ty Stange

to "play with the program" with other Dutch offices such as MVRDV or Neutelings, but BIG's approach reaches a level of geometrical purity and abstraction that will be later revealed in the Serpentine Pavilion that Ingels designed as a stacked series of empty metallic cells (Fig. 6).

The further, natural step of such a play between the poles of whole and parts happens when the relationship extends to larger structures and the form tries to reach and play with the idea of networks that are by definition "open".

## 4 From Parts to Networks

The notion of the tension between a whole and its parts, the design of a "structure" for a flexible set of components is a paradigm that can be easily found in contemporary design culture outside the specificity of Architecture. In many domains, networks and aggregations happen at different levels: from web portals to energy communities, the sense of a macro-structure hosting multiple contributions became a true means of expression. This is at the same time an organizational and a formal principle: it is practically allowed and pushed by digital networks, as well as by the growth of travel capacity worldwide.

How can architects and designers deal with these networks?

Can the project itself be seen as a structure that is related to its parts, without losing its architectural sense? In fact, the network of specialists that increases at many levels could subtract “design power” to the architectural work. They can be consultants or contractors, or even a mix between the two. In his constant reflection on modernity, and on the conditions of contemporary architectural practice, Koolhaas expressed such condition in the famous OMA/AMO diagram, expressing in two directions the extension of contemporary architectural practice as having to deal and manage a cloud of possible contributions and inputs (Fig. 7).

The type of interpretation of such a paradigm can be in two opposite ways: for some designers, the complexity drives towards a pure disciplinary approach, where architects become just a node of the network. On the opposite side, there is the chance, often recalled by several authors, of architects, designers embracing digital means to shorten and blur recurrent boundaries and bring back to themselves the power over the control of production, being its construction, in architecture.

Some design practices run over a “renewed crafting” approach. The work of Studio Mumbai is innovative despite being non-digital since it innovates the design-build

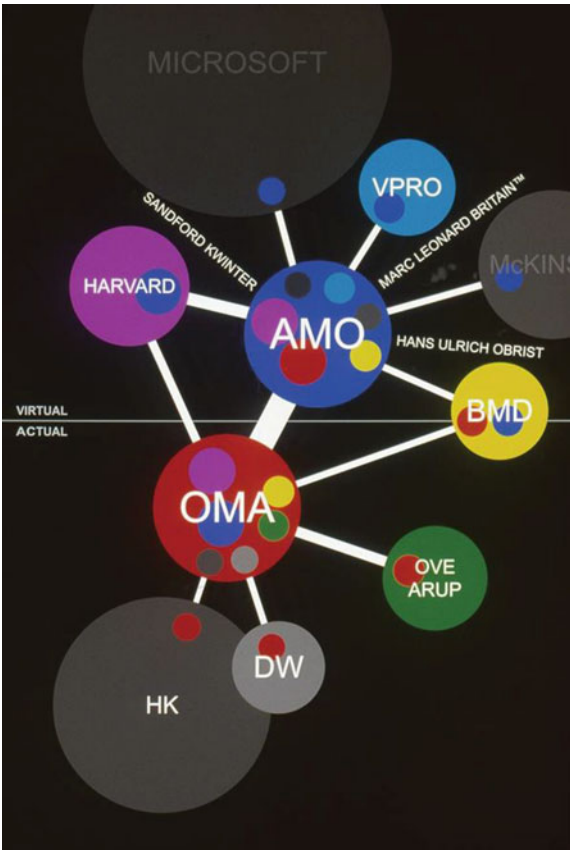


**Fig. 7** The “OMA/AMO diagram, showing the network of relationships and interaction of Koolhaas lead architectural practice. Courtesy of AMO

**Fig. 8** An image of the Palmyra House, the home built as a twin of pure boxes, animated by a variable series of components, that modulate light, opaqueness, enclosure and melting with the surrounding palm tree forest. Courtesy of Aga Khan Award for Architecture, photo by Rajesh Vora

chain through a day-to-day link to craftsmanship, in their case. The beautiful images of the office courtyard in the woods show a continuity between design, object, and part production, where somehow the distinction between the whole and the part is blurred in a diffused sense of materiality. This tactile feeling is so intimately connected to the office architectural expression that when asked to design an installation for the V&A Museum in London, Studio Mumbai built every single part in their own space, to deliver, then, everything to the UK (Fig. 8).

The relevance of the part in the work of Studio Mumbai, was shown by their first appearance at Venice Biennale, where they exhibited their office, made of tools, materials, and prototyped project parts. It also was evident in their Palmyra House, that melted with the surrounding forest of palm trees as an "open frame" populated of details, sunscreens and penetrated by wind and filtered natural light.

In these contexts, the management is no longer a cold activity, it can truly become a source of sense. If, on one hand, it is true that the amount of information to manage extends, and so does the responsibility, on the other hand it is also true that all these cases show that merging management and design, and eventually also formal exploration with construction prototyping can become a true space of expression.

This paper chooses as case study the work of RIMOND, a newborn company that was founded in 2015 with the somehow crazy intention to position itself in the gaps of the AEC process, where networks normally fail. This mainly happens in the biggest fracture, the one between Design and Construction, that is why the

Design-Build soon became its main field of interest and approach. The Gap, then is identified exactly in the same position that DesignToProduction occupied with its "bridging" coding and geometry activity. In this case, though, even if the company later evolved into a group, with a dedicated division for Construction services, the practice maintained a transversal collaboration, with people moving fluidly between design and field activity, developing a workflow based on negotiation and constant interaction with a network of partners.

This management role would normally be abstract, based on time, deliverable and cost approach. The choice of RIMOND was to strictly link such management with form development, with geometry, parts and design control. A pure manufacturing management model, brought into an AEC practice. This approach applied to constantly changing collaborations, where design can be either developed internally or in collaboration: what matters is to get inspiration from circulation of information and guarantee a steering approach. It turns out as an "Open" Design-Build approach.

The case of Al Wasl plaza became the framework to test and deploy a method to manage and generate design geometry in combination with physical prototyping, all under a "technical management" role.

## 5 The Al Wasl Plaza Dome: Managing a Network of Components

The competition design, by American office Adrian Smith and Gordon Gill, featured the central plaza of Dubai 2020 Expo as a gigantic dome, set up as a 360-projection surface, through a set of dedicated projector "pods" located all around the structure at a height of 20 m. The structure, being more a pavilion than a real "building", helped the process being it separable into few, clear packages: the concrete base, the prefabricated steel tubular structure, recalling the geometry of Expo 2020 logo, the textile projection surfaces, the two maintenance gantries and the huge projection and speaker pods. RIMOND approach was to establish since the very beginning a common ground of all parts: a wireframe geometry was created as "hanging centreline" to host and position exactly the mentioned packages. The first step of the process was the geometry adaptation to follow manufacturing optimization of steel components, in constant talks with fabrication specialists working directly from the company headquarters. The process led to apparently light changes that drove a huge simplification of welding profiles. During these trials the wireframe model allowed dynamic and efficient exchange with structural engineers of Thornton Tomasetti and physical visualization of structure with lead architects AS+GG. The ability to understand everyone's technical feelings was crucial to such a role. No exchange would have been possible without such a human design factor (Fig. 9).

The main model, then, once optimized in these first rounds, started to receive additional "hanging nodes", to host secondary structures, from inner MEP conduits to connections for outer components such as CCTV Cameras, LED lighting, shading

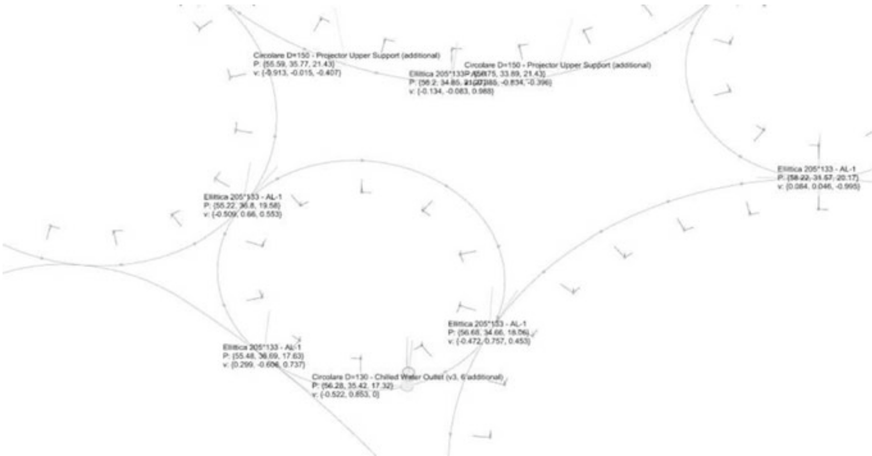


**Fig. 9** A screenshot of the "coded centreline model" of the Al Wasl coordination model. Courtesy of RIMOND, created by Lorenzo Pirone

fabric panels' brackets, all custom-designed to parametrically adapt to the changing angles and orientation.

This work was conducted indifferently to components defined and manufactured internally, such as the brackets, and to components coming from the network of subcontractors, mainly using an interchange with Manufacturing Models. The interaction with Mexican Manufacturers of Kinetica for the Speaker and Projection Pods was a very good example in that sense. Two digitally oriented manufacturers were able to act in a "build before it's built" manner, simulating final configuration and negotiating the points of connections (Fig. 10).

This project was driven by constant interaction, on top of a dynamic integrated but light model, based on clear design principles. The experience can be interpreted as the seed of a possible creative method, in a design-build framework, where the population of components from partners can influence the design development process as much as the process itself could constantly send them updated information to take into account.

Most importantly the population this way gets the flavour of construction and the feeling of tectonics into the digital environment, one of the effects of the use of mechanical models into the digital environment, that gets more underrated due to the "BIM abstraction". As indicated by Fabian Scheurer in a recent article commenting on the lack of fabrication models in the BIM evolution, if you remove from the model connections, detailing, often you might lose the true sense of construction logic and therefore of tectonics, in the architectural simulation.

At the same time, this experience showed, once again, how much the digital model cannot guarantee any automation in exchange activity alone: breaking certain barriers means an organizational change and fully embracing manufacturing (and its engineering) as a dynamic link to design, it's a matter of responsibility.

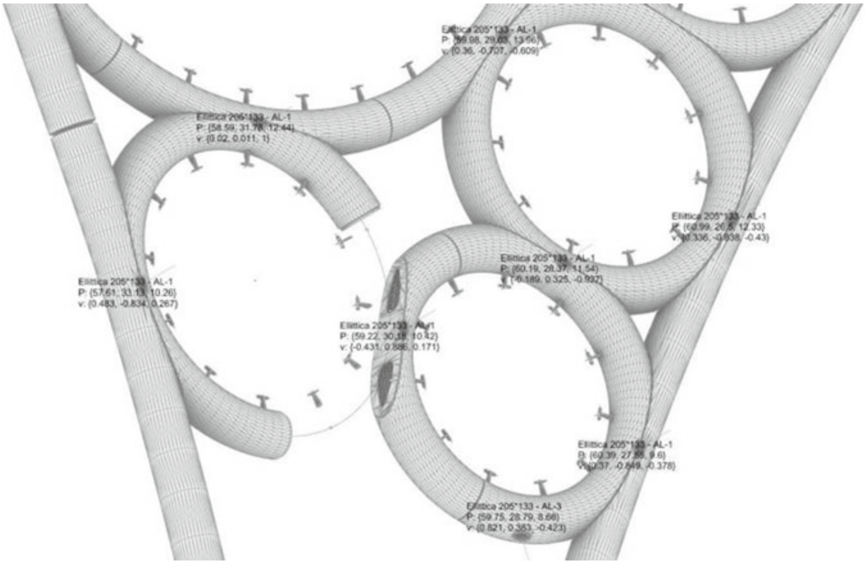

**Fig. 10** A screenshot of the population of constructive components from external sources on top of the "coded centreline model" of the Al Wasl Plaza dome. Courtesy of RIMOND, created by Lorenzo Pirone

Even if there is a technical need behind the shared detail definition, the simple possibility to directly use fabrication components into architectural models and negotiate their position, when not their shape, opens a design space. How about understanding, since the very beginning, the feel of tectonics in the architectural definition?

## 6 Beyond Design Management, Towards Design Freedom

The mentioned seed of Al Wasl Process recalls the possibility to overcome the "Design Management" and the "value engineering" approaches, both rooted in a mentality that somehow imagines a freezed design and a rigid set of phases. A new Design Space can on the contrary emerge into a continuously evolving process where construction definition can become imaginative and get an active role in the architectural development. Italy can look at its post-WW2 design tradition, when the position of delay in modernization linked to industrial mass production produced a generation of brilliant architects dealing with the potential of craft and its use in defining custom architectural detailing and original tectonic solutions, thinking of people like Ponti, Albini, or Nervi and Morandi but an interesting moment came later, when the crisis of modernism became a source of avant-garde inspiration. The season of the so-called Radical Architecture, that challenged the disciplinary boundary and the relationship between architecture and the urban environment also made its main actors become designers of objects, parts, and independent components.

Archizoom office expressed its positions in their research on the No Stop City, where their drawings were showing intentionally unbounded fields in which objects, parts could freely develop inside a set of geometrical and spatial set of references. In this research, building or even abstracting the frame of the "reference geometry"—to recall a previous introduced definition—is aimed at generating a freedom of expression of the individuals, and focusing on their own immediate environment, hosted by a continuous space described and drawn in analogy to the artificial, almost infinite space of supermarkets and factories (Fig. 11).

In his reference to the issue of Bigness in Architecture, Koolhaas evidenced the typological built consequence of what Archizoom foresaw, linking the dissolution of the perception of the envelope to the rise of artificial lighting and air conditioning, and attempted to deal with those issues. An interesting set of projects to analyze in that sense are a series of pre-pandemic projects for their Headquarters done by the big players of the Digital Scene. These projects came when these big players had just functional and anonymous designed buildings and came to deal with representing a new model of work, but also with the aim to represent their values at large, first to their employees and then to the general public as well. Significantly, Facebook selected Gehry for its new Campus but imposed to him its vision of a "Warehouse" (Fig. 12).

The relationship with such a client forced somehow Gehry back to his L. A. origins [6] when working on a local, bottom-up language made out of composition of parts that become architectural episodes, recalling the urban idea in their random sequence. The same issue of scale was faced and proposed by Google when looking at firms to design their own new location. The company has been in talk for a while with ShOP Architects and later ended with a design by BIG and Thomas Heatherwick. Google campus moved by a similar attempt to generate a "bottom up" space, made of parts, and establishing an almost urban inner condition, that strongly recalls Archizoom's radical space images. While SHoP's attempts in the Charleston East R&D extension focused on a dynamic layout, keener on the overall logic of pedestrian fluid connection through ramps shaping the building shape itself, the final design represented a move towards space continuity in every direction.

In BIG's and Heaterwick's design the framework, prepared to allow such freedom, is neither invisible nor cold. A brilliant and dramatic, tent-shaped roof covers a continuous array of spaces spanned in just two levels and organized by courtyards. Each courtyard hosts a vertical support reaching one edge of the hanging petals of the roof. This interconnection between elements, though, seems not to reach its full potential. The overall shape given to the roof to makes it appear in the landscape as a "giant Bedouin tent", forces its relationship with its bottom component parts, the support, and the courts. The whole in that sense takes the lead and the vision of the roof interior appears randomly from the bottom landscape made of slightly different levels. Its majesty can almost never be appreciated from inside as it is from far, but it fails as well to become "infinite but intimate" (Fig. 13).

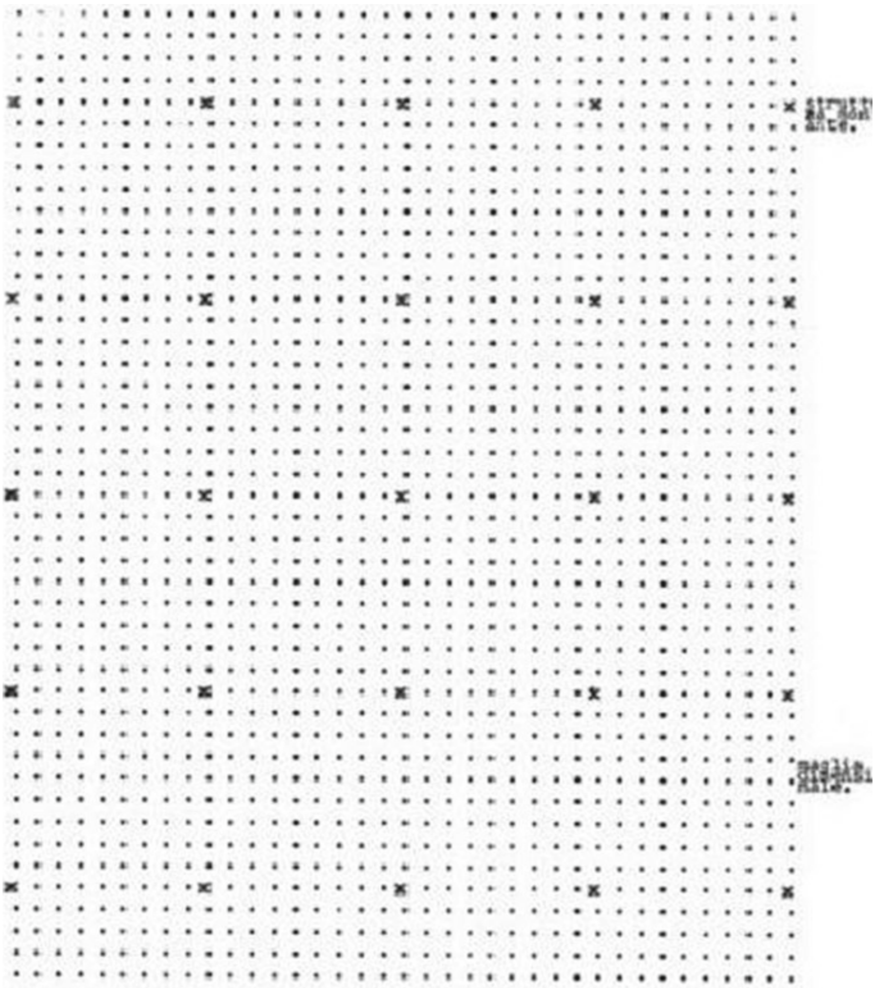

**Fig. 11** An extract of one of the most abstract attempts of No-Stop City project by Archizoom Associati office, 1970–1971. Courtesy of FOG Associates

The space has an undoubtful attempt for an open form, they could somehow find a possible variation in the interaction between petals and freely aggregated space beneath them. The architecture uses a language of extreme lightness in the light columns supporting an almost tensile and textile surface. A formal language that could remind the relationship between the light columns and the ceramic light vaults of Labrouste's Bibliothéque Nationale in Paris if you look at the impressive images of the empty space. When filled up, though, most of the magic gets lost in the relationship between the hanging roof and the chaotic space beneath. Despite a very clear logic in the search for a relationship between courtyards and the columns, the

**Fig. 12** Plan of Facebook campus in Menlo Park, California, designed by Gehry Partners. Courtesy of Google

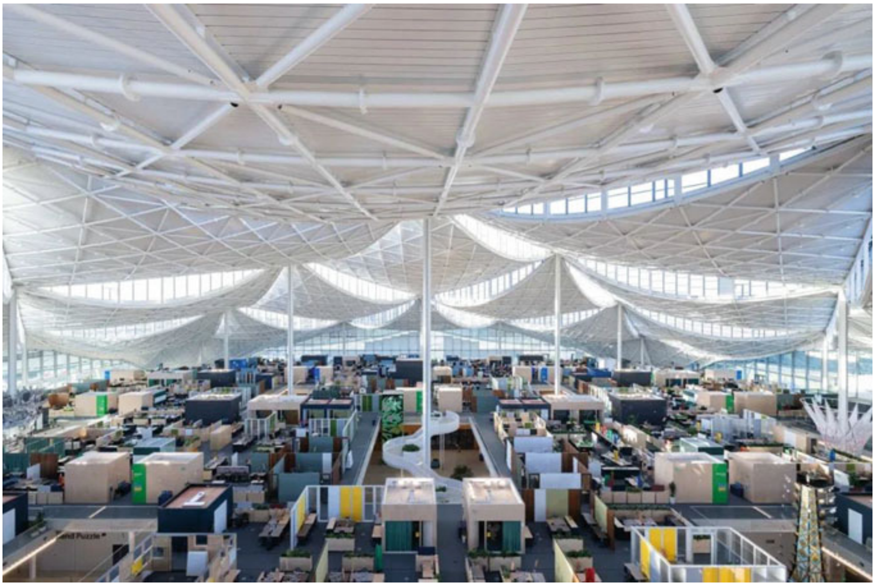

**Fig. 13** Interior view of Google's New Headquarters, designed by BIG and Heatherwick Studio. The photo is taken in the main building. Courtesy of EU Mies Award

overall effect ends up in separating the roof and the bottom world. This is probably the result of the lack of a strategy to allow a full openness of the layout, since the project forces the part free development to be packed to achieve the powerful image of the tent, mostly appreciated from outside, and undoubtedly powerful. This causes, though a strange effect in the campus: since the space was not falling all into one building, two more are added, smaller, and the overall image is composed by three, separate objects of different sizes generating a residual space in between and missing the continuity provided, for example by a similar attempt like Frei Otto's Olympic campus in Munich in 1970s with free roofs covering indifferently open space in the park, pavilions, and the stadium itself. Somehow, the whole campus misses the opportunity to become fully urban, recalling the problem, that, again Archizoom's vision fully anticipated in the No Stop City: "(…) *the exterior image of these organisms does not exist: the facade does not constitute the linguistic structure of the building, therefore it does not make explicit the functions happening inside. With the No-Stop City, the city becomes a continuous residential structure, that has no voids, and therefore no architectural images: big furnished plans, theoretically infinite, interiors illuminated artificially and micro-conditioned. Inside such a space it is possible to organize new dwelling typologies, open and continuous, for new forms of communities. The No-Stop City is a project for an amoral city, with no quality. Inside its big furnished plans, the individual can finally realize his own habitat as a finally set free, fully creative activity.*" Google search engine introduced in a very structured market a new approach user-focused, and flexible and dynamic down to the extreme of complete hiding and putting in background its supporting structure, to just show a blank starting page focusing and taking shape around each single user and its tailored needs. It represented, in digital terms, the closest concept to an open environment, with no "predefined" paths or shapes in data structures. Its headquarter though has a stronger overall image than a full feeling of space openness.

This, probably, due to the private and bounded feature of these spaces. When there is no public space, public access, there can't be a full urban effect, even in spaces structured around an interior path that allows free wandering and almost urban episodes, like in Gehry's quite successful interaction with Facebook. A company, though, that in digital terms, in comparison with Google's gully open approach represented for many people a step back, towards a more visible graphical and formally defined "framework" that encapsulates its content: Facebook is "first" Facebook and then its users. The third pole, in this balance between digital identity and its architectural representation is the manifestation of closed, controlled environment and form, with no ambition to open itself, provide independence to its parts and neither search or simulate an urban simulation is the absolute finiteness, and controlled closed form, embodied by the circular form of the "fortress" that Foster and Partners designed for the Apple Headquarters, designed by Foster and Partners, where no space is left to emergence of individual components neither in constructive neither in the layout attempt to foster visually the idea of collaboration and informal meetings. In that case, it certainly matches physical and digital approach clearly on a top-down approach.

The web itself, that was the stage for these companies to grow as global players, seems to develop in its next evolution more distributed, bottom-up structures. Dynamics like the so called web3, or the blockchain, but also the previous examples of peer-to-peer systems like Napster, BitTorrent and their heirs, are back on revealing the fundamental network-oriented nature of the global technical interaction, that as we have discussed opens practical possibilities of new work methodologies but also generate new sensitivities, or new materialities, as Antoine Picon brilliant definition suggests.

In that sense another way, probably most promising, is to find a dynamic and lightweight approach to form evolution, that allows some freedom in materiality definition. Can the structure of a design allow some freedom in its material definition?

Can some parts receive changes over time, inspire materiality without losing a sense of overall definition of the architecture? The emergence of a “rough” approach can be felt as following this procedure and authors suggested a possible future in such a “rough and provisional, but precisely built architecture [7] (Fig. 14).

One of the contemporary researchers that, although probably zero digitally focused, mostly succeeded in looking for freedom of expression in constructive terms can be found in the Parisian office of Lacaton and Vassal. Their work started simultaneously with the search of architectural components that could in their case make them exit the already established building process and associated architectural language. Anne Lacaton reminds in an interview their discovery of the technology of greenhouses as a possible exit strategy to gain control over the link between architecture and its materiality, breaking up the established process, their prices and get new space for their clients. What makes them fully part of the attempt of most of the digital research of the origins, somehow lost in the evolution of the technology into a commodity, is the revolutionary character, of its possibility to challenge traditional habits and gain back power to architects. An attempt to use technology for a political target, meaning with politics a change in the power balance, a play with it, in architectural terms. In fact, they achieved in a consistent and coherent research path,

**Fig. 14** Interior view of Palais de Tokyo, the operation of “reduction to frame” conducted by Lacaton and Vassal in their design for the new museum of contemporary arts in the former nineteenth century building. Courtesy of EU Mies Award

**Fig. 15** Exterior view of Lacaton and Vassal “Manifesto City”, in Mulhouse, France, 2014

many of the targets that can be shared with the digital pioneers. Another, significant one of them is performance, or to better state it a “performative approach” to design: they worked to achieve more square meters at the same cost, and to achieve a mostly passive energy behaviour in indoor climate control (Fig. 15).

This “reduction” to action can be seen much closer to a “Google approach” than many pioneers of the digital revolution tried to achieve. In Lacaton and Vassal architecture, there is a strong presence of what can be defined as a “built framework”, that seems to encounter the request of people for spaces of freedom, of regained freedom, being it gaining more space, like in the PLUS projects or more freedom of expression, movement, like in their provocative but meaningful intervention at Palais de Tokyo in Paris. They often mention how much, for them, the possibility to manage a technology, to force the process was crucial to the success of their attempt. “It was not possible to achieve under constraints and costs of established architecture”.

But significantly, they started their feeling and their reflection in Africa, with projects starting with simple moves. finding out that moving a chair in a shade or setting up a minimal meaningful environment with few simple moves interpreting local available things, somehow brings us back to the essence of being architects. An essence that is at the same time political, fully physical, and immensely rich, that keeps on existing even when complexity, number of parts, procurement chain and actors become richer, larger, and stronger.

**Acknowledgements** This article is one of the outcomes of the collaboration between Università degli Studi Roma Tre—Department of Architecture, and the R&D Division of RIMOND. The topics of this article are shared among the authors. Converso wrote paragraphs 1-2-3-6-7 and Pirone worked on 4 and 5.

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# *Adauctus Architectus Novus* on the Definition of a New Professional Figure

**Giuseppe Fallacara, Francesco Terlizzi, and Aurora Scattaglia**

**Abstract** This contribution proposes a reflection on the evolution of the professional figure of the architect thanks to the implementation of technologies brought by the fourth industrial revolution. Technology has continually transformed the architect, expanding his skills and potential through digital fabrication tools: these allow the figure of the architect to be elevated from a simple designer to a complete realizer of the work. The contribution is divided into three parts: the first investigates, in a critical key, how technology has been a constant that has assisted human evolution in its various phases, modifying, changing, evolving and, perhaps in some ways, dis-evolving man; the second part proposes to present the definition of the new professional figure of the architect, fruit of the progress brought about by technological evolution through the application of digital fabrication tools in the management of the architectural process; furthermore, among the new tools that enhance the figure of the architect, we can now register the impact of artificial intelligence. This can represent a new starting point in the reflection of the design process, making an essential contribution to what comes before the project itself, that is, the creative phase.

**Keywords** Technological innovation · Digital Fabrication · Artificial Intelligence · Human–machine interaction · Generative design

**United Nations' Sustainable Development Goals** 4. Quality education · 9. Industry, innovation and infrastructure · 11. Sustainable cities and communities

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_6

## 1 Introduction

We are experiencing a new evolutionary phase, perhaps revolutionary, among the many that have characterised the evolution of humanity: it is a process that stems from the fourth industrial revolution, and it's leading to fully automated and interconnected industrial production, in which products and means of production become networked and can "communicate," enabling new methods of production, value creation, and real-time optimization. The interaction between man and machine, which is diminished in the more authentic concept of augmented reality and into the transition from "digital" to "real" through additive manufacturing, 3D printing, robotics, communications, and machine-to-machine interactions, is certainly one of the directions of development on which Industry 4.0 products are having a profound impact. The link between humans and machines is marked by intricate reciprocal impacts. Following classical cause-and-effect reasoning, technology cannot be considered only a product of man. It feeds back on the man in an advanced form of circular causality. A circular interaction between man and technology requires one to look for the evolution of man in the complex interactions between biological evolution (Darwinian), socio-cultural evolution (Lamarckian), and development or technological evolution. For this reason, we can speak of human–machine co-evolution, identifying biological, socio-cultural and technological evolutions as interacting factors.

Technology has become an environment to live in, an extension of the human mind, a world that is intertwined with the real world, impacting and being influenced by how we design and build spaces. The introduction of digital technologies and media into architecture has sparked a design revolution that has resulted in substantial advancements in the discipline. Particularly, digital fabrication has enabled architects to overcome the gap between representation and construction, allowing for a seamless connection between design and production. The introduction of new technologies has forced a redefinition of the architect's professional identity. As a result, it is essential to evaluate the role of technology innovation in architectural design and implementation, as well as how it impacts how architects approach their profession.

The employment of digital fabrication and material techniques to achieve a balance between virtual models and actual artefacts is a topic of critical importance and urgency in this setting. As discussed by Robin Evans in "Translations from Drawing to Building" [1], the gap between drawing, the standard design medium, and building, the result of an architect's work, is the void in which significant innovation occurs. In architecture, digital approaches such as digital fabrication and generative processes can facilitate a seamless connection between design and manufacturing, allowing for better efficiency and innovation.

Against this backdrop, the reflection proposed in this paper is strongly related to the scope of this book, which seeks to systematize and analyze the greatest contributions and experiences in the professional, academic, and research sectors of architecture and design based on this new design paradigm. It has already been proven that the tools that have come with technological progress have changed the profession and made it necessary to work under a new definition of the professional figure, related to the potential and difficulties of the post-digital era.

## 2 From *Homo Sapiens* to *Homo Technologicus*. Reflections on the Cognitive, Emotional, and Social Consequences of the Pervasiveness of Technology.

"It's a turp of decadence!" [...] "Who cares about the Greeks and the Latins, good at most to furnish some roots to the words of modern science!"—exclaimed the old professor Richelot, teacher of classical languages, the protagonist of a posthumous narrative composition by J. Verne "Paris in the twentieth century". Written in 1863 and set in 1960, the novel describes the French capital as a hyper-technological metropolis where the invasion of machines has reduced human capital and the triumph of capitalism, of technical and utilitarian culture, has generated a grandiose, productive, and winning system, in which art, reduced to mere entertainment, no longer counts for anything, except as a ridiculous damsel in the service of science, with its lyrics to progress.

The paradox of the story lies in the fact that it is a futuristic fantasy that, with extraordinary foresight, in the mid-nineteenth century, predicts a future that is not the radiant one of the progresses promised by the sciences but is instead the gloomy one of the deaths of the humanistic dimension of human consciousness. Verne's distrust of machines and technology, which transpires with prophetic lucidity in this sort of visionary novel, made reflect on what the logician and the philosopher of language, Ermanno Bencivenga, considers to be the threat that is most undermining our time: the ability to reason which risks to disappears. For Bencivenga, this 'gentle catastrophe', as silent as it is devastating, is gripping the new generations, especially those who are more exposed to the frenzied proliferation of technological tools, as well as of information and communication media, which have now become too fast and powerful compared to the time that logical thinking requires. The disturbing result is that young people get increasingly used to the idea that someone else, or something else, will reason for them.

During our evolution, we have learned to speak, read, and write. According to anthropologist Arnold Gehlen and many others, technology has always been the means man uses to make up for his physical and mental deficiencies and therefore it can be considered as the extension of our senses [2]. In other words, technology constitutes for man an extension of his body, of his physical and psychic abilities; it is a prosthesis that allows the creation of augmented reality. For example, the hammer extends our hand for strength; the car extends our foot for speed; the mobile phone extends our ears and mouth to increase our communication skills. *Homo technologicus* has therefore grown up using digital technologies since birth. Among the latter, the remote control, the mouse, and the mobile phone: these tools, in fact, lead to different management of all information: today's children are skilled in controlling information flows, dealing with its over-availability, selecting it appropriately and according to their needs. Their non-linear behaviour, the control of information, the knowledge of how to navigate through information efficiently and effectively, how to communicate, and how to effectively build a network of peers lead to the development of crucial skills for a chaotic and creative society.

The paradigm of how technological science is changing us as people and how it is shaping our minds is represented by social media (Facebook, Pinterest, YouTube, Twitter, etc.): "social networks" that forge in their image and likeness an orthodox way of thinking and acting which, together with the automatic prompts of cell phone keypads, are drastically thinning our vocabulary [3]. Sigmund Freud argued that "it is impossible to know men without knowing the power of words" and "if words become thinner", as the psychiatrist Paolo Crepet points out, "they simplify, become ugly and horrible neologisms; if our emotions become small icons coloured on a mobile phone screen, even the bricks of our unconscious will inevitably become sand" [4].

*Homo sapiens*, with its rationality, which has always been its pride, has therefore transformed itself, since its appearance on planet Earth, into *Homo technologicus*, given the close, almost symbiotic relationship that has linked it to the various technologies from he discovered and built, and with which it can be said that he co-evolved.

However, it is necessary to "start thinking again" because we are all participating in the definition of a new evolutionary matrix that deprives the new generations of what they need more than anything else: the ability to think.

Nevertheless, what is meant by thinking? It derives from the Latin verb "*pèndere*", which means: to weigh, to estimate; alluding to the act of evaluating things with the intellect; thinking is reasoning, it is arguing, or "giving an account of what one is saying". To think, after all, is to preserve one's dignity as a human being because, without thought, there is no conscience.

In today's digital, globalized and connected world, we must preserve this ability in order not to become software, we must regain the ability to process thought, open up to the slow spirit of our brain and induce the new generations by educating them to focus attention on something other than a display in order to avoid—as caustically noted by the anthropologist Niola—inadvertently making them pass from the age of the "*Cogito ergo sum*" to the age of the "*Digito ergo sum*".

## 3 *Novus Architectus Adaucto* and "Adjacent Possible" of New Stone Architecture.

In the age of digital transformation that is characterizing these decades, changing entire industries and classes of professionals, the figure of the architect is the one who, thanks to the digital revolution, has undergone and will continue to undergo significant transformations.

It is now unthinkable to design structures without the help of computers. They are used throughout the whole of the architectural process, from conceptual design to actual building. The digital processes used by architects and building consultants include three-dimensional modelling and visualisation, generative form discovery, programmed modulation systems, structural and thermal evaluations, project management and coordination, and file-to-factory manufacturing. Digital Fabrication deals not only with additive technologies, which are only one of many pieces that make up a much more complex picture. In particular, it includes all those technologies that allow moving from a simple idea to its realization. These also include subtractive technologies—milling machines, numerical control machines, mechanical cutting and laser cutting—and all the technical knowledge related to the digital world necessary to juggle such machinery properly.

The combination of past and current technologies knowledge directs architecture towards an informed approach to ensure maximum performance, whether energetic or structural, but also aesthetic and cultural, prefiguring new paradigms for buildings, especially those in stone. The stone, compared to the modern materials, is considered difficult to submit both for the product design and for contemporary architecture. In addition, it is considered to represent an old material, or rather strongly connected to the forms of the past and tradition. On the contrary, it is known that, for a designer, there are no ancient or modern materials, but it is the way the material is transformed, worked, and shaped that makes it new and innovative rather than old and decrepit.

Certainly, the renaissance of the using stone nowadays is related to the evolution of digital fabrication in the dual aspect of both technological evolution of the parametric and generative three-dimensional modelling software and thanks to the robotics and numerical control machine tools applied to stone manufacturing. In the project-product process, a new and unprecedented direct relationship between designers and final product is established thanks to robotic production of stone components. The contemporary designer is a "*Novus architect adaucto*" or an "expanded designer" in the sense that he possesses new robotic arms which allow him to cut and shape the stone according to his direct requirements without any external mediation. In this perspective, the famous "dress architect" (the role of the architecte—*habit de l'architecte*) changes both because of the new tools at its disposal and of the new forms that he can produce.

In this new perspective, the role of the "fabricator", the person who creates the work, disappears. His role interposes between the author and the final work, but the designer becomes the maker of his work thanks to his new robotic arms that allows him to cut and shape the stone and to mount and assembly the masterpiece. The direct control of the making of the work by the author is the first step to redefine a new profession, paradoxically similar to the architect—master of the past.

Although there is great excitement, shown by the growing interest on the part of professionals in understanding how it is possible to integrate these technologies within their cultural background, the limits due to the construction process have not yet been completely overcome.

In this new scenario, the new architect of the future is the author and creator of his own work or at least the one who ensures the final work the most suitable correspondence with the original idea of project without mediation and/or constructive interpretations by others. The new designer takes on new critical skills, goes back to the real construction and assumes new ethical and civil responsibilities of his job. Thanks to the development and dissemination of digital knowledge related to manufacturing (FabLab—Fabrication Laboratory), this process of redefining the role of the designer could occur at any scale, from architecture to design product, and at any level of business activity, from big industries to the small workshop of the province.

Now, it is an incessant cultural process, not only within the stone world, which is based exclusively on a new culture of doing and of the strong contact with the materials, of learning and supporting the process concerning the incubation and birth of ideas. The latter is the most delicate and important aspect which is a key point for the reformulation of university programs and teaching methods.

The lithic prototypes come to life under the influence of research and innovation aimed to expand the "adjacent possible" of stone, according to what Steven Johnson argues in "Where Good Ideas Come From: The Natural History of Innovation". The adjacent possible, according to the author's statements, is a "kind of shadow future, hovering on the edges of the present state of things, a map of all the ways in which the present can reinvent itself". That is identify for us new possibilities and potentiality of stone even with the risk to exceed in the morphological/structural boldness, absorbing the lessons of constructive-technological areas, including external contributions not strictly related to the logic of stone. As Steven notes, the adjacent possible "captures both the limits and the creative potential of change and innovation."

Johnson identifies seven creativity "models", through which it is possible to search for innovation. Some of them can be identified within the designer intellectual work:

**Slow intuition**, which is preserved and stored in mind for a long time before it is shaped by the lightning of the immediate intuition.

**Serendipity**, which is a neologism indicating the feeling you get when you discover something unsought and unexpected while you are looking for another.

Serendipity is not only a feeling, but it also indicates the typical element of scientific research when important discoveries have been made while looking for something else. The term **exaptation** was coined in 1971 by the evolutionary biologists Stephen Jay Gould and Elizabeth S. Vrba: an organism develops a trait optimized for a specific use, but then that trait is redirected to a completely different function. A classic example are the feathers of birds, which initially appeared in dinosaurs to regulate body temperature and later evolved into flying instruments: a tool created by the evolutionary needs for a given purpose reveals unexpected utility for another purpose. A pen or feather adapted to warm up is "exaptated" for the flight.

According to Johnson, intuitions arise slowly over the time, but they materialize rapidly thanks to the composition of the last tile to finish the mosaic, giving the complete vision of the scene. The last tile comes like a thunderbolt! The innovative environments are those that encourage their residents to explore the adjacent possible, making available a wider and more versatile sample of spare parts—mechanical or conceptual—and promoting new ways to recombine them. There are many novel solutions and brilliant ideas, at your fingertips. The matter is to use the available resources in a different manner, in order to create new combinations. Most of the times innovative ideas do not arise from the strokes of genius, but from a good *bricolage*.

This adjacent possible concept is interesting and very useful in developing innovative routes. Although we are accustomed to think about innovation as a leap ahead in time and space or sudden swerving due to the genius of the inventor, we must agree that the history of cultural, artistic, and scientific progress is comparable to the "story of a door leading to another door, exploring the palace one room at a time". Researching, designing, making, building you may encounter errors or serendipity phenomena, which are both fundamental for scientific research: from mistakes and "casual discoveries" are born the best innovative ideas of our society (see Fig. 1).

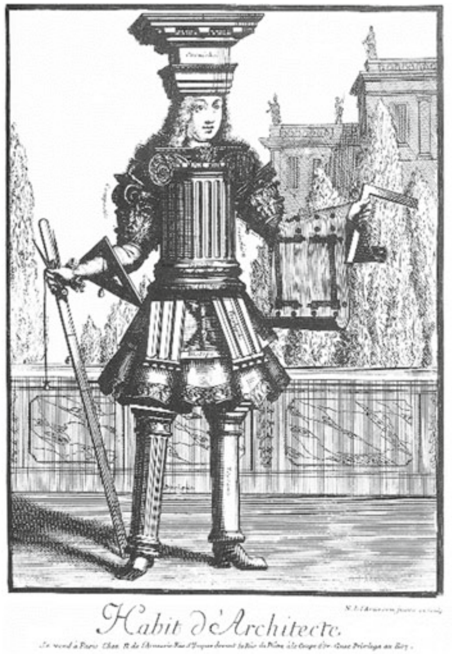
## 4 Architect with "*Extended Mind*": What Happens When Artificial Intelligence and Human Creativity Meet?

Just as digital manufacturing technologies have made it possible to enhance the figure of the architect, metaphorically equipping him with robotic arms that exponentially elevate his architectural abilities, a further upgrade can be accomplished at an intellectual level by implementing artificial intelligence within the design process. Artificial intelligence (AI) has permeated every aspect of contemporary life. It is used in everything from online recommendation systems to pricing algorithms, from providing personalized news and ads to suggesting the perfect ending to a sentence written by you.

In the beginning, it was science fiction that introduced us to the concept of artificial intelligence and the so-called "technological singularity". The term "singularity" was introduced by the science fiction writer Vernor Vinge in 1983, and it was brought into wider circulation by Vinge's influential 1993 article "The Coming Technological Singularity" [5]: it refers to the point in time when the advancement of technology will accelerate beyond the capacity of human beings to comprehend or predict it. Artificial beings, created by humans who share with them the ability to process complex thoughts, come into conflict with their creators. On the other hand, this event has already taken place in Mary Shelley's Frankenstein, published for the first time in 1818, and considered to be one of the most important literary forerunners of science fiction. But it was in Samuel Butler's dystopian book "Erewhon", published in 1872, where intelligent robots were first mentioned, perhaps forecasting our own technological culture. "Compared to the machines of the future, those of today are like the first dinosaurs to man. The largest, in all probability, will shrink a lot" wrote Butler a century and a half ago. Since then, science fiction books and movies have looked at the topic from many different perspectives, including philosophical and ethical ones. In an effort to both amuse and raise issues about the future, film and

**Fig. 1** **a**, **b** G. Fallacara 2016, Adauctus architectus novus, Interpretation from Habit de l'Architecte, engraving attributed to Nicolas II Larmessin, probably made in the seventeenth century.

**(a)**




**(b)**

literature have given us many complicated concepts in recent years. This translates into what is still the current debate between "technophobia" and "technofilia", where the optimistic hopes of "futurologists" clash with the visions of the most pessimistic "techno sceptics" who see artificial intelligence as the invention that would lead to the end of humanity.

Among the various sectors that have been permeated by artificial intelligence-based solutions, there are also the art and architectural ones. Art has always had a complex and evolving relationship with science and technology. Recent developments in machine learning have led to an acceleration in the exploration and discovery of the potential possibilities of AI applied to art through the adoption of technologies such as neural networks and deep learning. In recent decades, and with particular acceleration in the last five years, rendering algorithms designed to modify images in several ways have been developed. Furthermore, in recent months, social network boards have been flooded with images generated by artificial intelligence systems: algorithms capable of generating spectacular photorealistic images from text input.

The use of artificial intelligence in architecture design is not new. Attempts to replicate an architect's design abilities using a computer date back to the late 1960s [6]. However, AI research has gone through several phases of rapid decline, but it is currently on its way to a successful future [7]. As a result, particularly because to modern computers' enhanced capabilities [8], AI will soon massively empower architects in their day-to-day practice [9]. In any case, the employment of AI in the architectural profession will not be universally welcomed. Some may dismiss it, just as some did when computers first entered the mainstream architectural culture around thirty years ago [10].

In architecture, a typical project goes through conceptual or pre-design to the operations in order to manage the building itself [11]. Architectural design is a complex process that requires imagination and skills to generate new ideas [12]. Since the design criteria are not yet fully defined at the conceptual stage, the application of artificial intelligence to this process should not be directed toward finding a solution in a specified search area; this method should instead be seen as a study of the requirements and potential solutions to achieve those criteria during the conceptual design phase [13].

Today the designer has new tools at his disposal to create, and an "inspiring muse" who offers new opportunities to investigate his own emotions, and new languages capable of mixing reality with the product of the reinterpretations of neural networks. Artificial intelligence and machine learning play a fundamental role in today's lives, thanks to the development of increasingly advanced systems inspired by the human way of thinking, acting, solving, and creating. To talk about artificial intelligence means talking about what it means to be human in the age of AI. If there is one characteristic that belongs to humanity, it is creativity. Creativity is not limited to art, and creativity is very human. There is no precise definition of creativity, but one of them is that creativity could be defined as the production of new effective knowledge from existing knowledge, which is achieved through problem-solving [14]. Creativity is also a form of care and recognition of the different ways of being. Precisely for this reason, it is natural to ask ourselves whether it is legitimate to approach a term so strongly connoted by our sensitivity as living beings to something artificial such as a machine or software.

Creativity is one of the most mysterious and, simultaneously, most noteworthy qualities of all human existence. We can define it as the ability to create something that is innovative and recognized as such by the community. Indeed, human creativity is also the result of the stratification of acquired data because every artist draws, even unconsciously, from the fabulous creations of the past. Therefore, no work of human ingenuity is entirely self-sufficient and purely original. However, the human artist has free will. He chooses which field of art to dedicate himself to and the purpose of his work. On the contrary, an artificial intelligence system follows an algorithmic procedure that tells it where, how, and what to look for.

AI is about origination and novelty, doing things that nobody anticipated and that we did not expect. It has an emergent intelligence. We cannot predict quite the outcome that it is going to offer us. It is based on everything it was fed, but it not only giving back exactly what has been given. It is recombing it and giving back to us a in a new outcome. From this, it can be stated that there is something about a sort of autonomous creativity.

Nevertheless, what happens when machines, algorithms and artificial intelligence come into play? There is the need to imagine a new type of creator, a new breed of artisans who are at ease with these evolved instruments. Artificial neural networks are more than a tool; it has an intelligence of its own, and we must understand that when working with it. It can be seen as a medium, as something we work within. Indeed, there is a need to understand its properties. When a sculptor works with a piece of marble, he or she must understand the marble's feel. With AI, we must understand the way it sees the world and the way it thinks. It's something to work alongside.

It is essential to consider that an AI system is not self-sufficient in deciding what to do: at the base of its creation, there is information that man enters. Therefore, it is possible to believe that creativity can be improved by the collaboration and interrelation between man and machine.

AI can be seen as a kind of "extended mind": a prosthetic device that can enhance the natural intelligence of the human being [15]. It's another form of intelligence to work with. In this way, for the designer comes the possibility to work not only with his own mind, but with this broader sea of possibilities which can take him to a new place.

## 5 Conclusions

The impact of digital design and fabrication techniques on architecture is already far-reaching. The integration of digitally generated data to produce precise and complex geometry, to direct making and assembly process, and exploit material performance is returning architects to a position that had disappeared with the master-builders of medieval times. The tools provided by digital technological progress have allowed the designer to take control of and retool the entire design, fabrication, and manufacturing process, leading to the generation of the architect of the future: a professional figure based on a combination of the skills of the architect, augmented by computers and computer-driven machines. With these new powers, architects are now able to craft the digital tools and processes required to make architecture for the post-digital age.

The language of architecture, the figure of the architect as a professional, and the method of design have evolved, in tandem with the changing purposes that different societies have had for this profession and art, which is destined to undergo radical transformations in the coming decades. It is hoped that this contribution will not only spark the curiosity of readers, but also motivate them to engage in further research and participate in lively debates on the subjects at hand.

**Acknowledgements** This paper is the result of the combined work of three authors. The authors have revised all the paragraphs, and the paper structure and the research topics have been conceived together. However, paragraph 2 was written by Francesco Terlizzi; paragraph 3 by Giuseppe Fallacara; paragraph 4 by Aurora Scattaglia.

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# The Future of Architecture is Between Oxman and Terragni

**Mario Coppola**

**Abstract** What will be the future of architecture? Architecture is among the major culprits of the $CO_2$ emissions that cause the current ambiental crisis. The discoveries of coding, digital design and digital fabrication—including topological optimization, reactive skins, and lightweight technologies such as 3D printing of natural and environmentally friendly materials—are essential to finding an alternative path to those used so far. A road that not only addresses the "technical" issues of the climate crisis but is capable of proposing a new vision of the world, a spatial system that is structurally, physiologically and symbolically based on the concept of coexistence, of symbiosis, between the world of man, the house of man, and the rest of the biosphere. The work on biomaterials from the digital fabrication world assumes crucial importance in this perspective. It is the first research capable of demonstrating that the inert envelopes of architecture can become organisms and no longer in a metaphorical key: buildings like trees programmed to become skyscrapers, houses like pods and fibres that transport people by capillarity along with water and nutrients. Energy from domesticated photosynthesis processes, eyelids and hairs that grow to shield excess light. Architecture that reconfigures itself as a living form similar to what already happens in nature for the calcareous secretions that we call shell. Yet before we can indulge ourselves in transforming architecture within these new ways, there are at least two issues that cannot be ignored so as not to repeat the mistakes made by Modernism a hundred years ago.

**Keywords** Posthuman · Anthropocene · Ecologic · Regenerative · Computational

**United Nations' Sustainable Development Goals** 7. Affordable and Clean Energy · 11. Sustainable City and Communities · 13. Climate Action

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_7

## 1 Today as Yesterday. A Brief Introduction

The discoveries of coding, digital design and digital fabrication—Industry 4.0 foundations—are probably essential to finding a new road for architecture and design, a road that not only addresses the "technical" issues of the climate crisis—$CO_2$ production in the first place—but that is capable of proposing a new vision of the world, a spatial system that is structurally, physiologically and symbolically based on the concept of coexistence, of symbiosis, between the world of man, the house of man, and the rest of the biosphere. Yet before we can feel free to revolutionize architectural and design languages and tectonics, we must respond to some crucial questions so as not to repeat the mistakes made by Modernism a hundred years ago, when the discoveries of industry—for example, the mass reproducibility, that for the first time was free from size and cost limits—changed forever the face of the landscape and of the urban peripheries, generating immeasurable damage to human well-being and to terrestrial ecosystems.

Indeed, the profound changes that have affected Western society in recent years trigger an interesting comparison with the great transformations that took place in the first decades of the twentieth century. At that time, the Industrial Revolution changed not only the production method but the collective imagination itself: in the space of a few years, we have gone from a world of small and different architectures, made above all by hand, to a world populated by mammoth buildings children of the assembly line.

The architects of Modernism exploited these unprecedented production tools to give life to a new urban and architectural vision, formally based on the standard, of the repetition of simple and economic elements. But behind the desire for "a house for all"—a need that continues to animate a large part of the construction world, for example in China—and the figures and languages invented by the masters of the modern, there was not only the will to exploit new construction techniques to offer an architecture more suited to post-mechanization lifestyles nor just the intention to increase the size of buildings and reduce costs. Argan wrote in 1947:

> We can therefore consider the so-called architectural "rationalism" as a close analysis or critique of tradition, aimed at tracing its most authentic and original foundations, at restoring its essential values: therefore, it leads back, albeit against academic classicism, to an ideal classicism and against a customary naturalism at the very foundation of the idea of nature. When European culture wants to go beyond the rationalistic limit of scientific Cubism and the architecture that is connected to it, it has only one way: to overturn the problem, to oppose the value of consciousness to the value of the unconscious. It is the closed road of Surrealism. [...] Wright does not know enough about the history of art to be able to give a precise historical objective to his irritated aversion to classical art and in general to the great Western figurative tradition; but he is keen enough to identify the cause of the aversion in the principle of authority on which that tradition is founded. But faced with the basic argument of the European anti-traditionalist polemic he remains doubtful: even mechanical civilization has its myths and its principle of authority. Wright sees the symbol of the principle of the authority of classical and Catholic civilization in the dome of St. Peter; in the skyscraper he sees the symbol of mechanical civilization. Wright does not flatly condemn the mechanical character of modern civilization, but he wants the machine to serve man in his work and not the other way around. [1]

The desire to re-propose and restore the essential values of tradition, of the anthropocentric law inscribed in classical tectonics—composed of orthogonal geometries, not existing in nature, and detached from the ground through the *crepidine*—is the deep cultural movement that constitutes the substratum, the humus from which the "abstract", "minimalist" research of modern architecture takes shape. A law issued by a world two thousand five hundred years old, in which man's main need was to be emancipated from the rest of nature, a hostile habitat from which to get out in every possible way, starting with the perceptual, cultural, and symbolic-spatial one [2].

Therefore, if it is true that the current urgency is, on the contrary, to find a way to coexist, a symbiosis between human civilization and the rest of the biosphere—the biosphere of which humanity is an integral part, of which humanity needs to exist while the opposite is not true—it would seem evident that the discoveries of digital design and digital fabrication brought by the great technological revolution of the last few decades are the key to overturning this relationship, transforming submission and exploitation into a harmonious and balanced relationship based on the idea of interdependence and non-differentiation between man and nature. A relationship that should be structurally different from that set up by contemporary society, based on the capitalist consumer economy. But in history it frequently happens that great transformations produce tsunamis and violent settlements and also involuntary self-sabotage, internal reactions that are contrary to the intentions made explicit at the outset. Just think of the damage perpetrated in suburbs by the naive claim to build buildings that were hundreds of meters long, without differentiations, unable to establish empathy and produce psychosomatic well-being, focusing everything on the use of structural elements (pillars, trilithons, etc.) and typological archetypes from the great Western architectural tradition that, alienated from decorations, materials, proportions, should have been enough to make the places thus obtained habitable.

For all these reasons, before concentrating the creative energies on the possibilities offered by the new tools, and looking for the ecological revolution we desperately need, it is necessary to ask ourselves about two questions. The first: is it just designing slicing, parametric arrays, and topologically optimized structures enough to produce an architecture that is in harmony with nature? And, even before that, what should we mean today by "nature"? The second: can we produce, in the name of coexistence and symbiosis, figures that are radically, epistemologically different from those shaping every urban scenario, proposing once again the cultural mechanism of the *tabula rasa*?

## 2 Parametricism and the Global Market Society

On May 6th, 2010, Patrik Schumacher, Zaha Hadid's partner and founder of DRL master at the Architectural Association, published in the Architects' Journal a long text entitled "Let the style wars begin". The text contains the description of Parametricism the German architect considers the next hegemonic architectural style on a global scale. The article ends with a lot of details about the new language rules and a series of heuristic principles, divided into “dogmas” and “taboos”.

More or less from the publication of this manifesto, many architectural practices belonging or tangent to the international movement (so far summarily defined as “digital” architecture) started to rally in the label coined by Schumacher.

However, after the appearance of Folding Architecture by Greg Lynn in 1993, all the subsequent attempts at defining Hadid’s, Himmelb(l)au’s and other post-deconstructivists’ architectures had already changed their expressive register while abandoning the concept of the “fold” as an inter-individual continuity-complexity, a nature-culture continuum. From these attempts, several definitions of architecture came out: “blob”, computational, algorithmic, generative, procedural or, simply, computer-aided. All of them lost sight of the profound reasons for a hybrid, multiple, open composition: they focused only on technique, therefore encouraging the mass distribution of mannerist-by-definition research. The result was a language accessible to anyone who, though in a lack of culture, talent, and sensitivity, can use morphogenetic software. With the coming of Parametricism—that in a very short time acquires global importance, transforming parametric architecture into a label known by most architects—focus definitely shifts onto the tools, and technology, in a perspective, that sees architecture as a technical affair devoid of cultural variables, in which the search for new architectural “phenotypes” can be carried out automatically through scripting and genetic algorithms. In this perspective a living architecture is being theorized but it does not represent the real change of a cultural paradigm, first of all in an ecological and therefore, as Edgar Morin clarifies, anti-capitalist key.

As a matter of fact, the term “parametric” refers explicitly to the information technologies related to post-deconstructive research [3] since setting those technologies as fundamental and characterizing reasons. So, this global movement is based on a design that comes from the selection and manipulation of numerous parameters that define the final status of the project. It is an architecture that becomes, according to Schumacher, an instrument serving customers, as if the only function of architecture should be meeting the needs of the dominant economic/productive model in the industrialized Western society. Schumacher says that parametric architecture is the most effective tool—he repeatedly underlines, in recent years, architecture is not art but a tool to organize space in the most “productive” way—to ensure better, faster operations of the contemporary production based on a network society.

So, architecture is just an instrument of “progress”, which suggests a spatiality made to support, optimize, and maximize an economically intended “productivity”, accepting that the architect’s role is not to propose an innovative political vision or even criticize the socio-economic political existing model, but just improve the users’ performances according to the needs of today’s business production. From Schumacher’s perspective, that appears to be very different from Zaha Hadid’s vision (i.e. the MAXXI, the way it connects both with the city tissues both with the river), in other words, parametric architecture aims to “reinforce” and improve the processes of a society that Zygmunt Bauman defines, with a very different connotation, liquid [4]; i.e. it deals with those processes of post-industrial production in their hyper-capitalist evolution, which produce such phenomena of relocations as needed by a globalized exploitation of human and natural resources, governed by elusive, constantly moving super-managers.

The target of Parametricism seems therefore that to give a physical body to a society in which competition and abuse between individuals, and multinational groups' power is encouraged and promoted at the expense of human relationships, happiness, survival of communities and ecological balances. It is interesting that the German architect, after having explicitly written about the attempt at approaching, through digital tools, the «compelling beauty of living beings» [5], decides to abandon this definition and names Parametricism the architectural style emerging from this research.

A choice that shifts the focus from an expressive nature referred to the living form—that evokes the need for negentropy, i.e. order and complexity as mentioned by Morin [6] and recently demonstrated by contemporary neurosciences as far as the deep bond between human beings and terrestrial ecosystem is concerned—to the technical, instrumental form, omitting the starting choice, the tendency towards a "natural beauty" that, detached from social and ecological thinking, would reduce everything to an ephemeral hedonism.

Similarly in the definition an aspect is minimized: the choice of "primitive" geometries (more or less smooth lines, curved surfaces, elements of which the spatial shell can be made) that determine the final appearance of a parametric project, that, instead, can take on both the characteristics of Malevich's Architektons and those of a cellular tissue during mitosis. Almost as if it were possible or desirable to bypass the designer's will, which instead remains central also for parametric design—since, paraphrasing Gianluca Bocchi, technology without man is stupid–, so as to emphasize this way the exquisitely technical nature of the latter.

As for the difference between architecture and art, Schumacher seems to suggest that the designer cannot act of his/her own free will because he/she should "inform" the computational tools of the right parameters as regards the activities and the project constraints. So, while the German architect describes the question of productivity, in the manifesto there is no trace of the term "openness", the concept of "urban carpet" and in general the concept of a private–public, outside-inside, anthropocentric—non-anthropocentric interpenetration. There is a neutralization of all cultural and political contents of the project—the critical elements regarding the organization of the contemporary architectural order—and of the rules concerning the external characteristics of the fluid and "internally correlated" language, where all the generative systems are an organic multiplicity, systems of correlated systems, the only objective of which is to ensure the readability of the three-dimensional spatial continuity to make it easily navigable by its consumers.

The character, at least ambiguous, of this formulation is already clear: there is no intention of defining a "parametric" architecture in a literal sense (because through parametric software it is, of course, possible to create any style and then any project including the traditional Mediterranean house with gabled roof), on the contrary it refers to a bio-mimetic language that would be able to organize the growing complexity of contemporary social systems that are increasingly interconnected, dense and dynamic, and, we add, more and more competitive, egocentric and anti-ecological. For these reasons, this deals with the proclamation of a "biomorphic" architecture that, in full contradiction, expresses the post-Fordist capitalist economy, the engine of today's oedipal "liquid" and biodiversity-destroying society.

## 3 A Total Biomimicry: Renunciation of Complexity

Starting from the "post-factum" rules related to the work carried out in the past (such as "use elastic and non-rigid shapes" or "avoid repetition and standardization"), a checklist of "biological" geometries emerges from nearly thirty years of Hadid's design when the naturalization of the architectural language was instrumental as to a project that aimed at revitalizing and reconnecting parts of the city and therefore was freely inspired by the self-organized structures of living forms (to design them Parametricism was not needed, as shown by Michelangelo's projects of the Florentine fortifications in '500 and Paolo Soleri's designs, or Musmeci's work and Moretti's "parametric" stadium in the 60s). Yet these geometries, deprived of any relational desire, bring back the matter to a mere grammar, which can be used to say everything and its opposite. What therefore remains is the use of complex forms through a technological medium that would seem to guarantee the automatic success of the project, or, at least, the positioning of the project within the "parametric paradigm", as Schumacher himself defines it. The contradiction that results is very similar to that which gave rise to the reproduction of international architecture on a world scale starting from the famous five points for architecture by Le Corbusier: this simplification extends the contradiction to the very meaning of architecture, which this way has nothing to do with the themes of weaving city and landscape, regenerating biodiversity or generating bio-centric communities, and refers instead to a sequence of curves, "blobs" and other bio-digital images, as happens in the Chinese project Galaxy Soho dominating and crushing the humble context using some monumental convexities. These figures result in a machination which, by simulating the lines of the living world, in most computers of young designers inspired by this research, becomes a fetish, the illusion of a new computer-generated corporeity running away from the complexity and ecological, urgent needs of the real world.

So, the computational research chases, inside the computer, an intricate feminine sensual curvilinearity which seems to be an attempt at re-appropriating a missing corporeity/promiscuity, i.e., a missing contact with nature. They can catch a sterilized literalness of the biological dimension, enclosed in a virtual dimension: this refers to the process described by Bauman about the use of social networks, where new generations are trying, often unsuccessfully, to find contact with one another and with the body—as evidenced by the success of the online porn—which appears elusive in a real-world that is increasingly atomised, alienated from the body dimension. So, the results of this research represent a spatiality that, instead of regenerating a lost connection with the body-biological sphere, multiplies the distance between environment and building, megalopolis, and biosphere. It seems a new extremism that to the “all culture” (as a drift of “humanization” the philosopher Roberto Esposito writes about) of historicism opposes an “all nature”. As a matter of fact, it deals with the view of nature as a tool, a technique, once again an “object” in the human being’s hands replicating its shape in the laboratory, through the most “advanced technology” (in line with the function of technology of a part of the anarcho-capitalist transhumanism), so as to put it at the service of his own individualistic utility. This brings to a construction that is also losing the uncertainty, unpredictability, and chaos that, in nature, contribute to determining the epigenetic landscape from which life emerges with its organized but never “perfect” structures, that are always unique, asymmetrical, rough, hybrid. In this reality as a network of unpredictable possibilities, algorithmic architecture replaces a hyper-deterministic scenario, locked in the mathematical values chosen by the designer, without capturing exceptions, without expressing any freedom and often producing an imitation of the autopoietic structures of the living world, pretending to be a sort of “second nature” [7].

The morphogenetic dream pursues rooms like cells, spaces like organelles able to correlate, open up to be penetrated by light and air through the right exposure; corridors as arteries and capillaries, structures like self-optimized skeletons, integrated to space divisions so as not to “drill” spaces/organs; a mediation space, like a nervous system, keeps everything together, interconnected, without a way out, without providing a coexistence of different solutions as happens in the ecosystem. So, from parametric masterplans (as, for example, the Kartal Pendik Masterplan by Zaha Hadid Architects) a new totalitarianism seems to emerge. It generates a reproduction of closed “perfect” systems, where no indeterminacy differentiates each body (think for example, on the contrary, of the imperfect symmetry of the human body), and where new buildings are indifferent to the languages, morphologies, typologies, chiaroscuro and even to the scale of the spaces in which they are settled.

On the contrary, each wild landscape is surprising because it is full of different characteristics and different unpredictable logic, as well as each living form is always at least in part different from the others. Even a bacterium is only a phenotypic “attempt” because the organic molecules that make it up are not generated by simple digital algorithms but by a complexity of factors and contributory causes—also random and therefore undeterminable—that it is not possible to predict any outcome. There are no unique solutions since life presents itself in a “rhizomatic” multiplicity of unpredictable phenomena in the same context: a form of life can proliferate in different habitats as well as the same habitat also belongs to an immense variety of different life forms as for structure, “seniority” and complexity. It is like an equation in which, even maintaining fixed parameters, there is not one only correct result—that is, “able to live”—but an immense wealth of compossibilities [8] all having an equal organic dignity, all having equal rights to exist in a perspective in which biodiversity is not only a variable but a real value, as well as ethology itself becomes a system of values in which every living being is autonomous yet linked to the fate of all the others.

Finally, even if we could plan a system containing the variable of indeterminacy as a random fracture of some logic, that is, even once an “artificial ecosystem” consisting of a perfectly optimized organic form, it is not certain at all that the human being would feel at ease and choose to live there. The same could happen even in the presence of an exceptional natural environment, with beautiful landscapes, and even intimate and comfortable natural sites like a sea cave or a clearing surrounded by trees. A temporary enjoyment does not imply the will or ability to live in a place without making any change, i.e. without "humanizing" the environment by a "cultural" trace. Because the human species (and many scientists start thinking the same even for other species, respecting due differences) possesses an "external genetic code", handed down through language but even through the environment—architecture—which forms the main framework: an "exoskeletal" culture that can be certainly developed and transformed but cannot be ignored or bypassed. Even this—the set of external factors constituting the cultural code—is part of nature and in recent years, on the other hand, various scientific theories have shown that culture and in general experience, as an event external to the body occurring after birth, for example, a trauma, changes the genetic code itself handing down the change to offspring. This is left entirely out of the parametric/biomimetic system, which instead of triggering a transformation of the existing architectural language, provides for a replacement, ignoring that tabula rasa occurs in nature only on the occasion of tremendous disasters destroying entire ecosystems, bodies and their "cultural trail". Even in this case—think of the impact of the meteorite that, as it is assumed, almost completely destroyed the ecosystem about 66 million years ago—most of the next species probably would preserve a structure very similar to that previous, as if the earth scenario contained in itself rules and information that can shape the living structure. Recent research has highlighted, through studies on different types of samples, that the bony tissue of mammals is nearly the same in the different species as if there had been a topological deformation of one only starting form that modified only the extensive properties while maintaining the geometric relationships between the different parts. That's why the linear transposition of morphogenetic research in architecture is not only literal to a fault—it frequently shifts the focus from the relational issue generating introversion—but falls into the temptation starting "from scratch", excluding the existence of the starting point that is represented of course by the millennial architectural types, rooted, and developed in their epigenetic landscape. In this, it differs from the previous and current research of many other designers that hybridize and regenerate the existing such as, for example, in the BIG's Courtscraper, a typo-topological contamination between a skyscraper and a court. The types, that is to say, would be nothing more than a mnemonic registry, the code (DNA) of architectural species that the Earth's epigenetic landscape—bio-anthropogenic—has shaped with time, in a transformational continuity that was first triggered by the biological matrix (which originally turned primates' physical structure into that of the human) and later continued through the historical process, passing from the mutations generated by "primary" needs to those connected to the more and more complex, up to the "cultural" needs, that weave together biological, social and political necessities. This is the concept behind the chreod Sanford Kwinter refers to [9].

But to translate this concept is essential to broaden the speech to the multiplicity of factors in architecture that make up the landscape conforming to the anthropic space, without locking it up in the everlasting values—and then in the codes and conventions developed over the centuries for psycho-social cultural needs of an earlier era—but even without reducing it to a purely biological process of the elementary forms of life, through a return to prehistoric origins that sets architecture in a "uterine" figuration, designed for a man-fetus with no memory. This shows the relationship between spatial type and geographical context, where geography is defined as a geo-political interlacement that contains both the factors related to the environment and landscape (and hence the natural peculiarities in terms of insolation, ventilation, humidity, etc.) and those related to the economy, politics, uses and customs of the historicised place. Once again, the appeal to the biological shape is not enough to produce architecture, since the latter, even and above all in the complex vision, can only be a hybrid architecture, linked to the present cultural living system of mankind, as a remedy for the self-destructive motion of marginalization from the biosphere [6]. Because space influences and simultaneously stimulates the sensory-tactile sphere of the body and memory.

The "systemic" changes of Thompson's deformations—that in the case of post-deconstructivist architecture are easily reproduced through nonlinear deformers (see modelling programs like Maya)—refer once again to a type of mutation that maintains its continuity, readability and recognition of the original figure, i.e. its geometric relations and maximum proportions, without interrupting the membership to its own epigenetic landscape, as happens in the vast majority of animals and humans, where the characteristic features of the face (two eyes, two cheeks, two ears, forehead, nose, mouth and their disposal) are always the same, making an inter-species empathy possible. This would suggest, instead of trying to start from scratch, a hybridization with the biological language that can graft onto the existing architectural code the characteristics of interactivity, openness, continuity, multiplicity, interconnection, flexibility, and adaptability which are now socially, economically, and ecologically necessary in a symbiotic vision. And this is the reason why we need to aim for something that is simultaneously sensual, that is psycho-somatic, cultural, and socio-political. On the contrary, the bio-mimetic way tries to appeal to a pure imitation of natural shapes and in most cases does not take into account the minimum energy-environmental issues (the renewable sources such as solar, wind, etc.), the bioclimatic essential mechanics (passive exploitation of natural resources to reduce consumptions), the necessary grafts of fauna and flora (to regenerate biodiversity) and does not look after the choice of eco-friendly materials and technologies (which would require the renunciation of double curvature) in favour of research fixed on the language.

From this perspective, the research on 3D printed structures in harmony with the physical characteristics of the materials carried out by Neri Oxman represents the apex of the discourse. Cellulose, chitosan, pectin, and calcium carbonate are among the most abundant materials found in nature and are biodegradable: their choice automatically solves all problems relating to pollution and $CO_2$ production. Yet, we must ask ourselves what it means "to design a culture attuned to the systems of nature", as Paola Antonelli writes about Oxman's research [10], when human "culture" is just a part of "nature", as all the other species' cultural forms.

Oxman is developing a way to “write” the genetic code of the building or the furniture, whether it is made up of the “recipe” of the biopolymer blend, the geometry of the envelope, the path that the robotic arm will follow to create the component: thus an organism is created capable of functioning in all respects as the exoskeleton of an arthropod, and therefore the final structure assumed by the project belongs to the same anatomical/physiological/aesthetic domain as the “biological” one. In this way it is certainly possible to satisfy the needs related to structural resistance—as bones and vegetable fibres do—or to thermo-hygrometric well-being—insulating membranes, more or less transpiring and transparent, which interact with solar radiation or with the need to look outside—but what remains of human expression that is intrinsically linked to the languages thus far produced and developed by civilization? In other words, also—and above all—in Oxman’s material biomimicry there is no longer any trace of what is normally understood as architectural culture: if nature, understood as a non-anthropic domain, as a self-organized place, becomes the “primary customer”, paraphrasing her writings, the planning operation necessarily transforms itself into the most radical linguistic and formal tabula rasa. The same attempted by modernists to historical architecture but even more absolutist, since, even in the cruciform skyscrapers of Ville Radieuse, there was an echo of classical tectonics, the formal system that has characterized architecture since the dawn of times. It is a very critical point. Because the human being is a 100% natural and 100% cultural animal [6]: he is born and grows orienting himself through the spatial structures he experiences, and it is in the relationship with those systems that his memory develops, its identity, its ability to feel at home in a given habitat. It could be said, then, that biomimicry replaces the anthropocentric system, where “nature” is simply the “outside” of the anthropic territory, the “other” space to occupy, consume and from which to differentiate in all respects, with an opposite—therefore formal—value system, where man is effectively cancelled from the equation. A cultural operation that evokes the dramatic results described in Kafka’s Metamorphosis; as if, overnight, we were forced to communicate through a different body and a different language.

On the other hand, as we have seen with the so-called parametric architecture, the insertion of a biomimetic structure—both a piece of furniture among other furnishings in the home environment and a building among other buildings in a city—does not show any will of coexistence but re-proposes the simple juxtaposition. It is always the same separation logic—the Cartesian one between subject and object, mind and body, culture, and nature—which is the very basis of the anthropocentric culture responsible for the ecological catastrophe we are starting to experience. Just look at the images of the Aguahoja pavilion inserted in the museum environment to find this extraneousness.

Yet Oxman’s invention is equally valuable because it is capable of showing a new path. Imagining an architecture where structure, spatial partitions, and casings are made with the same material as the shrimp shells is essential to shift the axis of design from anthropocentric ontology—the man who uses and consumes terrestrial materials without worrying about the ecological effects—to a different ontology.

## 4 Conclusions: Towards a Posthuman Architecture

At a time of profound change, characterized by economic, political, social, and environmental crises—inextricably linked to one another—shaking contemporary societies, it is certainly necessary to critically rethink the role of architecture and architectural research in terms of today's transformations. It seems evident that it is unthinkable to continue reproducing and representing the same traditional spatial model of settlement as if nothing had happened and nothing was happening, proposing again the Western split between culture and nature, mind, and body.

Therefore, in the perspective of a transformation, the problem cannot be to "eliminate" computational technologies from the project.

On the contrary, an architecture capable of supporting and promoting the creation of a community of men and ecosystems—a post-anthropocentric [11] community—as well as any form of art aiming at understanding, inspiring, and transforming today's world, can and must take advantage of the expansion of possibilities provided by 4.0 Industry computational technologies. In other words, the possibility to hybridize, and transform a space that so far has spoken about man, strength, and autonomy of civilization, into a crossbred *post-human* space able to cancel the sense of alienation towards the rest of the planet, to tell of weaving, interdependence and symbiosis. A road open to life but without amnesia, capable of recomposing the ancient contraposition between organic and rational, implementing the code rather than rewriting it from scratch.

An architecture that is capable of evoking the figures of history, talking about our deep need to differentiate and emancipate from the violent necessity of natural life, and simultaneously drawing from the negentropy of our bodies and the other natural structures, telling about our awareness and comprehension of our membership and interdependency with Earth, inserting a revolutionary element: mestizo tectonics, where the trilithon and orthogonal volumes would come to life, taking on mechanical strength, transforming themselves into light Voronoi conformations, paving the way for the use of zero impact materials and making it possible to hold the *two worlds* together [12–17].

This would be a biocentric ontology, in which man neither prevaricates nor cancels himself but establishes a fertile exchange with natural otherness; an architecture that is not just a temple or an exoskeleton but a hybrid space, a contaminated language, a meeting place.

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# Open-Source for a Sustainable Development of Architectural Design in the Fourth Industrial Revolution

**Giuseppe Gallo and Giovanni Francesco Tuzzolino**

**Abstract** Ten years after the first conceptualisation of Industry 4.0, we took part in the largest ITC experiment ever conducted. When during the quarantine, governments chose digital as the exclusive means for education and work, revealing its inclusion limits. Issues that also affect architecture, and in the perspective of the sustainable development of our role, force us to think about inclusivity, starting with the tools we use. When considering the fragmented panorama of software, it is possible to make a distinction according to a gradient going from proprietary to open-source. The latter guarantees the greatest inclusivity and is a requirement for architectural design to continue to develop within the horizon of research. As described in our article, open-source is already alive and present in contemporary architecture, and its contributions can promote quantitative and qualitative turning points. There is a clear tendency to distrust open-source tools: a condition that, in the perspectives stimulated by the industry 4.0 enabling technologies, risks placing architects in an eccentric position on the project. Based on these observations, our article reconstructs the diffusion of open-source tools and formats, outlining the contributions and possibilities ensured by an effective knowledge exchange: a condition necessary to keep the architecture as research, shared and comparable. Interviews with architects with extensive experience in digital tools enrich the article in a path that highlights problems caused by proprietary software, and the solutions promoted by designers who are already aware of the need for open-source tools in the AEC industry.

**Keywords** Open-source · CAD · Digital architecture · Digital tools · BIM · Inclusion

**United Nations' Sustainable Development Goals** 8. Decent work and economic growth · 10. Reduced inequalities · 9. Industry, Innovation and Infrastructure

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_8

The global quarantine of 2020 and the response of governments and institutions that have chosen the digital as an exclusive tool to convey relationships, education, and work have highlighted the limits of inclusivity that the digital paradigm brings with it [1]. A condition that concerns architecture, both as a response to human needs and as a design practice that increasingly evolves using digital tools. While digital tools allow the project to reach a capacity for technical analysis and prediction that is unprecedented in the history of analogue architectural design. It is important to remember that an instrument is never neutral to the purposes for which we use it [2], and it always leaves its mark on what we produce with it, constraining the process. With the development of Industry 4.0, this seemingly invisible trait will take on an increasingly important weight in the design and production of architecture.

In the early 2000s, when CAD tools had not yet reached their current diffusion, we imagined a future in which architects would become aware authors of increasingly advanced tools [3]. To date, this has only happened in part in the few studios that can customise or create their own tools thanks to computer skills that most architects do not have. Everyone else has become de facto consumers, often unaware, of products developed by companies specialised in software for architectural design [4]. These companies feed a market animated by a commercial narrative that is geared towards economic purposes transversal to architecture.

Today, the paradigm of Industry 4.0 promises to overcome the separation between design and production that characterised architecture in the modern era, expanding the scope of digital methods and processes through automation. This extends the architect's responsibilities, in his capacity as a human-centred designer, as a producer or simply as a consumer of tools, and requires him to make an inclusive effort at every level, starting with the software used to design architecture.

A condition that is only possible through the development and adoption of open-source tools, which are the only ones capable of keeping the evolution of the architectural project within the research horizon, removing the risk of transformation into a blind application of methods, further marginalising the role of the architect in society.

In this paper we reconstruct the relationship between architectural design and open-source software, describing the often invisible but crucial contributions that open-source formats, programmes, libraries and cultural approaches bring to architecture, guaranteeing the degrees of freedom necessary for the coherent development of our profession. This is also possible thanks to the interviews [5] with architects of great experience in digital architecture: Steven Chilton, Director of SCA, Daniel Davis, former Director of Research of WeWork, Aurélie de Boissieu, London Head of BIM Grimshaw Architects, Xavier de Kestelier, director of Hassell, Al Fisher, Head of computational development of Buro Happold engineering, Harry Ibbs, Europe design technology director of Gensler, Arthur Mamou-Mani, director of Mamou-Mani studio, Edoardo Tibuzzi, director of AKTII and Pablo Zamorano, head of computational design of Heatherwick studio.

## 1 From Free Software to Open-Source

We encounter the term open-source more and more often in the specialised press and the general media. Opinion makers, journalists, politicians and experts declare the importance of developing an open-source policy based on the free exchange of knowledge: a very current paradigm that is finding a growing number of supporters in academia and also in architecture [6].

A seemingly recent phenomenon, which truly dates back to the beginnings of information technology, when researchers conceived the first computer programs as scientific products, like mathematical or physical research, with scientific experiments, hypotheses, methods and results. Similarly, authors distributed software sharing its source code, so that others could carry out evaluations and develop further applications of the methods described.

This initial phase come to an upheaval when software attracted market interest, with the establishment of commercial groups aimed at the development and distribution of packages for specific purposes. It is the birth of commercial software and licences, defined according to jurisprudence that has evolved over decades to protect products that fall under trade secrets and distributed as executable files for a fee. Thus, also thanks to extensive and systematic marketing activities, commercial software has reached an ever-increasing number of users, attracting investment and developing innovative functions and features at a pace that free software cannot support. This contributes negatively to the reputation of free software, which is perceived as unreliable and of poor quality.

We owe the term open-source to an informal group of developers belonging to the free software movement. They were aware of the ambiguity of the term free software, and proposed a repositioning aimed at improving the perception of open-source collaborative products and methods [7]. It is possible to classify free software according to the possibilities its licence allows: starting with public domain software, not protected by any copyright: anyone can create a new version of the program to which to declare rights.

Something not possible with open-source licenses, which however allow the software distribution in its textual code, including organisation, functions and parameters. These license, therefore, permit anyone to modify the original program and distribute a newly edited version according to rules defined upstream.

The first solution that goes in this direction is proposed by Richard Stallman, founder of the GNU project, who introduced the Copyleft practice in 1985. Copyleft provides additional protection for the distribution terms set by the author of a package while allowing for modifications and preserving the same rights in any derivative product [8].

In 1989 Stallman himself, together with the Free Software Foundation, drafted the first GPL, the General-Purpose License. A license that aims at the legal protection of free software and allows the free distribution of the original programs and the subsequent versions created by their modification. The license, expanded and articulated over the years, is now widely used to guarantee open-source software. It is based on what Stallman [9] and the Free Software Foundation define as the four basic freedoms of software users:

1. The freedom to run the program, for any purpose;
2. The freedom to study how the program works, and change it so it does the computing as the user wishes;
3. The freedom to redistribute copies so users can help others;
4. The freedom to distribute copies of modified versions to others.

These freedoms are not limited to use and distribution, but also provide for the possibility of modifying the program in all its parts. As set out in freedoms number one and three, which make the source code sharing mandatory.

## 2 Project Culture from the Reims Cathedral to the Linux Bazaar

Computer science and architecture have a much closer connection than we usually think. Nowadays, architects look to IT companies as models to replicate their successes. In the second half of the twentieth century, when software engineers were looking for models that could solve the software crisis, they looked to architectural design culture and tradition. Among them was Fred Brooks, pioneer of software engineering and author of the famous book *The Mythical Man-Month* [10], where he describes software development as an exercise of complex interrelationships. For Brooks, there are several similarities between architecture and software development. The latter is divisible into two distinct phases: essence, the mental conceptualisation of the software, and accident, the software implementation or construction phase of the program.

The essence represents defining the conceptual structure of the system and is the most important part of the IT development process, which the author relates to architecture.

As an example, Brooks compares ideal software development to the construction site of Reims Cathedral (Fig. 1). Most European cathedrals result from combinations of elements from different periods, built according to different styles and influenced by external changes. In this large series, Reims Cathedral is a rarity, built at different times by several generations that followed the original project and produced a fortunate architectural coherence [11]. Similarly, the approach to software development must strive for uniformity, avoid inconsistencies due to the work of different actors, and not add features that, even if valid, would make the system uncoordinated and inefficient.

An important cultural turning point in Brooks' model is related to the best-known and most recognised open-source software: Linux. Conceived in 1991 by Linus Torvalds, then a university student, it is a powerful alternative to proprietary operating systems such as Microsoft Windows and macOS.

**Fig. 1** Notre dame de Reims, photo Reno Laithienne

Today, Linux is the basis of many applications created by multinational IT companies, research institutions and data centres. We use it every day when surfing the web and on every Android OS: created by Google on a Linux kernel. The success of Linux is undisputed from both a technical and commercial point of view, so much so that multinational companies such as Microsoft, Amazon, Facebook and Google invest millions of dollars every year in its development [12]. The cultural evolution that this operating system has brought with it lies above all in the openness and sharing that the project has maintained from the very beginning and which it still keeps thirty years after its birth.

Inside his *The Cathedral and the Bazaar* [13], Eric Raymond, already part of the informal group to which we owe the term open-source, retrieves the image of Reims Cathedral, suggesting for Linux that of a large and confusing bazaar. An environment teeming with projects and approaches that even contradict each other, from which only a miracle would have allowed the development of a stable and coherent operating system.

On the contrary, Raymond admits that the bazaar method worked very well for Linux, strengthening the process, rather than throwing it into chaos, proceeding at a speed that was difficult for those who wanted to build cathedrals. The merit of Torvalds, says Raymond, is that he has made the most of a virtual community without geographical boundaries, extending a solitary activity like programming thanks to the intelligence and power of a community. By anticipating Web 2.0, Linux represents an important turning point for open-source software, since then expanded in every field. Today, this different cultural approach contributes to the success of epoch-making initiatives such as Wikipedia, which is based on the open-source platform

MediaWiki. But also OpenOffice, a free alternative to the Microsoft Office package, collectively developed by a worldwide community that today includes thousands of authors [14].

## 3 Open Source and Architectural Design Software

The success of Linux, Wikimedia and other initiatives have confirmed the strength and scalability of open-source projects, which today have touched every industry, paving the way for new approaches that are now applied in all fields of knowledge.

Open-source diffusion is rather limited in the AEC industry, where the main digital tools adopted by architects are often proprietary software, created by a few large companies specialised in the design and development of packages specifically tailored to our sector. This is true for BIM programs and digital modelling software used since the early stages of projects: programs covered by trade secrets and protected by proprietary licenses. Less when we turn our gaze to advanced computational tools, often integrated into commercial applications and that are increasingly the result of open-source initiatives shared by groups of heterogeneous users.

### *3.1 Three-Dimensional Modelling Software*

The predominant role played by a few software houses or even single programs is not limited to our industry, but has gained considerable weight in architecture. If between the late 1900s and the early 2000s many architects considered Autodesk AutoCAD the ideal software to develop their projects, today, with the spread of the BIM paradigm, architects, engineers and builders are increasingly opting for Autodesk Revit. A program that, despite all the alternatives, is on the verge of becoming the standard in the global architecture industry [4]. This circumstance brings with it the danger that architects will find themselves in an eccentric position to the project. While it is almost inconceivable today to approach architectural design without the aid of digital tools, the commitment of BIM, set by various governments around the world, translates into a constraint on the use of Autodesk Revit.

As evidence, consider an event that shaped the history of architectural software in 2020: the open letter to Autodesk about the rise in Revit costs. Signatories include international firms such as Zaha Hadid Architects, Grimshaw Architects, Rogers, Stirk, Harbour + Partners, Mecaano Architecten, Diller Scofidio + Renfro, MVRDV and other firms that alone make up an important part of the Autodesk Revit market. In the 5-page letter [15], the studies lament an increase in licencing costs of over 70% in five years, stagnation in software development and Autodesk's inability to understand the dynamics of the AEC industry.

Regardless of the content and the subsequent response from Autodesk, which has activated initiatives to share objectives and gather feedback, the letter alone is a clear signal of how commercial software is affecting our profession, and it shows the powerlessness of architects in addressing the software problem. This happens despite several three-dimensional modelling software currently available on the market under an open-source license. The longest-running of these is BRL-CAD, one precursor in the CAD family. Initially developed within the US Army, it is available for free in both executable and source code form since the early 2000s, allows three-dimensional modelling, and also integrates rendering tools [16].

Another feature-rich tool is FreeCAD, which was released in 2002 in an open-source format for mechanical engineering. It integrates not only two-dimensional and three-dimensional modelling functions but also advanced finite element analysis (FEA) methods that are rarely available in commercial CAD programmes. Most importantly, it falls into the category of BIM software, as it allows for a proper parametric description of architectural models and also supports the IFC format [17].

Among the champions of open-source digital modelling, we should therefore mention Blender, a programme born in 1994 and developed for digital animation, like the most famous Autodesk Maya. Unlike the package used by protagonists of the first digital turn, such as Greg Lynn and Zaha Hadid Architects, Blender is not proprietary software and it is available for free. In the nearly thirty years since it was first released, it has grown to include advanced features peculiar to other commercial programmes. These include NURBS, subdivision surface methods, physics simulation techniques, rendering packages, virtual reality engines, and an indefinite number of utilities that the user community has developed and distributed for free [18].

### *3.2 File Formats*

The transmission of information has always been central to architecture as we know it. Traditionally, architects have represented their projects through technical drawings and documents on paper to share them with clients, engineers and builders. With the proliferation of CAD, designers have translated the same information into digital dimensions and although there were no reference formats at first, the widespread use of Autodesk AutoCAD has made DWG files a de facto standard in AEC. Autodesk introduced DWG, an abbreviation for the English Drawing, as a binary file for storing two-dimensional drawings with the first version of Autodesk AutoCAD. It is a proprietary, licenced file format owned by Autodesk for the management and operation of the various applications developed by the company. With the presentation of DWG, Autodesk also released DXF, Drawing Exchange Format, developed as a solution for data exchange between Autodesk AutoCAD and other programmes.

While Autodesk has never released technical specifications useful for developers of other companies to integrate DWG functionality into other programs, with DXF, the company publishes substantial documentation [19]. However, the success of this extension is limited, probably because of the lower possibilities of representing objects and solids that have enriched the different versions of DWG files. So much so that all CAD programs developed over the years support DWG as the main file exchange format. This is possible, not because Autodesk decided at some point to make the format characteristics public, but because a non-profit consortium, the Open Design Alliance [20], engaged in the reverse engineering of the format, creating open-source libraries available to anyone who wants to interpret and create DWG files within programs not developed by Autodesk. The enormous diffusion of Autodesk AutoCAD and the forced opening of the DWG format by ODA will contribute to the diffusion of the format, which is now available on any digital modelling tool.

Among the companies that develop programs for architectural design, one of those that have shown greater attention to open-source practices so far is certainly McNeel and Associates, which distributes Rhinoceros 3D with a proprietary license but has kept the 3DM format open, sharing the source code through the Open Nurbs project [21]. An initiative aimed at developers of CAD programs, who can rely on the company's format for the creation and management of many geometries including NURBS, B-rep, meshes, point clouds and SubD objects, store data and manage them through programming languages such as Python, JavaScript and C #. The Open Nurbs initiative became decisive in the success of the 3DM format, allowing programmers and designers the development and distribution of applications and utilities often published with open-source licences.

To testify to the growing attention towards open-source, and the need for a neutral format for sharing information and interoperability between programs, we mention the establishment of the IFC format, Industry Foundation Classes, proposed as a standard for the BIM software [22]. The author of this format, registered as an ISO standard since 2013, is Building Smart, an organisation founded in 1994 and which today brings together some of the major AEC software companies, together with a large group of multinational technology and construction companies.

### *3.3 Software Libraries*

A sometimes underappreciated contribution to software is that of libraries: sets of functions or data structures that allow programmers to reuse code written by others and thus extend the functionality to their projects. As an example, consider some of the most complex software ever developed, such as social networks: systems that combine hundreds of different functionalities, perceived by the public as monolithic entities, but which could not function without libraries created by third parties. Instagram, one of the main promotional vehicles for contemporary architecture firms, uses almost 30 open-source software libraries, without which it would not be possible to view images and videos on our mobile devices or even simply register on the platform [23].

Even 3D modelling packages integrate third-party libraries, such as mathematical models, that allow them to solve geometric problems, from describing basic elements such as points and lines to more complex ones, such as curved surfaces. Among these, a very special place in the history of contemporary architecture is that occupied by the splines, without which the protagonists of the first digital turn would not have been able to conceive the continuous organic forms that characterise their works.

The recent history of splines, and T-splines in particular, highlights the problems and toughness of using proprietary software within the design process. This technology, developed in 2004 by a US start-up company, has proven successful in several firms interested in designing organic shapes. For about 6 years, the company distributed the library as a plug-in for the Rhinoceros 3D and SolidWorks packages. This happens until 2011, when Autodesk acquires T-Spline Inc., first eliminating the plug-in for SolidWorks and then discontinuing the upgrade and sale of the t-spline plug-in for Rhinoceros 3D, preventing the activation of new licenses to keep the t-splines only on Autodesk Fusion 360 [24].

The inability to activate new licences for Rhinoceros 3D has caused many problems within architectural firms, that until that moment have used the t-splines on Rhinoceros 3D to rationalise the shapes designed in the concept phase with subdivision surface methods on other packages such as Autodesk Maya and Blender. This has negatively impacted workflow in design studios, which, with the new versions of Rhinoceros 3D from 6 onwards, have sought alternative tools. We directly observed these setback when we took part in some meetings of the BIM group of the Zaha Hadid Architects studio in 2019. At one of these meetings, the team of architects tried to address the problem, as the t-spline tool was part of their internal workflow and the limited number of licenses owned by the studio, together with the inability to activate new licences, led to many slowdowns within the practice. They could find a temporary solution thanks to the availability of McNeel and Associates, who provided them with an ad hoc version of Rhinoceros 3D 5 with some features of the newer version.

Problems like this would not occur if the t-splines libraries were under an open-source licence that allowed users to view and modify the source code, take part in their development and make it common knowledge. A decision made by Pixar, a company that has shaped the history of digital modelling, with the first release of Opensubdiv in 2012 [25]. This open-source library for subdivision surfaces was developed together with Microsoft and other volunteers, who collaborated on a method to use the efficiency of parallel computing to produce organic surfaces starting from meshes.

Some ten years after its initial release, the library is available for architects and designers to use in some of the leading 3D modelling programs such as Autodesk Maya, Autodesk 3ds Max and Blender.

### *3.4 Visual Programming Languages and Open-Source Culture*

The category of software where a cultural evolution in the relationship between open-source culture and architecture is most evident is undoubtedly that of visual programming languages. Environments that allow defining complex algorithms through a graphical node interface and that, even when distributed under a proprietary license, allow communities to extend the software capabilities by including features developed by others.

This openness to other actors has been crucial to the spread of Grasshopper 3D, which, as Pablo Zamorano, Steven Chilton and Xavier de Kestelier testify, has established itself among visual programming languages for architecture and design, thanks to its community gathered on Food4Rhino. The site hosts a group of hundreds of thousands of users who have collectively developed over eight hundred plug-ins and components in about ten years. On the website it is possible to find products of different quality and breadth, from components that perform a single function, to real packages with dozens of different utilities for architecture, engineering, robotics, digital manufacturing and much more [26]. As proof of how much the opening towards open-source is primarily a cultural phenomenon, it is important to note that almost 90% of the plug-ins developed are free to use, and most of them are also open-source software. While the success of Grasshopper 3D is certainly due to its community and the incredible number of open-source tools developed independently by users, McNeel and Associates released it under a proprietary license. This permit the company a relative control over the evolution of the central application needed to develop new components.

A limit exceeded by Dynamo, a direct competitor of Grasshopper 3D in the category of visual programming languages, which was developed by Ian Keough and released under an open-source license in 2015. The package, now also integrated within Autodesk Revit, allows designers to adopt algorithmic strategies according to a syntax similar to that of Grasshopper 3D, and is rapidly enriching itself with new components that users can create and share directly through the program interface. A feature that facilitates the flourishing of new shared computational strategies within the community. Today the number of packages created and shared by users had exceeded 500 units [27], and we also observe how several developers already authors of Grasshopper 3D components have translated them to be used on Dynamo.

## *3.5 Simulation and Optimisation*

The methods of computational simulation and optimisation in terms of topology and environmental sustainability mark the clearest difference between the architectures of the first digital turn and contemporary approaches. As architects today, we are aware of the urgency of adopting these strategies, part of the collective effort in contrast to global heating. What we are probably less aware of is the fact that it is still almost impossible for architects to develop some of these strategies without open-source tools.

One of these, well known by many contemporary architects, is Kangaroo Physics, a plugin for Grasshopper 3D developed by Piker [28]. With over half a million downloads, it is one of the most popular among the VPL plugins, because it allows interactive simulation, optimization and constraint solving. The program, totally open-source, permitted many users to adopt form-finding strategies similar to those experimented with by Frei Otto, favouring the development and dissemination of innovative approaches not easily obtainable through commercial packages [29].

Another popular open-source plug-in available for both Grasshopper 3D and Dynamo is Lunchbox, a collection of computational tools that includes functions for managing data and geometries, but also for the rationalisation of architectural forms, to favour the interoperability, and adopt generative methods. The tool, created and distributed by Proving Ground, has over 600,000 users around the world and architects use it to define facades and divide them into regular panels according to grids with square, rhomboid and triangular modules [30].

Among the open-source tools available to all Grasshopper 3D users interested in developing architectural sustainability strategies, it is worth mentioning Ladybug tools, an application created in 2012 by Roudsari [31]. As an architect and IT developer, he felt the need for a tool to simplify the modelling activities, and speed up the architectural workflow, then slowed down by repetitive operations. The plugin also aimed to solve interoperability problems between different instruments and integrate tools for environmental analysis. 2013 is the year of the first release. It now includes thirty different components for integrating environmental data, solar radiation models and levels of brightness of the building environment. Subjects of great importance to achieve sustainability within the architectural project, and that any designer can today address via this powerful tool, close to becoming a standard within the contemporary architectural workflow. After several releases, the application has evolved, also integrating Honeybee, another package aimed at connecting architectural models with tools for the simulation and energy validation of buildings such as Radiance, Energy Plus and others.

Ladybug is an excellent example of how the opening towards open-source contributes to the improvement and dissemination of new shared design approaches. While before its release, architects could conduct similar strategies only through commercial tools, purchasable at sometimes prohibitive costs. Since its first distribution, over 300.000 users downloaded the package, making it one of the most used tools in sustainable architectural design. Several developers and architects have also taken part in the project, collaborating in the development of new features. As Chris Mackey, who, on the occasion of his thesis in architecture at the Massachusetts Institute of Technology [32], developed a thermal comfort analysis tool now part of the plug-in. Or as it recently happened on the occasion of other tools, developed by volunteers, and which now allow the connection between Ladybug and other advanced software useful for data management and to extend the environmental simulation to entire portions of a city.

The need for a different understanding of the architectural artefact through simulation practices has led designers to get closer and closer to physics and its computational methods. Similar tools are often created within major international universities and released under an open-source license. This is the case of Open FOAM, Open-source Field Operation And Manipulation, a numerical simulation application released by Henry Weller and Hrvoje Jasak in 2004 [33]. The tool, created for the solution of continuum mechanics and fluid dynamics problems, is currently adopted by some large architectural firms to predict wind effects on buildings and optimise comfort in public spaces.

In our process that collects the main open-source tools adopted by contemporary architectural designers, we have followed a path that starts from generalist CAD tools, up to programs created for resolving specific problems and the deepening of the architectural artefact in environmental terms and optimization. A vast and heterogeneous ecosystem populated as much by free programs developed by small groups as by large corporations specialised in creating programs for architecture: companies that at different levels have adopted open-source strategies and related business models.

The relationship between open-source and architecture, however, does not stop with programs created by companies or informal groups. It becomes even more solid when the architectural firms directly address the development of tools based on internal needs. An increasingly frequent eventuality, as confirmed by Aurelie de Boissieu, who in describing the internal practice of her studio, tells how frequently architectural designers, BIM technicians and developers work together in defining new tools sewn around their internal workflow. This software is often born as scripts composed of a few code lines of code, structured to automate processes, link different programs together, or correctly carry out internal praxis. As witnessed by the interviewee, these scripts frequently evolve until they become real packages, available to those who cannot understand computer languages.

This is also possible thanks to Python, an open-source text programming language that has become one of the most widely used languages in architectural firms thanks to its ease of use. Developed in 1991 by Guido van Rossum, the language is now integrated into the main architectural modelling programmes, from Grasshopper 3D to Autodesk Revit, and has thus become a fundamental tool for the establishment of design strategies aimed at environmental sustainability.

## *3.6 Interoperability*

The multiplicity of tools available for architectural design and the impossibility of solving the complexity of the project with a single software has presented architects with an issue that has caused not a few delays in the studios: interoperability. A subject that, despite the commitment of various actors and the creation of IFC, has not led to the definition of a standard capable of integrating the algorithmic components of the architectural project into an interoperable BIM model. This means that to develop algorithmic processes and optimisation of architectural forms, several studios today rely on Rhinoceros 3D and Grasshopper 3D during the early stages of the project and subsequently translate the model according to the BIM paradigms on Autodesk Revit. A transformation that results in the loss of algorithmic information. Despite the new possibilities offered by integrating Dynamo into Autodesk Revit, the node logic and the algorithmic syntax do not find a direct counterpart in any of the currently available standards.

This discontinuity creates many difficulties for designers, as confirmed by Pablo Zamorano, who is familiar with the common problems in contemporary architectural practises and also testifies to how his firm has found an effective solution to the problem thanks to Flux. An application developed as part of the research programmes of Google X Laboratories, a Google offshoot that deals with energy and economic sustainability issues. The goal of Flux was to solve interoperability between software, enabling remote collaboration via cloud systems, and data management between actors taking part in the design process. It created a dialogue between packages, converting models and information according to the intrinsic logic of the different programmes.

Unlike other data sharing systems based on file transfer, Flux users had to install it as a plug-in on each software to be connected, it then acted as an exchange node between programs and enabled the sharing of projects, analyses and other data in real-time. It instantly linked Rhinoceros 3D/Grasshopper 3D and Autodesk Revit/Dynamo pairs with each other and with Excel, Autodesk Autocad, and Sketchup [34]. Since 2010, the year in which the project began, the research group has grown, detached from Google, became a startup, getting 8 million dollars in funding in 2014, and developing a large collection of useful interoperability tools for architectural workflow [35].

Utilities, which as Zamorano recalls, have become part of the tools adopted by designers in many offices, where architects converted their workflow to operate with that system. Despite this, the company interrupted the Flux project in March 2018, bringing back the architectural firms to confront again with problems already solved: a case incredibly similar to the one that has already occurred with t-splines.

Given the clear need for an interoperability solution for architectural design, other initiatives filled the void left by Flux, developing applications and utilities aimed at facilitating the exchange of information. Among the various platforms recently released, one of the most complete is undoubtedly Speckle, a data exchange system started by Dimitrie Stefanescu at the University College of London in 2016. The project took the form of a start up at the beginning of 2020, proposing as its main product a system for sharing information between professionals connected remotely, also allowing the desired connection between the pairs Rhinoceros 3D/Grasshopper 3D, Autodesk Revit/Dynamo and other tools. Speckle is based on a web infrastructure, it enables users to structure highly configurable interoperability systems, supporting the creation of specific data classes created by end-users also integrating structured formats such as IFC. The data transfer system runs on a server installed on each computer, which serves as a node for sharing information and processes, and ensures the correct functioning of the system in case the other nodes in the network are offline by recording any operation on a shared model.

Speckle implements a hierarchical access system, which grants effective control over the processes and actors who collaborate in the project's definition. An integrated utility named SpeckleViz allows the real-time visualisation of the processes shared between different users through the server, collecting each operation and illustrating architectural workflow in real-time [36]. Unlike Flux, which was a proprietary software and requested the subscription of licenses, Speckle is free to use, and it is an open-source initiative. This bodes well for its longevity, less influenced by market fluctuations, and capable of growing based on a community of users and supporters [37].

A turning point in solving interoperability issues between Rhinoceros 3D and Autodesk Revit is certainly the 2019 solution proposed by McNeel and Associates, which displacing the competition introduced under the new features of version 7 of Rhinoceros 3D, the open-source Rhino.inside component [38]. The utility allows the popular modelling package to be used in any other programme, starting with Autodesk Revit, extended to include Rhinoceros 3D's modelling capabilities and Grasshopper 3D collection of plug-ins, ensuring levels of bi-directional interoperability never achieved.

In the interviews, Al Fisher testifies the growing role of open-source within the AEC industry, talking extensively about The Bhom, Buildings and Habitats Object Model, an interoperability platform started by his office in 2018 [39]. With the Bhom, Buro Happold intends to create a shared elastic infrastructure, accessible and modifiable by end-users who can easily integrate new functions and connections thanks to the innovative paradigm represented by the ECS, Entity Component System. This is a different IT structuring paradigm experimented with for the first time in 2007 within the video game industry. While BIM currently follows the model of OOP, a paradigm which allows the users to create entire families of objects from shared properties and functions, ECS adds new degrees of freedom to the system, determining entities based on data that define them, and thus allowing to include new properties and functions as the project needs change [40]. Inside the interview, Al Fisher cites a practical example that helps to understand the usefulness of ECS. If on the occasion of a project at an advanced stage, the lighting specialists want. To change the characteristics of a lighting system, it will be necessary to return to the definition of those objects to vary their properties upstream of the workflow. An activity that the ECS speeds up and simplifies, allowing an easier injection of new properties without incurring problems and viscosities that currently delay the project. The Bhom provide designers new flexibility in terms of interoperability and easier integration of new tools, but also and above all, it represents taking responsibility for a common problem, and trying to solve it in collaboration with other actors in the AEC field through open-source.

## 4 Limits to the Development of Open-Source Software for Architectural Design

Despite the open-source contributions to contemporary architectural design, although several architects exploit the strength of open source tools for the design and analysis of architectural models, it is palpable a lack of awareness and a substantial distrust of open-source software within the industry.

While many of the interviewees, such as Arthur Mamou Mani and Edoardo Tibuzzi, recognise the contribution of open-source tools, and testify to their use, hoping for a greater shared effort in their adoption. It is also true, as Daniel Davies states, that most architects limit themselves to using proprietary software. According to Aurelie de Boissieu, the limited adoption of open-source tools in our industry is because of the relative novelty that digital represents in architecture. A factor that binds architects to the use of commercial tools, but which the industry will overcome in the coming years.

In April 2019 we took part in a talk on the digitalisation of architecture organised in London, a debate between three important experts in architectural design and digital tools: the aforementioned Aurelie de Boissieu, head of the London BIM department of Grimshaw Architects, Mauro Sabiu of Zaha Hadid Architects and Benedict Wallbank of Viewpoint Construction Software, a multinational specialised in the development of applications for the management of the architectural order and the construction of architectural artefacts [41].

On the occasion of the debate, I asked the three what their opinion was on the role of open-source tools in architecture, engineering and construction, and it is interesting to note how the opinion of these experts varies. While de Boissieu sees open-source as the only solution to free designers from the constraints imposed by development companies. Wallbank, which admits how the open-source paradigm can lead to resolving specific problems, also argues that the broader problems, shared in the global landscape of digital tools for architecture, will be more easily solved by large companies rather than by individual developers or informal groups. Referring in particular to data sharing and the digitalisation of the built environment.

This diversity of opinions is not uncommon, while on the one hand, there is a shared opinion that open-source programs have a role to play, and even are fundamental for the sustainable development of the entire sector. Many think that the small number of individuals involved in open-source software will never reach the reliability of a large specialised company. An opinion shared by Harry Ibbs, who sees the limits of open-source initiatives in the modest size of their groups, a characteristic that makes them less solid, unable to provide continued support, and guarantees that architects receive by multinationals against the payment of commercial licenses. The interviewee compares, as an example, the proprietary software Autodesk Maya, with the open-source Blender. Affirming that the latter is a perfect alternative to the first, able to perform all the functions of a commercial competitor, sometimes even better.

Despite this, Ibbs continues, very few architects adopt Blender. To achieve this, there would need to have in the team a specialist who cannot make the best use of the software, but also to customise its structure and functionality to compensate for the support that Autodesk provides for Maya to anyone who has purchased a licence. Without this kind of support, or someone with specialist knowledge in the studio, architects risk getting stuck and experiencing costly delays in the design process.

This is true for Blender and for dozens of other open-source tools that perfectly fulfil the functions of commercial packages but offer no support. With this in mind, the interviewee said, anyone who wants to encourage the use of an open-source tool for architectural design needs to provide users with reliable support. According to Ibbs, this could come directly from the developer community by creating an ecosystem aimed at both feature development and end-user support.

Ibbs sees another difficulty in the market of software for architecture. Whereas until the end of the 1990s there were only a few companies specialising in the production of digital tools, these companies have now become real giants.

So if it is relatively easy even for a small group to propose an application to solve a particular problem, developing a programme like Autodesk Revit, which has released dozens of new features over the years, would require an investment of tens of millions of euros. An investment into which additional funds for marketing activities would have to be added. Similar budgets are hardly available for small informal groups. Even if they produce innovative products, they are often acquired by large companies that can alternatively develop similar functions and integrate them into commercial tools.

## 5 Conclusions

Although not all architects are aware of it, the relationship between open-source software and architectural design is already alive and well and is likely to develop further in the coming years. As several interviewees testify, architects mainly work with proprietary software developed by a limited group of specialised software houses. But, when the architectural project reaches the complexity of environmental sustainability, topological optimisation and simulation, the tools used to develop it are mostly open-source software.

The open-source culture is spreading in architecture thanks to ever-increasing proximity to disciplines such as computer science and physics, areas where open-source initiatives have been alive for years, proving their reliability and capturing important market shares. This cultural evolution is evident in the success of Grasshopper 3D, proprietary software that would not have achieved the popularity it has over the past 15 years without the help of a community of thousands of developers willing to share the source code of their plug-ins. Similarly, and at a different pace, some software houses that base their business on proprietary software are approaching open-source, starting with formats and ending with the release of fully open-source applications.

Meanwhile, individuals and small groups of architects-programmers are busy solving specific problems, developing effective software and orienting their business models towards open-source. These small groups certainly cannot compete with the software giants in developing complete modelling programs. However, there is no shortage of solid packages capable of offering solutions similar to those of proprietary software and delivering results of the same quality, as with Maya or FreeCAD, in which it is possible to invest, either economically or through direct collaboration.

Buro Happold's The Bhom initiative is not only a sign of openness towards open-source directly promoted by a professional firm, but an important precedent for the future of architecture. This is because it represents a willingness to face the problems common in the AEC industry with the declared intention of sharing processes and results.

To avoid problems and delays like with the DWG format, T-splines and Flux, or even worse in the future, AEC professionals and especially architects need to develop a greater awareness of the weight that tools have in our field. This means that we need to perceive our role differently as consumers and, where possible, producers of architectural design software. Alternatively, we can think of sending letters of complaint to the companies that develop the products we use every day.

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# Educating the Reflective Digital Practitioner

**Ioanna Symeonidou**

**Abstract** The chapter discusses the processes of a designer's reflection-in-action when employing simulation-based design tools. It revisits Donald Schön's seminal work on the Reflective Practitioner, considering the current technological mileu where simulations of physical or environmental behavior educate future architects on how to reflect in action during the design process, rather than analyzing and modifying their design a posteriori. Schön argues in favor of the idiosyncratic element in design decision making which is based on practice. Hence, the digital practitioner of our times develops an intuition and knowledge that derives from the exposure to simulations and computational tools. The chapter will expound on processes of experiential learning in architecture and discuss the findings and experiences from architectural studio case studies that employed computational tools for form-finding to provide real-time feedback on the behaviour and geometry of the projects. The curriculum aimed at combining teaching strategies, digital media and design processes towards the objective of educating the reflective digital practitioner of the future.

**Keywords** Algorithmic design · Physics simulation · Donald Schön · Architectural education · Design computation · Form-finding

**United Nations' Sustainable Development Goals** 4. Quality Education · 9. Industry · Innovation and Infrastructure · 12. Responsible Consumption and Production

## 1 Introduction

Architectural education has always followed an experiential learning approach, which in older times took the form of apprenticeship near the master builder, and gradually evolved into a systematic study in design studios, which until today are considered as the signature pedagogy of architectural education, placing a strong

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_9

focus on physical models, tacit knowledge, hands-on experimentation and several cycles of reflection and modification of the student projects. In his seminal work "*The Reflective Practitioner*" Donald Schön argues that practitioners develop "*reflective conversations with the situation*" [1]. Architectural education has a long tradition of craftsmanship and 3D models and a strong connection to the means of industrial production. The BAUHAUS pedagogy was a response to the 1st Industrial Revolution, introducing workshops for industrial production of artifacts ranging from furniture to ceramics, metal working and weaving, all of which aimed to train students with regards to the construction methods of that time. Gropius highlighted the necessity to educate '*a new generation of architects in close contact with modern means of production*' [2], exemplifying the benefits of standardization and mass production. Similarly, the 4th Industrial Revolution is marked by the increasing interconnectivity of tools and processes, the automation of production methods and mass customization. According to BAUHAUS pedagogy, Josef Albers would affirm that students should develop a "*feel*" for materials and processes. Similarly, Schön considered primordial that designers are to develop a "*feel*" for situations as the sine qua non of design practice. He argued that there is a shift from "*problem solving*" to "*problem setting*" which would nowadays become of crucial importance if seen through the prism of Industry 4.0, as the current generation of architects have in their disposal computational tools that accelerate design thinking and can compute a large number of parameters in a simulation-based design process. The question that arises here, is how do we prepare future architects for the challenges and opportunities of Industry 4.0? Furthermore, how can we instigate concepts of reflective practice when we shift from physical models to digital simulations? The chapter aims to address the importance of educating the reflective digital practitioner of the future, to discuss contemporary design education protocols and examine the way students develop a "*feel*" for digital media in concurrence with the ideas of Schön about reflection in action. Although the understanding of computational tools for simulations evidently falls within the spectrum of "*hard*" knowledge of science and scholarship, this chapter wishes to explore the "*soft*" knowledge of artistry and unvarnished opinion with regards to simulation-based design processes, inquiring the epistemology of digital practice, opting for an insight into the professional knowledge of competent digital practitioners and enriching contemporary design teaching protocols with tacit knowledge and experiential learning.

## 2 The Legacy of Donald Schön

Donald Schön, professor of education and planning at MIT, has often been a reference for architecture educators [3–12]. Schön is known for developing the concept of reflective practice and contributing to the theory of organizational learning. In his book "*The Reflective Practitioner - How professionals think in action*", Schön inquires the epistemology of practice. He considers that a competent practitioner should not only be able to solve a problem but emphasizes the designer's ability to construct a problem. Problem setting and framing of the context is of crucial importance for Schön, and this can directly translate to computational design simulations, where the actual parameter setting is more important than the solver itself. Schön researches the epistemology of practice that is inherent to intuitive design processes, the spontaneous response of an experienced practitioner. As he explains "*We are often unaware of having learned to do these things; we simply find ourselves doing them. In some cases, we were once aware of the understandings which were subsequently internalized in our feeling for the stuff of action*".

In his writings he describes the difference between "*knowing-in-action*" and "*reflection-in-action*": Knowing-in-action is "*….the repertoire of routinized responses that skilful practitioners bring to their practice*", gained through training or experience [1]. He expounds that if we operate outside our normal routines, outcomes are not as expected—surprises, uncertainty or non-understanding occur. Therefore, we need to "*reflect*" on our actions, on the spot, so we can still have an impact on the outcome. "*Our spontaneous responses to the phenomena of everyday life do not always work. Sometimes our spontaneous knowing-in-action yields unexpected outcomes and we react to the surprise by a kind of thinking what we are doing while we are doing it*", a process he calls "*reflection-in-action*". The reflection "*… has a critical function, questioning and challenging the assumptional basis of action, and a restructuring function, reshaping strategies, understanding of phenomena, and ways of framing problems*" [1].

Based on this assumption, a designer should be trained not only with regards to the technical requirements and programming skills that are needed to create a simulation tool for architecture, but this knowledge should target the ability to reflect in action within the dynamic context of a simulation. An experienced digital designer will intuitively know which parameters of the simulation need fine tuning, without necessarily being able to explain why. An analytical mindset would turn to science or engineering to understand the influence of parameters on the result of a simulation. However, a design practitioner without engineering or scientific background, after several iterations of experimentation with simulation-based design tools, will be able to intuitively predict the behaviour of the simulation and drive the design outcome. Within a digital simulation environment, a designer can reflect in action, by varying parameters, combining and recombining a set of figures "*within the schema which bounds and gives coherence to the performance*" [1].

During the educational activities presented in this chapter, the students engaged in simulation-based design processes, in a highly experiential approach, where their choices and "*spontaneous responses*" highly depended on the material or software at hand. Both in the digital as well as in the physical environment an elastic material would form different geometric configurations if stretched in a certain way, whereas a steel rod would spring back within certain range of bending and obtain a permanent deformation if the elastic limit is exceeded, therefore changing its behaviour and the experimentally obtained geometries. Similarly, in cases of doubly curved surfaces that comprise of planar parts, a planarization algorithm will behave differently depending on the size of panels and their anchorpoints, giving rise to a range of solutions that are feasible and can be digitally manufactured, capitalizing on the potential of Industry 4.0. The interconnectivity between machinery and design processes, has not yet been fully exploited by contemporary designers, but there is already evidence of a broad range of projects that adopt strategies of performance-oriented processes with the aim to reach informed design solutions. In this realm Schön's reflection process, with the necessary adaptations for the current technological milieu, offers a huge potential for architects to envision new ideas, solutions and theories:

> Depending on the context and the practitioner, such reflection-in-action may take the form of on-the-spot problem-solving, theory-building, or re-appreciation of the situation. When the problem at hand proves resistant to readily accessible solutions, the practitioner may rethink the approach he has been taking and invent new strategies of action. When a practitioner encounters a situation that falls outside his usual range of descriptive categories, he may surface and criticize his initial understanding and proceed to construct a new, situationspecific theory of the phenomenon [1].

## 3 The Challenges of Digital Design Media in Architectural Education

Never before in the history of architectural education was there such a drastic shift in the way we design and make, and furthermore in the way we think. The next generation of architects, which are currently being trained in architecture schools, is a completely different one, there is a big discontinuity taking place. Marc Prensky refers to them as **digital natives**[1] while their educators are undoubtedly the last generation of **digital immigrants**.[2] We are therefore passing through a moment of "*singularity– an event which changes things so fundamentally that there is absolutely no going back*" [13], and this is marked by the arrival and rapid dissemination of digital design tools.

Digital technologies have changed the nature of architecture; this was inevitably reflected on architectural education. "*Educators in engineering schools are experiencing a new pressure to change the way they teach design-related courses in order to equip their students to interact with CAD/CAM/CAE systems and have a knowledge of their fundamental principles*" [14]. This transition is currently occurring in a rather unplanned manner, as new tools are quickly adopted by schools around the globe, as a chain reaction and without proper curriculum planning and organization. Technological advancements took place so fast and architecture schools were the early adopters of computational media, therefore, learning how to integrate new tools in design, almost on the go, without prior strategic planning. The rush to engage with digital media was further accelerated by the market needs and the digital culture in all media of our everyday lives. Within this transition phase several

[1] Digital Natives refer to the students today, as they are all "native speakers" of the digital language of computers, video games and the Internet [13].

[2] Digital Immigrants learn—like all immigrants, some better than others—to adapt to their environment, they always retain, to some degree, their "accent," that is, their foot in the past [13].

educational experiments have taken place, and new design opportunities appeared. Currently, in architecture schools around the world, both students and educators have already gone through several years of experimentation with digital media, some of which have proven to be particularly useful for the advancement of education and architecture in general. With regards to digital design media in particular, the use of simulation tools for design represents only a very small percentage within the possibilities offered by digital media. However, it is an indicative example where research and production tend to agglomerate towards two extreme cases. On one hand there are the engineers that are fluent with setting up simulations, and even programming routines from scratch but with little or no design training at all. On the other hand, there are the competent designers who lack background knowledge in fields of science or applied science who may use readily available simulation tools but are not always capable of understanding the underlying parameters so as to frame the design problem. The current generation of computational designers respond to this knowledge gap, bridging the two extremes, by either working in multidisciplinary groups or by opting for dual degrees and specializations. Edgar Schein in his book "*Professional education: some new directions*" discusses the three components of knowledge, with each component relying and building upon the previous [15]. He distinguishes between science (ex. math, physics) applied science or engineering (ex. computation, engineering) skills and attitudinal component (ex. computational designer) that is based on the previous but eventually is responsible for delivering a project. More specifically for simulation-based design processes, this would require an understanding of the underlying mathematical and physical principles. But is this always possible for design students? Could we possibly bypass the lack of background knowledge by employing apprenticeship models like those proposed by Donald Schön?

Although a lot has been said and written about the education of architects, very little has been said about the preparation of teachers of architecture [16]. It is interesting to observe current trends in architectural education, looking at established theories like constructionism [17, 18] and experiential learning which have been embraced by architectural educators, and speculate how new technologies and digital media can be integrated in the architectural curriculum, exploiting the new possibilities offered by the use of simulation modeling towards novel design processes that boost creativity and innovation.

## 4 Jumping in at the Deep End

Introducing students without scientific background to simulation-based design processes might seem like throwing the students in at the deep end and letting them "*sink or swim*". Several educators would claim such approach to be stressful for the students as it is forcing them to act outside their comfort zone, however Schön would claim that "*the student must begin to design before she knows what she is doing*" [19]. However paradoxical that may sound, it proved to be more time-efficient and resourceful than traditional academic learning, that would request a robust knowledge of the underlying science prior to experimentation. Students are often unaware of the knowledge that is already there and find themselves acting as a reflective digital practitioner, learning and reflecting in action. As Schön would explain, through reflection a student can "*surface and criticize the tacit understandings that have grown up around the repepitive experiences of a specialized practice, and can make new sense of the situations of uncertainty or uniqueness which he may allow himself to practice*" [1].

The three design studio projects presented in this chapter are on one hand systematic, based on traditional learning theories, incorporating contemporary technology, software, employing new methods of knowledge documentation, and on the other hand chaotic with regards to the use of digital media and algorithms in architecture, facilitating the acquisition of tacit knowledge about emergent behaviors, multi-criteria optimizations, structural simulations and agent-based systems. By revisiting the theories of Schön, we are now able to take advantage of the technology to seamlessly transfer design ideas to projects. The three case studies presented in this chapter are drawn from design studio courses taught by the author. In all cases students had no previous experiences with computational design. All three studios employed simulations that were undertaken in Kangaroo Physics engine developed by Piker [20], as it is a relatively simple interface and students can intuitively draw parallels between the material feedback and behavior that would occur in the digital and the physical world. Kangaroo comprises of a collection of algorithms that computationally simulate some aspects of real-world physical behavior of materials and objects, acting as vehicles for design experimentation and innovation. Simulation based design processes and form-finding fall within a well-established design methodology, where dynamic models are influenced by internal or external parameters. In the case of a physics simulation, the architectural form is obtained as a negotiation of forces, environment and constraints. All of the above are eventually design parameters that drive the design towards a state of equilibrium were the design intent and the design criteria are met. Hence, Schön's persistence to shift the weight to problem setting rather than problem solving becomes more topical than ever. The simulation will eventually reach one or more solutions that optimize form and performance for certain parameters. What drives that design however is the way the problem is set and not the solution itself. Design decisions are reflected in the way the problem is set, and the hierarchy of parameters within the simulation. Surprises and unexpected results do occur, due to the emergent character of simulation-based design models. Simulations of physical forces for architectural form generation are increasingly gaining ground in architectural education as there is a broad selection of computational tools readily available that allow quick experiments to be conducted. The integration of simulation tools within the process of architectural design with digital media will be seen in the three case studies that follow.

### *4.1 Tensile Structures and Dynamic Relaxation*

The studio which took place at Graz University of Technology, introduced students to the design of tensile structures through analogue and digital form-finding (Fig. 1). Being the basis of most design-oriented simulations, spring-particle algorithms have become a great design tool for architects; they allow experimentation and computational form-finding of a great variety of forms, ranging from catenaries and gridshells, to membranes and cable nets.

Spring-particle systems are based on lumped masses (particles) which are connected by linear elastic springs. Each spring is assigned a constant axial stiffness, a rest length, and a damping coefficient. Springs generate a force when displaced from their rest length. Each particle in the system has a position, a velocity, and a variable mass, as well as a summarized vector for all the forces acting on it.

The students used dynamic relaxation which is "*a computation modeling, which can be used for the form-finding of cable and fabric structures […] The system oscillates about the equilibrium position under the influence of loads. The iterative process is achieved by simulating a pseudo-dynamic process in time*" [21].

There are many benefits of structural form-finding using spring-particle systems. It embeds criteria of structural optimization from the first stages of the design process, while it assists architects to increase their intuitive understanding of the structural behaviour of geometrically complex forms. While traditional architecture and engineering aims at the structural optimization of an existing form, a dynamic form-finding system can lead to a real-time discovery of structural form [22] encouraging the morphogenesis of optimized structures rather than a post-design optimization. Understanding the association between geometry and material behavior, the elastic properties of membranes or computational spring meshes and the obtained form, leads to a '*synergetic approach to design integrating form, structure, material and environment*' [23].

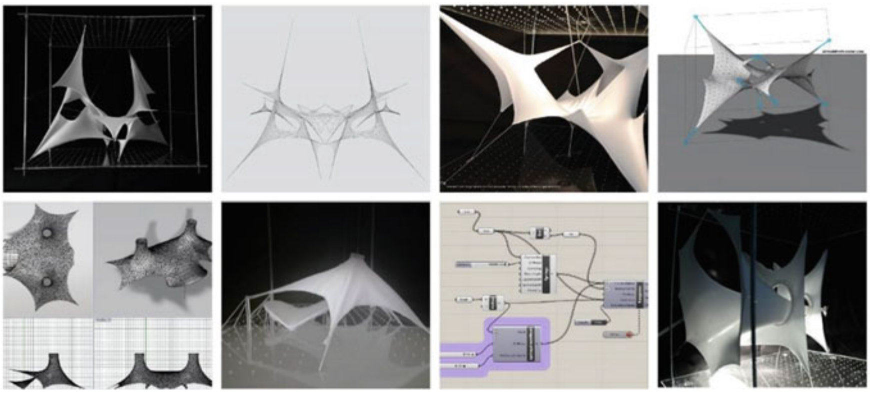

**Fig. 1** Physical models and digital simulation models for tensile structures from the studio at Graz University of Technology

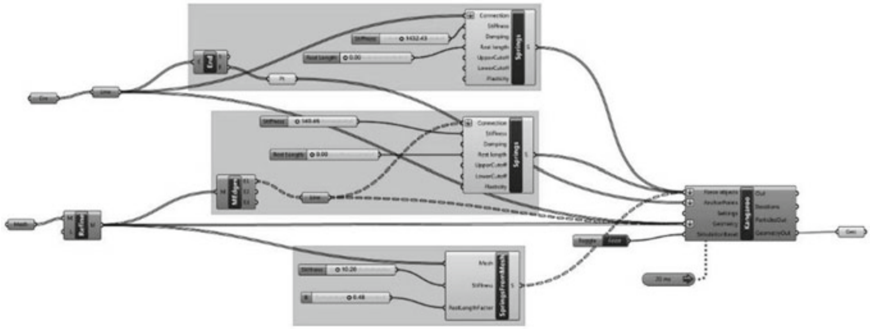

**Fig. 2** Typical parametric definition including simulation of spring-particle systems, setting the rest-length of springs, variable stiffness values and anchor-points for the simulation in Kangaroo Physics Engine

In an attempt to mimick the physical behaviour of a material system, we translate physical properties into mathematical equations that generate the geometry in the computational enivironment. Thus an elastic textile can be represented by a spring-particle system (Fig. 2), translating mesh vertices to particles and mesh edges to springs, a system of points and lines (Fig. 3). Having obtained an understanding of the forces acting upon the models through manual model making and observation, the students were able to build their own grasshopper definitions, compare the results to the physical models and fine tune the process.

In all of the student projects, there had been several cycles of design generation and modification, both in analogue and digital environment, in order to reach the desired geometry. What the students percieve as trial and error proved to have an enormous educational impact. The process they followed is what Kolb would describe as "Do-Observe-Think-Plan" [24]. Through this iterative process the students were able to take design decisions, and reflect in action as Schön describes, for example for achieving the tensioning of a membrane, they would increase the stiffness of the computational springs or decrease their restlength, when the simulation would not give the desired result, they would devise alternative solutions such as stabilizing it with edge cables of different stiffness, etc. During the process, students would observe the result and reflect upon it, comprehend which actions benefit their model and extract the knowledge from this observation. These realizations would help them further plan their digital experiments based on the new tacit knowledge they acquired.

As Piker explains "*one great advantage of physically based methods is that we have a natural feel for them, and this intuitive quality lends itself well to the design process*" The biggest benefit of form-finding in Kangaroo, is that the designer can embed rapid simulation in early design stages, enabling reflection in action and driving the design towards informed and optimized solutions. In Piker's words, "*through the application of real-world physics we can make computational tools that really work with us to design in a way that is both creative and practical*" [20].

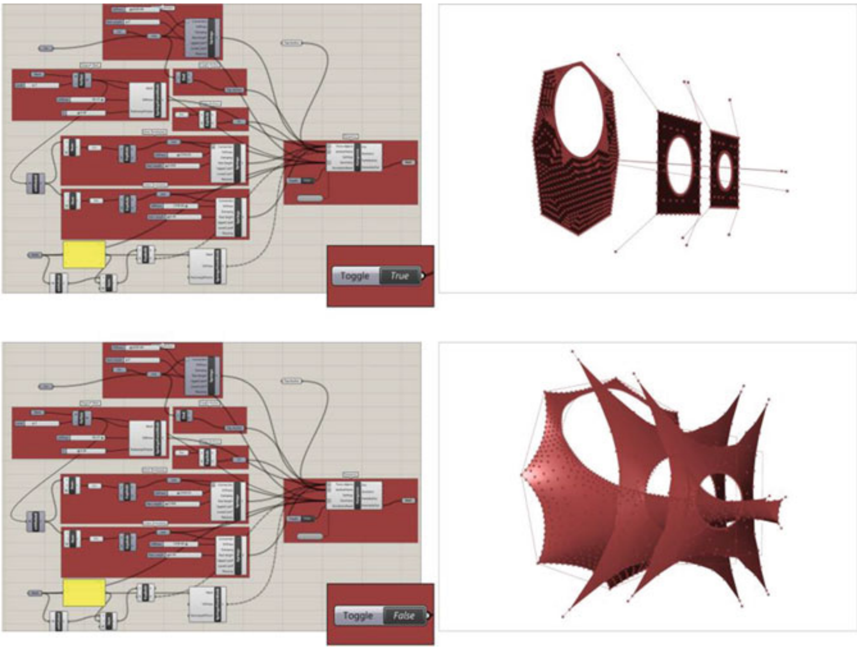


**Fig. 3** Computational model before and after the dynamic relaxation of spring-particle systems

The experience highly relied on a learning-by-doing process, understanding the correlations between problem setting and design result. The students would conceptualize and understand the forces in play, extract valuable conclusions about the amount of tension and its repercussion on geometry and realize the role of reinforcements and edge cables.

## *4.2 Bending Simulation as a Morphogenetic Tool*

The design studio about computationally simulated active bending took place at Graz University of Technology. It introduced students to the design of elastically bent rod and surface structures through analogue and digital form-finding. The aim of the workshop was to utilize bending behavior as a design tool for formal experimentation [25]. A system of bending rods, just as any other form-found structure tries to minimize its energy to span between the given borders. Eventually, the material system settles in a stable configuration.

Though form-finding is regarded as an intuitive process and experimentation with analogue media leads to tacit knowledge of materials, there is a considerable knowledge gap in the mathematical and computational understanging of the geometry of bending. Architect Marten Nettelbladt has been experimenting with the geometry of bending and has created an important online resource of experiments and observations concluding that all elastic deformations follow the same principals and therefore the same geometry [26]. Recent developments in *Kangaroo physics engine* can provide a very good approximation of bending geometry, and for this reason this tool proved to be a great resource for simulating the geometry of elastically bent elements, particularly when more bent elements interact resulting in tridimensional spatial curves (Fig. 4). Kangaroo works in an iterative way calculating the interaction among predefined forces, springs, bending resistance, pressure and gravity, and their repercussion on the geometry, until a stable form is reached.

Comparing the results obtained from the simulation to the physical models, there is great precision when simulating a single bending rod or a small set-up of interacting rods. The digital experiments become more demanding when several interacting rods are in play, adding to the complexity of the system [25, 27]. At the same time the physical form-finding experiments revealed some unpredictable results that emerged from the self-organizational capacity of the system to regulate and distribute forces to reach equilibrium.

For the simulation of bending behavior, as Achim Menges explains "*there are no simple mathematical equations which can describe the entirety of a surface defined by the equilibrium of applied force – be it tensile, compressive, or pressurized*" [28]. Having acquired some intuitive understanding of bending behavior through the analogue experiments, the students were able to reflect in action while experimenting with computational simulations of bending rod behavior.

During the studio the students used the recently incorporated hinge components, which means that apart from the standard spring-particle parameters like rest length,

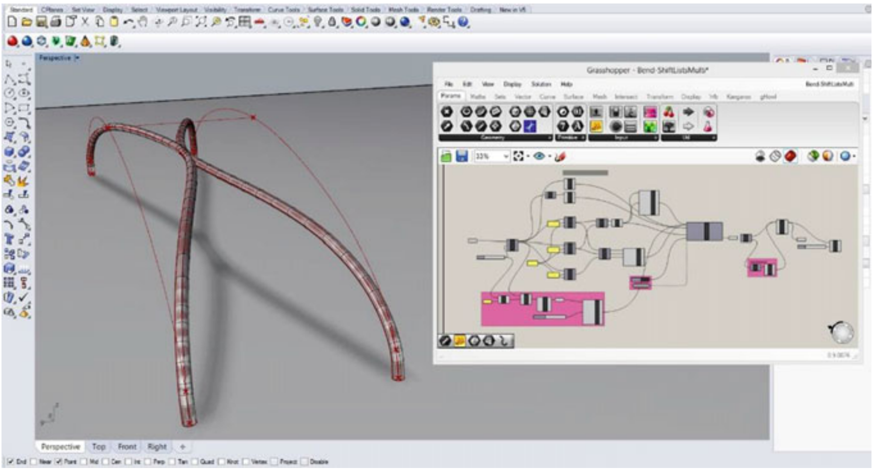

**Fig. 4** Digital form-finding model of two rods constraining the tangency of the rod axis to be parallel to Z at start and end points and a connection point in their mid-length. Rods self-organize through dynamic relaxation and obtain a common tangency near the connection point

spring force, damping, they would define a rest angle for the hinges to be computed during dynamic relaxation. For the case of elastically bending rods, the initial geometry is represented by a curve which is divided into a finite number of line segments which will be introduced as springs with a fixed length and high spring stiffness (for avoiding changes in the total length of the rod). The rest angle (the angle between the tangents of two consecutive line segments) is set to 0, so that the natural tendency of the rod is to spring back to its initial straight condition. As the overall length of a rod is not negotiated during the simulation, it is important to set the start and end conditions of the rod. The designer would decide the degrees of freedom at the two ends of the rod, in the case of pinned connection, the end point of the spring would be anchored to fixed xyz coordinates, whereas for simulating a fixed connection we would require to constrain the start tangent. This would geometrically mean to set the first two control points of a degree 2 curve in the desired direction, or in the case of spring-particle systems with hinges, to set the position of the first two particles as fixed for the desired tangent direction. The knowledge gained from the physical models was directly fed into the design decisions in the digital environment. Having mastered the bending behavior of a rod or a group of rods, the students experimented with bending planar surfaces (Fig. 5). Similar to the previous case, the aim was not to increase the overall area of the surfaces through bending, as it would happen with membranes and tensile structures. The obtained geometries were shapes of single curvature, however in often cases there were some unpredictable results, with the surface bending inwards or outwards when the start tangent was not constrained. Nevertheless, the students were able to understand the behaviour of the simulation and modify the parameters accordingly, usually in real-time, without necessarily restarting the simulation, they were able to reflect in action when the obtained result was diverting from their expectations.

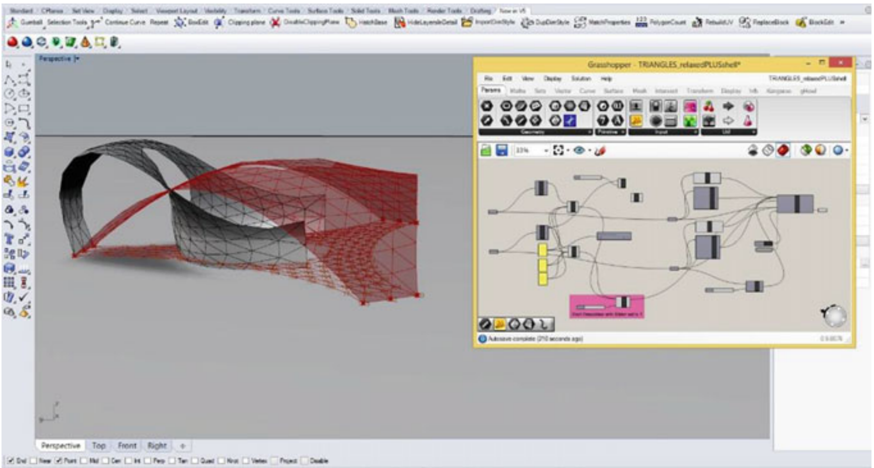


**Fig. 5** Digital form-finding model of a surface element that bends in two directions

### *4.3 Planarization Algorithms for Design Rationalization*

The studio Digital Tectonics which took place at the University of Thessaly, introduced students to simulation-based design processes for design rationalization and construction optimization. Some geometric problems, like the discretization and paneling of freeform surfaces with flat elements [29] cannot be easily solved through a mathematical approach. In several cases, a simulation-based strategy is necessary [30]. With the aim to design architectural structures that embed fabrication criteria and cost-effective design decisions, students set up a simulation that implements planarization algorithms in Kangaroo, as a design decision tool, that would drive the overall shape of their constructions towards feasible solutions.

Students had to decide the approximate shape and size of the panels, and their distribution on the freeform surface. They would have to decide the anchorpoints, in this case the edges of the panels that would connect to the ground (Fig. 6). During the simulation the rest of the vertices would move, until they find a stable position when the requirement for planar panels is met. To visualize this, a surface from planar curves is created for each panel. When the condition of planarity is met, the surface is created, when the vertices snap out of plane the surface will not be created. Therefore, the visual hint of planar subsurfaces that are parametrically created from boundary curves, is indicative that the simulation has found at least one of the possible solutions. During the design process students would try several different panel configurations, shapes, boundaries and volumes. If the system is overconstrained, it will not reach a solution with planar panels, hence the simulation does not always result in valid solutions, it may occur that some polygons due to their constraints and acnhorpoints never become planar. Such event would require either the modification of the overall geometry, or the shape and density of the panels. Alternatively, opting for a variable panel density based on the curvature may lead to an optimized configuration.

The students' intuitive understanding about the discretization of double curved surfaces into polygonal flat panels led to the variation of panels, Among the parameters that influenced the simulation result were the polygon sizes, anchorpoints, adjustment of the overall height of the shell (Fig. 7). The aim to design a complex tridimensional form that can be constructed from flat panels led to intuitive design decisions, and real-time design modifications during the simulation. As there were plenty of cases that could not be solved for construction with planar elements, the simulation helped define the optimized cell size. Students could reflect in action and modify the design parameters so as to obtain the desired result.

It was interesting to observe that after several iterations of Experience, Observation, Conceptualization, Experimentation, also known as Kolb's Cycle,[3] the students started to develop a capacity for reflection in action within the digital environment. Even if they hadn't been capable of explaining the reasons why they adjusted the parameters of the simulation, the design decisions they took were at all times coherent to their design intent, and surprisingly enough the modification of parameters of the

[3] Kolb's Cycle comprises of 4 stages: 1. Concrete Experience 2. Reflective Observation 3. Abstract Conceptualization 4. Active Experimentation.

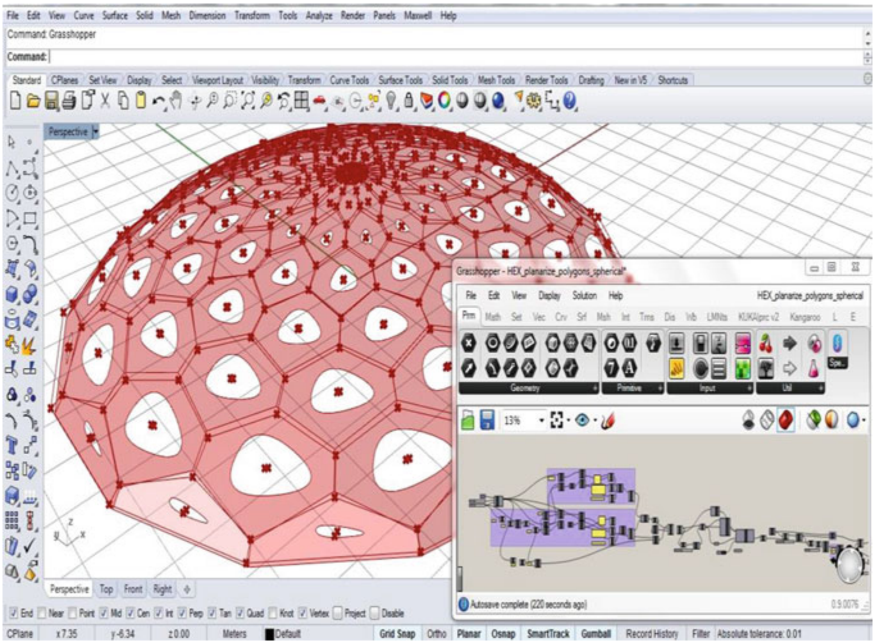


**Fig. 6** Semispherical shell structure comprising of polygons with planarization constraint

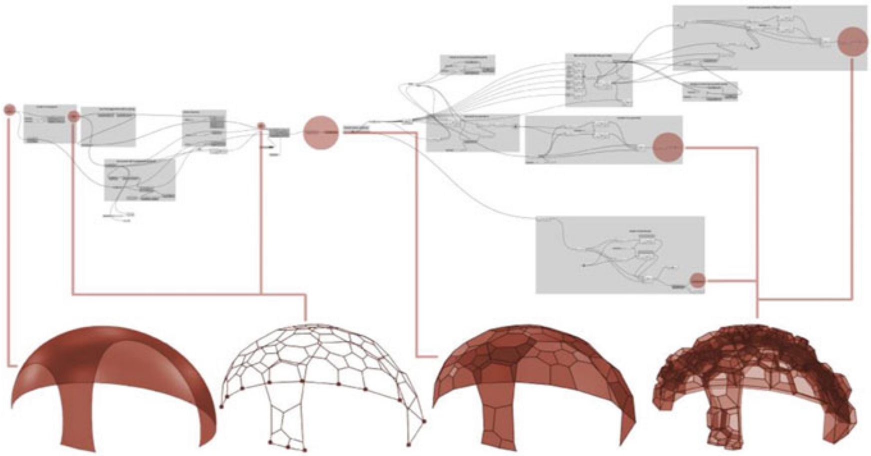

**Fig. 7** Simulation-based modeling of a shell structure employing planarization algorithm (Kangaroo Physics Engine)

simulation was almost always in the right direction to obtain geometry that was optimized for fabrication. Beyond doubt, the students had obtained tacit knowledge about the simulation by experimenting through practice. The simulation in turn would educate the designer which design decisions would benefit the design with regards to the criteria of planarization and feasibility of fabrication.

## 5 Conclusions

In an era of transition from manual to computerized and further on to computational design, the ideas of Schön seem to be evergreen. In our days the computer has become the main tool for sketching and drafting, and very often a tool for thinking. We have only seen a small fraction of the great potential that computation has to offer to the design disciplines. We are currently witnessing a growing interest in emergent design technologies and processes, where experimentation gives rise to new design opportunities. Yet, how do we explore unknown grounds? How do we train future designers to reflect in action, to be alert and creative at the same time, to seize the design opportunity? Is it always possible to be in full command of all new digital tools? Or are we seeking to develop our capability to adapt to the new challenges regardless of previous computation skills? The designer's ability to reflect in action becomes of crucial importance for dynamic digital design processes. Simulation-based modeling offers immediate visual feedback to the designer, a modification in design parameters can inform the design in real time. While theory, science and technology courses will answer the questions about "knowing that", the involvement of students in hands-on exercises and simulations of physical forces will train them with regards to "knowing how" [31]. Dewey in his writings about "*Experience and Education*" [32] polarizes the two extremes, traditional and progressive education, referring on the one hand to structured and disciplined education and on the other hand to unstructured, flexible, student-led process. While the first one lacks an holistic approach and is overly focused on content rather than process, the second is based upon a very weak philosophical basis of freedom in education. Dewey therefore suggests that educators should move beyond such "*paradigm wars*" and instead of contrasting theory with experience, employ a "*theory of experience*". According to Dewey, past experiences influence the future experiences in the sense of "*continuity*" while the notion of "*interaction*" takes the theory one step further by examining how past experiences interact with the current situation. Computational tools marked a new epoch in the design disciplines. Industry 4.0 calls for new education models, that are more open ended and adaptive. There is no clear answer about how digital media and simulation modeling should be incorporated in architectural education. Simulations of physical forces and interactions (stretching, bending, planarizing) are difficult to build from scratch, but at the same time for a designer that uses a readily available tool like Kangaroo, the process and design outcome is self-explanatory in the sense that the designer can observe the dynamic model oscillate around its stable position until it reaches equilibrium. The design studios presented in this chapter had exactly this goal, to experiment with readily available computational tools and train the students' ability to reflect in action within a digital environment. Simulation-based modeling affords us the opportunity to envision computational design tools of the future and learn to adapt to change, to learn through experience and develop new design tools and methodologies. As Keeton and Tate explain, experiential learning is the "*Learning in which the learner is directly in touch with the realities being studied. It is contrasted with the learner that only reads about, hears about, talks about or writes about these realities but never comes into contact with them as part of the learning process*" [33]. This type of learning is the link between the classroom and the real world. In an era of abundance of information through the worldwide web, the students need to develop skills of filtering the received information, but also of combining existing knowledge.

While the traditional academic set-up helps students to develop skills related to symbolic and perceptual aptitudes, behavioral and affective abilities are better fostered through active involvement of the student, through hands-on activities. A lot has been said about our ability to retain knowledge; Edgar Dale published a visual model of knowledge retention, the Cone of Experience, a visual model for classifying mediated learning experiences.[4] According to Dale, our ability to retain knowledge relates to the type of instruction; the Cone of Experience exemplifies "*Direct, Purposeful Experiences*" over "*Visual and Verbal Symbols*". This is in line with the famous Chinese proverb attributed to Confucius 450BC "*Tell me, and I will forget. Show me and I may remember. Involve me, and I will understand*".

It is important to highlight here, that not any computational design experience can lead to learning, only experience that is reflected upon can yield new knowledge. It is the duty of the educator to provide the circumstances where an educational experience produces learning. Michael Polanyi had always supported the importance of "*tacit knowledge*", the special type of knowledge that cannot be put into words, the experiential knowledge usually related to creative disciplines, associated with the actual praxis of design. Polanyi's belief that "*we can know more than we can tell*" [34] may be the way to describe the students' early experience with simulation modeling in architecture and Schön's legacy may form the basis for educating the reflective digital practitioner of the future.

**Acknowledgements** The work presented in this chapter is based on doctoral and post-doctoral research projects of the author. The educational experiments took place at Graz University of Technology in Austria and the Department of Architecture of the University of Thessaly in Greece. The author would like to acknowledge the work of the students that participated in the design studios, and express gratitude to colleagues and student assistants for their valuable input.

[4] There have been several variants of Dale's Cone of Experience, some of which are known as the Pyramid of Knowledge, offering percentages of the learner's ability to retain knowledge. However, such adaptations of the original model are not based on scientific research and are falsely presented by researchers as evidence about knowledge retention. The original model by Dale as presented in the book is not aiming to be presented as the outcome of scientific model, it is suggested as a conceptual, visual model.

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# Teaching Digital Design and Fabrication to AEC's Artisans

**Maurizio Barberio**

**Abstract** This contribution describes an operative research activity within the teaching of digital design and fabrication to Architecture, Engineering and Construction (AEC) artisans. The didactic approach described arises from the lack of academic paths thought for AEC's artisans, highlighting the reason why this aspect is relevant for both the AEC and the artisanal fields. In particular, the article reports a research project carried out by two artisans who attended the C.E.S.A.R. Course, an annual university course organized by the Politecnico di Bari in collaboration with Les Compagnons du Devoir, a historic French professional association. In particular, the research project concerns the study and the digital transposition using digital design and fabrication processes and tools of the "Bridge over the Basento River" designed by Sergio Musmeci.

**Keywords** Digital fabrication · Digital crafting · Architectural didactics · Digital artisans · Basento Bridge

**United Nations' Sustainable Development Goals** 8. Promote sustained · Inclusive · And sustainable economic growth · Full and productive employment · And decent work for all · 9. Build resilient infrastructure · Promote inclusive and sustainable industrialization · And foster innovation · 12. Ensure sustainable consumption and production patterns

## 1 Introduction

The paper aims to describe an educational experience of designing and building a prototype using digital fabrication techniques and its consequent didactic implications. The experimentation is based on the didactic method of learning by doing and experiential learning, where knowledge is transmitted not only through lectures but also and above all through proactive and laboratory experimentation. This approach

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_10

has already been adopted by the author, with other colleagues, and with architectural students during the design workshops in the third and fourth years. The method is particularly useful when it is necessary to acquire skills in complex and interrelated topics such as digital design and fabrication, architectural geometry, and form-finding. The case study of Musmeci's Basento Bridge was chosen because it is suitable for bringing all these aspects together and giving students an overview of such aspects. In particular, the paper refers to the teaching of digital design and fabrication to professional artisans without a specific background in AEC design topics, which is an uncommon didactic case study for architectural schools' agenda. The advanced digitalization of the craftsman operating in the AEC sector (both inside factories and building sites) is essential to reach the new 4.0 standards of the fourth industrial revolution, also when they are employed in SMEs, or they are self-employed.

## 2 Background: Digital Design and Fabrication Within the Academic Context

Digital fabrication is intended as the manufacturing process in which the physical model is produced through machines controlled by the computer starting from a digital model. Between the 1990s and the 2000s, the widespread use of computers in architecture changed the way buildings were designed and built. In 1992 the Gehry Partners LPP studio created a fish-shaped pavilion to be placed on the Barcelona seafront. The three-dimensional IT model was obtained starting from a study maquette. The surface thus generated was then utilized to perform the structural analyses and to obtain all the building components. For the first time, the production and assembly of the components of the structure were completely directed starting from the digital model [17: 8]. Kolarevic and Male-Alemany [13] emphasized that, following Gehry's example, the architects understood that the information of the digital model could be used directly for fabrication and construction, thanks to the use of numerical control machines. Kolarevic stated that the most interesting potentiality of integrating digital fabrication in the architecture practice is to revitalize the close relationship that once existed between architecture and construction: "By integrating design, analysis, manufacture, and the assembly of buildings around digital technologies, architects, engineers, and builders have an opportunity to fundamentally redefine the relationships between conception and production. The currently separate professional realms of architecture, engineering, and construction can be integrated into a relatively seamless digital collaborative enterprise, in which architects could play a central role as information master builders, the twenty-first century version of the architects' medieval predecessors". In this direction, other authors [6] stated that the contemporary designer can be defined as a novus architetto adaucto; in other words, an "expanded designer" who possesses new (robotic) arms which allow him to cut and shape the materials according to his direct requirements (almost) without any external mediation, paradoxically like the architect-master (or master builder) of the past. Anyway, as for architects and engineers, there is no evidence to exclude artisans from this important change. In fact, like during the Middle Ages, when stonemasons directed the construction of the cathedrals, being effectively responsible for how they were built, nowadays artisans can take part in the design and construction choices of the contemporary building sites, if adequately prepared and skilled. It is a fact that digital fabrication brings a significant change in Architecture, Engineering and Construction (AEC) industry, particularly in the planning and execution phases. As a result, scholars have already highlighted that it is expected that current construction roles will evolve, and new roles will be created: the responsibilities of the construction workers will shift from unsafe and hard conditions to safer and less labour-intensive, such as monitoring and control automated processes by transferring their know-how to the robotic systems [5]. In the absence of specific academic training paths for artisans who operate in the AEC sector (that we call "AEC'S artisans"), the acquisition of digital competences is left to the resourcefulness of individual workers or to the companies where they work. The birth and diffusion of the Internet have contributed to creating a pervasive digital culture (makers culture), that has allowed us to fill formative gaps casually and informally. Lee [16], analysing the "maker mindset" and its implications for education, has defined this mindset as playful, asset-and growth-oriented, failure-positive, and collaborative. Some scholars believe that the Fab Labs could potentially challenge the structure of society in the coming years because with their diffusion, knowledge is no longer statically placed in universities, companies, or research centres, but it is increasingly moving towards the creation of a fluid and adaptive network able to informally spread knowledge and innovation [17]. Despite this view, it is undeniable that the academic context had a crucial role in the birth of the maker's movement: the first digital fabrication laboratory (Fab Lab) has been founded at MIT in 2001. Again, at MIT in 1998, Neil Gershenfeld - director of the Center for Bits and Atoms - inaugurates the course called "How to make (almost) anything". As a computer scientist, Gershenfeld conceives an interdisciplinary course, in which students can learn how to use CNC machines of industrial derivation to develop fully functional experimental prototypes [10]. Afterwards, several scholars studied the relationship between didactics and digital fabrication, especially in architecture schools. For example, a 2-year course called "File-to-Factory Digital Fabrication" has been launched at the University of Nebraska-Lincoln in the early 2010s. The course goal was for students to synthesize various disparate architectural assemblies and materials with the file-to-factory digital fabrication process to understand the making architecture [11: 22]. A mix of classes and lab periods has allowed the students a better understanding of digital design and fabrication processes and the production of physical prototypes [11: 29]. Another didactic model, called "Digital Design Build Studio" has been organized in both individual activities (first part of the studio) and group work (second part); for the final part one project has been selected and developed further, to test ideas on a 1/1 scale, to allowing "the studio to fit in the existing curriculum but also allows for an investigation and research that goes beyond the regular design studio setting" [21: 201]. In a study about engineering education, Sheppard et al. [22] proposed the categorization of laboratory instruction into three levels. As summarized by Celani [4: 476], the first level concerns novice students that must follow the instructor's directions strictly, step by step, to reach the desired results, which will demonstrate a concept. Next step concerns intermediate students, that must do some exercises to understand the mathematical description of the theory. The last step consists of developing laboratory simulations that illustrate the same phenomenon, in which advanced students can validate the concepts learnt by testing them with different parameters and conditions. Celani states that "as digital fabrication labs become more common in architecture schools and are assimilated by design instructors, they can promote changes in architectural education, allowing students to become closer to the production process and to have a better control over building parts and materials" [4: 480]. Furthermore, Celani affirmed that digital fabrication laboratories have the potential of promoting experimental methods in architecture together with a scientific approach, which is the basis of contemporary architectural practice [4: 480]. In fact, in the last decade, several digital fabrication laboratories have transformed their pioneering explorative research into a scientific activity, with the design and fabrication of full-scale models (that we may also call "proto architectures") that aim to demonstrate the goodness of an empirical hypothesis. Anyway, these advanced research activities are not usually accessible at the undergraduate level of education, but they are thought for master's and Ph.D. students, generally enrolled at Institutes of Technology and Polytechnics. To overcome this limitation in the so-called "post-digital era", Figliola [9: 35] proposes the inclusion of modules relating to computational design and digital fabrication in educational programs starting from the first university education cycle. As stated before, a similar approach was developed by the author's research group during architectural design studios held during the 3rd year course (out of 5 years degree program) at Politecnico di Bari [7, 8], in which a "learning by designing" approach was adopted both in the realization of scaled models of building components, realized by using digital design and fabrication tools, and in the architectural design of the whole buildings, which embedded those components into the overall design. Stavric et al. [24] underline that the teaching approach for learning digital design and fabrication should be based strongly based on geometry, mathematics, programming, hardware computing and material behaviour. Again, the translation of digital models into physical ones is one of the cores of the teaching activity. Anyway, other scholars argued that the introduction of digital fabrication and design in upper primary and lower secondary schools poses several issues related to the contradiction between a curriculum-based and highly goal-oriented school setting and an experiment-based and highly explorative maker culture. The study revealed that teachers were not technologically or methodologically prepared for an educational program that did not align with the structure of conventional training, because the explorative nature of digital fabrication challenged the authority of the teachers and jeopardized their feeling of being in control [23: 46]. In any case, the education on digital design and fabrication seems nowadays essential for all kind of students, especially for those will start an academic path into STEM disciplines or for those that will work into companies related to manufacturing or engineering. Numerous architecture schools all around the world have incorporated digital design and fabrication coursed into their degree programs. Regardless of the education path of each, Gershenfeld believes that the digital revolution in manufacturing will allow people to produce objects and machines on demand, allowing the birth of new hybrid professionals, named "makers" or "digital artisans".

## 3 A Didactic Approach for AEC's Artisans Within the Academic Context

In [3] Richard Barbrook and Pit Schultz coined the term "digital artisan" in their Manifesto for describing who works within hypermedia, computing, and associated professions. Even if the definition is not specifically related to who commonly can be defined as "artisan", their Manifesto does not preclude the inclusion of them, because the authors intended to celebrate the Promethean power of the digital artisans' labour and imagination to shape the virtual world. They imagine that digital artisans will build the wired future through their own efforts and inventiveness by hacking, coding, designing, and mixing. Thus, the introduction of such topics into traditional teaching programs poses different challenges but it could also be an important opportunity for developing a holistic approach and developing critical thinking skills. Anyway, the use of the Internet to share knowledge openly and fluidly within the makers' context is one of the reasons which is not easy to establish proper academic paths to transfer knowledge from universities to qualified workers who need to update (or create) their digital skills. In other words, it is easier for them to search informal didactic resources (articles, blogs, tutorials, etc.) rather than start an academic formative path. There are two reasons for it: the first lies in the lack of academic coursed dedicated to AEC'S artisans; the second lies in the fact that often a professional diploma is not a sufficient requirement for being accepted in a traditional academic course. These challenges can be overcome by establishing innovative formative partnerships between professional associations and academic institutions, joining their efforts to support workers and companies in the so-called "lifelong learning". Regarding the relationship between the AEC industry and the artisanal field, there is a need to formulate a didactic approach adequate to train artisans (who may be employed both by manufacturing and construction companies) in a way that they can be part of a holistic framework where design, fabrication, and construction aspects are seamlessly linked together. The recent development of the Industry 4.0 imposed the development of the homologous "Architecture 4.0" in which designers (architects and engineers), artisans, workers contractors, suppliers and construction companies share the same language and the same processes [2]. Lanzara [14] states that the involvement of the academic world plays an important role in the process for the improvement of collective awareness towards a multidisciplinary collaborative ecosystem, by sharing advanced activities to support training and entrepreneurial activity of students or artisans, and for developing a digital conscience.

## 4 The Theoretical Models Adopted for Teaching Digital Design and Fabrication to Artisans

The operative research described in this paper is representative of the experience that the author has accumulated over the years at the C.E.S.A.R. Course (Cours de Enseignement Supérieur en Architecture et Restauration), held annually since 2015 at the Politecnico di Bari. The uniqueness and the novelty of the course stand in the fact its goal is to create and train a professional profile who can create a closer connection between the restoration site manager (architect or engineer) and the various specialists involved in the study, protection, restoration, management, and enhancement of the architectural heritage, also adopting contemporary tools, such as parametric and digital modelling software or digital fabrication techniques. Inside the overall didactic scheme of the C.E.S.A.R. Course, the classes held by the author about digital design and fabrication are essential for training the new generations of "digital artisans". The digital design classes concern the understanding of the different levels of interaction between the designer and the digital environment, also explaining the differences that exist among the various 3D modelling techniques (Table 1). Digital fabrication classes followed a similar structure that those regarding digital design themes. They are summarized in Table 2. They are concerned essentially with the relationship between the design outputs allowed by using different digital fabrication tools and techniques. In other words, the intention was to transfer the design thinking underlying the different projects who take advantage of digital fabrication processes.

The course is incardinated on the use of the NURBS-based modelling software Rhinoceros. This software has been adopted not only for its user-friendliness but also for its versatility which allows transforming the software into a powerful platform, capable of easily embedding different 3D modelling techniques (NURBS, mesh and subd modelling) thanks to both its native features, above all, using specific plug-ins (for example Grasshopper for parametric modelling, VisualARQ for Bim, etc.).

**Table 1** Digital modelling strategies topics of the course

| Modelling strategy | Modelling typology |
|---|---|
| Direct modelling | Solid |
| | Parametric solid (semi direct) |
| | Polygonal |
| | NURBS |
| | Sub-d |
| | VR modelling |
| | Digital sculpturing |
| Non-direct modelling | Procedural |
| | Parametric-associative |
| | Computational |
| | BIM |

**Table 2** Digital fabrication strategies topics of the course

| Fabrication strategy | Fabrication typology |
|---|---|
| Subtractive fabrication | Cutting of flat elements |
| | Cutting of volumetric elements |
| | Carving of volumetric elements |
| Bending | Bending of rigid elements |
| | Bending of flexible elements |
| | Bending of flat elements using a cutting pattern |
| Formative fabrication | Digital weaving |
| | Stretching of elastic material |
| | Thermoforming |
| Additive fabrication | Material extrusion of monolithic objects |
| | Material extrusion of discrete assemblies |
| | Binder jetting of monolithic objects |
| | Binder jetting of discrete assemblies |
| | Additive formworks |

Furthermore, Rhinoceros allow the investigation of the three levels of interactions aforementioned: direct modelling, parametric-associative modelling, and computational modelling. Direct modelling refers to the use of modelling software through a consequential but static process. In other words, the digital model is manipulated directly by the user, but any additional modification makes it impossible to go back. In this type of modelling, it is therefore important to preserve the fundamental steps of the modelling process, to be able to return to an earlier phase of the process. It is a typical design process in which we start from the global geometry up to the definition of all the details. A change in the initial global geometry determines the need to restart the modelling process from the beginning. Parametric-associative modelling refers to the use of a parametric modelling software or application for defining the digital model. In this case, the designer concentrates on defining the logical consequentiality of the various steps, which can proceed from the overall geometry to the detail or vice versa. Thus, the designer does not directly generate the digital model, as in the previous case, but generates a parametric "code", i.e., an algorithm governed by some fundamental parameters that define the geometry. For computational modelling, we mean the use of a programming language (embedded or not in a parametric or modelling software) for the definition of an interactive model, in which the designer can simulate various types of phenomena characterized by high conceptual or geometric complexity. Also, in this case, we can proceed from the global geometry up to the detail or vice versa.

The course goal is not only to transfer the artisans some 3D modelling skills but to provide critical thinking to understand the theoretical differences between the different levels of interactions and their use to achieve different fabrication results.

This is because the modelling strategy to be undertaken cannot follow predetermined paths but will be influenced by the need of the specific case. Summarizing these differences, direct modelling is indicated in all cases in which is possible to generate the 3D model easily and at the same time it is not yet possible to define the project parametrically, due to the uncertainty on the road to be taken. This is particularly useful in the initial study phases of the forms. Parametric-associative modelling can be useful when the project is still in an exploratory phase, but it is already possible to define some parts of it from an algorithmic point of view (for example, the tessellation of a vaulted system that is not too complex). In this way, different solutions for a specific design aspect can be examined more easily. This type of modelling can be useful even when the complexity of the project is not so high that it must necessarily use more sophisticated computational tools. The increasingly widespread dissemination of parametric-computational strategies in the design field has made it possible to apply new operative models of computer origin also in the fields of architecture and engineering.

In general, it is possible to state that the computational and parametric design can follow two models: top-down and bottom-up. Both models have been theorized in the field of computer science and are used as strategies for writing parts of program codes. In top-down models, the starting point of the design process is represented by the formulation of a general systemic idea, from which all the sub-problems that compose it follow. The model provides the progressive finishing of all parts as they are designed, and new elements are added to the system. In bottom-up models, the starting point of the design process is represented by the detailed definition of individual elements of the system, which are subsequently connected and interrelated to each other, up to the definition of the overall system.

## 5 Operative Research: The Digital Design and Fabrication Transposition of the "Bridge Over the Basento River" by Sergio Musmeci

In this section, top-down operative research (final exam) carried out by two student-artisans is described. This project is described as an example of the application of the didactic approach described before, concerning the study and the digital transposition using digital design and fabrication techniques of the shape of the "Viadotto dell'Industria" (Industry Viaduct), commonly known as "Ponte sul Fiume Basento" ("Bridge over the Basento River"), designed by Italian engineer Sergio Musmeci and built between 1971 and 1975. Musmeci's Bridge has been chosen for different reasons: firstly, the project is a unique engineering (and architecture) masterpiece, and it is also a clear example of what is possible to achieve when the architectural shape is completely linked to structural behaviour aspects. Plus, the project has been originated by generating different physical models, as described afterwards, and it is generally considered one of the precursors of contemporary digital form-finding techniques. Lastly, the bridge presents a non-Euclidean, complex shape, suitable to be used as a case study to train the students in advanced and parametric modelling, digital fabrication, and architectural geometry.

The operative research method was based on the learning-by-doing approach. Thus, a sequence of tasks has been assigned to the students to allow the acquisition of knowledge on the chosen topic proactively and progressively:

1. Historical investigation of the case study and understanding of its cultural value for architecture and engineering.
2. Investigation of design and form-finding strategies to obtain the overall shape of the bridge.
3. Critical evaluation of the design and form-finding outputs and the model-making feasibility.
4. Definition of the final digital design and fabrication process.
5. Critical evaluation and description of the design issues and improvements.

## 6 Historical and Cultural Research

Basento Bridge is one of the best examples of a shell structure built during the XX Century in which physical models have been used to determine its optimal shape. Even if physical models have always been used in architecture for different reasons, like representing the project, studying its proportions, its structural behaviour, etc., the models used for searching the optimal shape of a given structure are of more recent introduction. It is important to underline that not all scale models can be used for structural purposes. The phenomena or structural behaviours that can be scaled linearly, concern the linear dimension of a structure, the funicular form of a vault, of a dome or a shell, and the stability of a masonry structure subject to compression only [1]. In the Sixties Sergio Musmeci used a form-finding technique originally developed by Otto and Rasch [18], to determine the initial form of the structure of the Basento Bridge. The technique consists of the immersion of metal profiles of the desired shape in soapy water, and it has been used to research the shape and to start the initial calculation processes [15]. Musmeci continued the research by building a neoprene model that allowed the study of the tensions in the two perpendicular directions. Subsequently, a methacrylate model of two spans of the bridge was then built on a scale of 1:100 to verify the correspondence of the form to the design program and was subjected to elastic tests that allowed a first partial control of the calculation forecasts. Finally, before the construction of the bridge, the Superior Council of Public Works requested the construction of a scaled-down (1:10) model made of micro-concrete for loading tests [19: 17–24], a technique already used by Eduardo Torroja in 1933 for the project of the colossal dome of the Algeciras market in Spain. Later, different analogue form-finding techniques have been translated into the digital environment, especially in the last decades.

## 7 Investigation of Design and Form-Finding Strategies

Among the various digital form-finding techniques developed, like Dynamic Relaxation, Force Density Method, and Thrust Network Analysis, students investigated the use of the Particle-spring system for the investigation of the bridge's shape. As the name suggests, the Particle-spring system is composed of a set of particles connected by a system of springs: the particles represent the points where the mass is concentrated, and the springs are schematized as elastic lines connecting two points. Applications of this form-finding system within computational design have been developed by Kilian and Ochsendorf [12] conceiving CADenary, and Daniel Piker who developed Kangaroo Physics, a particle-spring tool available inside Grasshopper, the visual programming language of Rhinoceros [20]. Considering this background, a particle-spring form-finding technique has been used during the course to train students to understand the relationship between architectural geometry and structural optimization and behaviour. Kangaroo 2 has been initially used for trying to recreate in the digital environment the form-finding process utilized by Sergio Musmeci. The simulation consists of creating a basic flat mesh placed on the XY plane, which represents the membrane on which to apply the form-finding process. On the base mesh, the designer defines the anchor points that will remain fixed while the other points (particles) are free to move according to the resistance of the elastic lines (springs) that connects the various particles. However, in this case, the process provides that some anchor points will no longer be on the XY plane, but they are moved on the Z axis to give the bridge the actual arcuate shape (Fig. 1). Students were asked to replicate the form-finding process described to evaluate the feasibility of physical model fabrication, considering also different materials and production methods.

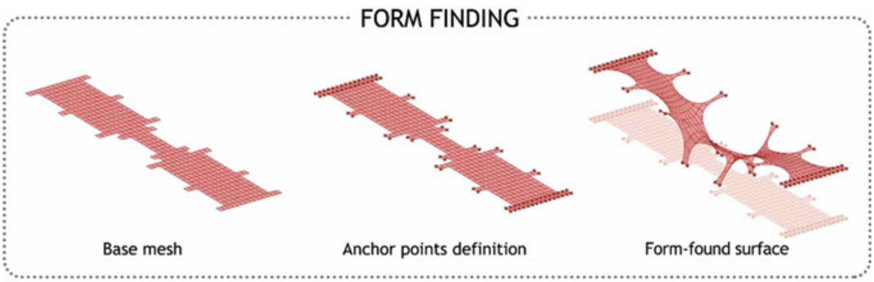


**Fig. 1** Particle-spring form-finding workflow

## 8 Critical Evaluation of the Design and Form-Finding Outputs

Although the output model was fine in its pedagogical value, it was not for its geometrical properties. The form-found model was quite different from the actual shape of the bridge. This difference is because the actual Musmeci's bridge is not a funicular compressed-only shape but, instead, it can be approximated by a tensile minimal structure. For this reason, it has been decided to realize a more accurate 3D model analysing the laser-scanned survey carried out for the restoration study of Musmeci's Bridge. In this case, a mix of basic and advanced modelling has been used to achieve the result. The multiple modelling approach has been encouraged by the author because in this way students had the chance to be aware of the different possibilities that can choose to accomplish the fixed goal. It is important to note that the research goal was not to recreate a surface perfectly identical to the original. Instead, the main interest was to use digital processes and tools to study how to evocate the bridge's shape by taking advantage of the bending properties of a typical material available in a FabLab, like thin plywood, dividing the whole shape into small pieces. This implies the development of a comprehensive computational strategy (although simplified due to the didactic nature of the experiment), from design to fabrication.

## 9 Definition of the Final Digital Design and Fabrication Process

The author guided students during the development of the whole process, which is formed by several steps (Fig. 2):

- Recreation of the bridge's shape by extracting the fundamental curves from the survey, using them for creating the base NURBS polysurface of the bridge.
- Conversion of the discontinuous NURBS polysurface into a mesh model by creating an ultra-simplified network of quad meshes (coarse mesh).
- Subdivision of the previous mesh using the Catmull-Clark algorithm by simultaneously pulling the obtained mesh onto the base polysurface.
- Extraction of transverse and longitudinal mesh edges (u and v directions).
- Creation of the continuous NURBS surface by a network of curves using the ordered lists of mesh edges of the previous step.
- Study and test the tessellation pattern shape, the material type, and its physical properties (like bending).
- Population of the continuous NURBS surface according to the chosen pattern.
- Testing on a smaller part of the whole prototype the chosen pattern and material behaviour.
- After validation, production of the final model (all the pieces need to be numbered and oriented).

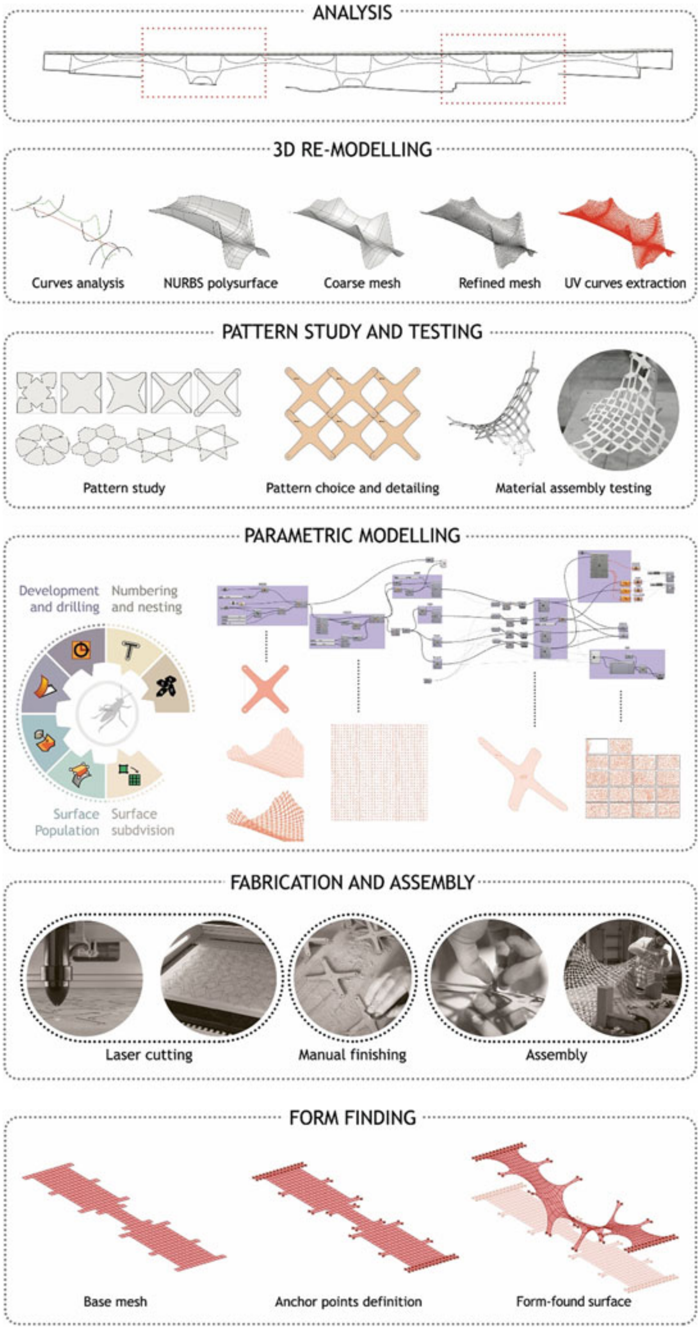


**Fig. 2** Project workflow

- Nesting of all the pieces into the defined sheets of material.
- Fabrication through laser cutting tools.
- Final assembly.

## 10 Critical Evaluation and Description of the Design Issues and Improvements

Some considerations on the consequences of the didactic value of the learning-by-doing approach need to be highlighted. The first assumption of the research was to build a complex surface using only small flat elements. At the start, students intuitively came up with the idea of triangular modules because they are always flat. Anyway, students experimented several challenges testing triangular tessellation, as for example, the problem of the junctions between each element that converges in a point. They tried to solve this issue by adding a soft leather part to each end, but the solution was expensive, difficult to realize and inelegant. After abandoning triangular tessellations, they started to experiment with quadrangular patterns, especially studying the relationship between material bending properties and the pieces' shape. Soon they discovered that using quad pieces allowed a much cleaner and more efficient division of the surface, a better data order into Grasshopper, and a great bendable of the modules if constituted by 4 branches (Fig. 3).

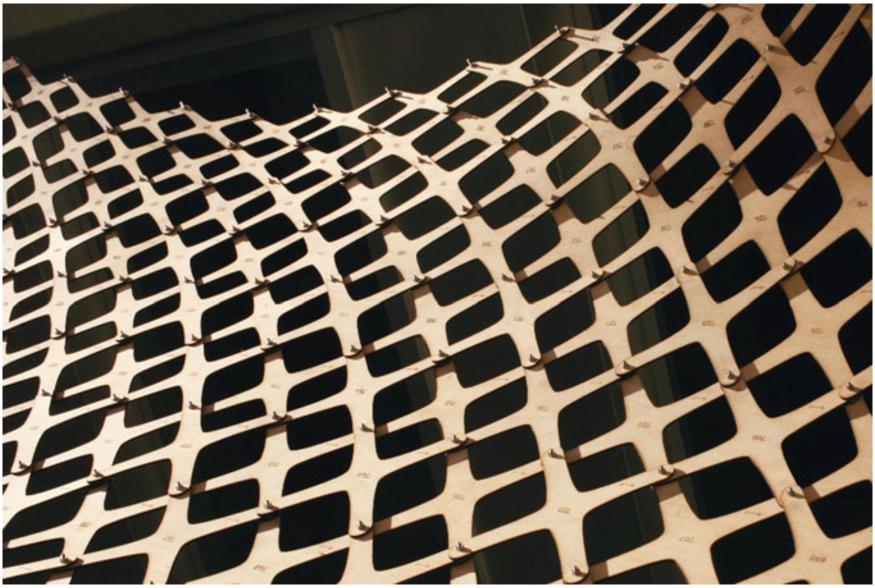

**Fig. 3** Details of the assemble plywood elements

Finally, the used pattern was chosen for its aesthetics, but also and above all for its shape: the four branches that make it up are narrow, which has improved the flexibility of the modules. In this way digital and physical models have been conceived together, one influencing the other and vice versa. In fact, after the design phase, students needed to make the first prototype to assess the reaction of the material to the double curvature. The goal was to push the limits of the material as much as possible. For that, they modelled a surface like the bridge one but with a stronger curvature. After having cut all the plywood pieces, they assembled the structure by starting flat. They soon noticed that as they added more pieces, the overall shape began to form due to the tension established by the bent pieces of wood. Indeed, the fact of forcing the parts to be aligned with respect to the screw holes forced the structure to find its final shape (Fig. 4).

In the end, the final model was formed by 980 unique pieces of plywood, fabricated by means of a laser cutter. Each piece has been overlapped and fastened by bolts with to the adjacent one. The model is held on itself, using nylon threads that keep it under tension across its width. The final model has been suspended in the air at the atrium of the Architecture Department of the Politecnico di Bari: the “Flying Musmeci” prototype is ready to intrigue the next generations of students (Fig. 5).

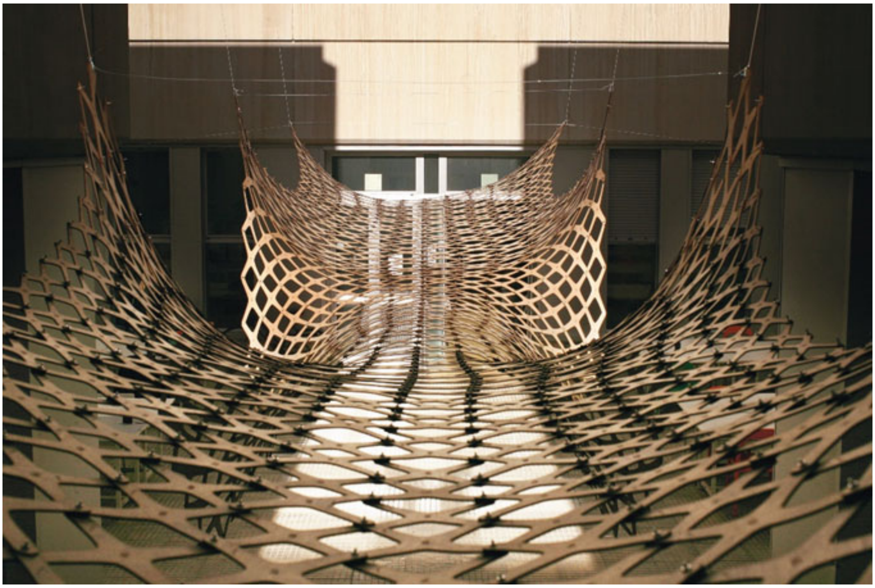

**Fig. 4** View of the finished model recalling the shape of the Basento Bridge

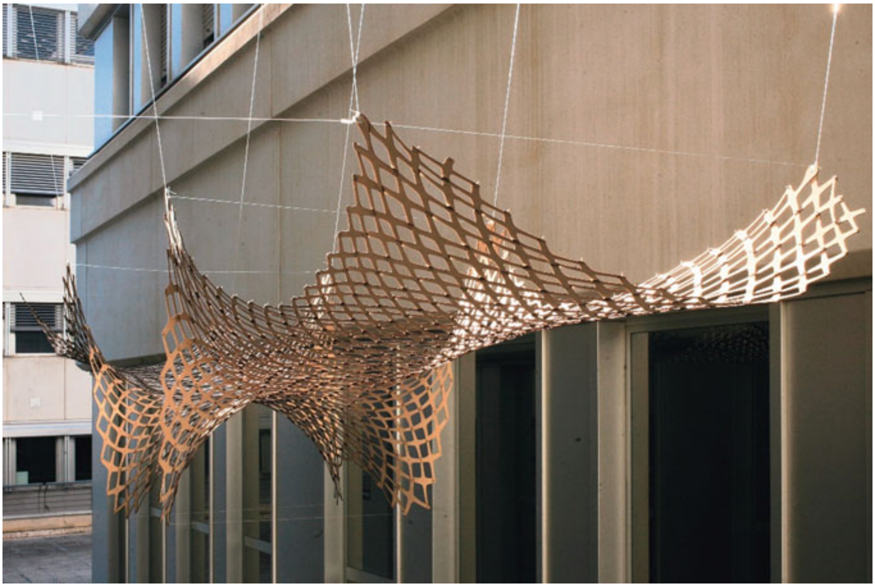

**Fig. 5** Picture of the suspended model inside the atrium of the Politecnico di Bari's Architecture Department

## 11 Conclusions

Through the operative research presented, the proposed didactic approach shows a possible learning path for the education of professional artisans. The framework used for guiding the didactic experience of the students suggests that establishing academic paths on the critical use of digital design and fabrication tools could be a feasible way for enhancing the digital awareness and skills of artisans employed in the AEC industry, with benefits for the entire chain. It can be considered also a reference for new lifelong learning didactics for reskilling operations for experienced artisans who need to gain new abilities required by the labour market. Lastly, it's possible to state that the same approach may experiment also for the undergraduate student's curriculum (i.e., bachelor's degree) because they have similar general knowledge of AEC verticals compared to artisans, especially in the first year of studies.

**Acknowledgements** The research project was carried out in 2020–2021 during the academic Course named C.E.S.A.R. (Cours de Enseignement Supérieur en Architecture et Restauration) at the Politecnico di Bari, where the author has taught digital design and fabrication starting from 2015. The author thanks the students of the Course, Louis Gibault, and Timothée Michel for having carried out the operative research presented in this paper. The author thanks also the Director of the Scuola di Specializzazione, Prof. Monica Livadiotti, and the Course Coordinator and Supervisor Prof. Giuseppe Fallacara for the scientific support. A special thank goes to the associations Les Compagnons du Devoir et du Tour de France and the Fondation de Luxembourg for funding the student's scholarship and to Politecnico di Bari's FabLab and the company Romeo Srl, for

supporting the realization of the physical models of the Course. Video of the project can be watched on YouTube: https://www.youtube.com/watch?v=31TH20mWMdA.

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# The Corona Decade: The Transition to the Age of Hyper-Connectivity and the Fourth Industrial Revolution

**Alexandros Kallegias, Ian Costabile, and Jessica C. Robins**

**Abstract** The COVID-19 pandemic continues to profoundly affect the world socially and economically. The quarantine and isolation strategies adopted globally have advanced online trade to a new level, as people are finding new ways to provide products and services from home. Several digital tools are gaining popularity and delivery services are ramping up production to meet the increased demand. This paper analyses the current situation considering the impact of COVID-19 in technology and society. The first part of the analysis consists of historical connections between epidemics and technological progress. The paper charts the impacts these have had on society and where they have come to define each industrial revolution. The second part of the analysis explores the different strategies to contain the coronavirus and protect economies. Comparisons between countries are developed through available data and displayed in charts. Furthermore, the paper demonstrates the impact of the strategies on social lives and the economic shift from physical to online. It explores the creative adoption of platforms and technologies that are driving the new revolution. As a case study, it also focuses on "the field of architecture and reviews the case of the live data collection process that is made after the erection of an edifice. Through a practice-based project, it speculates on enhancing the energy performance of a building via applying computational techniques to the collected data. It describes the system of an ad-hoc sensory device that gathers energy data from a building as a different option from existing HVAC systems. Considering COVID-19's high impact on society, drastically altering the way the market operates, we suggest this moment as the true beginning of the Fourth Industrial Revolution, bringing with it a new historical narrative.

**Keywords** Real-time · Data-conversion · Architecture · Computation · AI and machine learning

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_11

**United Nations' Sustainable Development Goals** 11. Make cities and human settlements inclusive, safe, resilient and sustainable

## 1 Introduction

Several technology developments from the previous decade have gained enormous market strength as a result of the COVID-19 situation, and major digital enterprises are now expanding even further. In the AEC industry, it became evident through COVID-19 that there is an increasing dependence on technology to accomplish sustainability goals, with technology serving as a catalyst for much-needed innovation. These goals are related to a variety of urban production but also to climate change challenges. Architectural technology is driving the way toward adaptable design and building systems, from material science to equipment, tooling, and software development. With the use of robotic techniques and decision support systems, it is essential to consider technology beyond the mere collection of physical components generated via tests and assembled to create new goods. There is also experimental thinking that enables technological progression. Together with the AEC industry, several digital and online platforms have benefited from the lockdown, as a swarm of users and consumers have appeared online. Society, economy and culture are being abruptly reshaped and online trade has finally become mainstream. Here, we announce the Fourth Industrial Revolution and a new decade marked by the 'corona' disruption, brought on by a pandemic that has completely changed the system.

## 2 Epidemics and Industrial Revolutions

For design and technology, the consequences of this pandemic are fundamental. It has forced humanity to stop climbing the ladder of prototype technology and to go directly to the world of stable digital design. As documented in history, unprecedented events have instigated the First, Second and Third Industrial Revolutions. The First Industrial Revolution began around the 1760s and was mainly characterised by steam and water power, along with advances in mechanised factory systems [1]. Although the causes of this revolution are various [2], this was preceded by a series of epidemics caused by diseases such as the plague [3], which have driven societies to invent new ways to operate. For instance, the Black Death (1348–1350) killed between a third and half of the European population, and for Britain and Italy, this resulted in a rise in wages [4]. Workers earned three or four times subsistence [5] and marriage ages increased, since there were more female employment opportunities, particularly in animal husbandry [6].

The Second Industrial Revolution generally corresponds to the period of 1870–1914 [7], marked by the development of public utilities such as gas, water and sewage systems, along with railroad and telegraph networks, further leading to electrical power and the invention of the telephone. The large number of epidemics happening throughout this revolution, such as the third plague pandemic (1899–1940) in Europe [8], several cholera pandemics and the flu pandemic (1889–1890) [9], are seen as contributors to this revolution and have motivated technological developments. Dirty and contaminated water was discovered to contribute to the spread of diseases, and this made improvements in public utilities and sanitation vital for survival. Furthermore, horses in urban communities contributed to the transmission of diseases, which is argued to have sped up their replacement by automobiles in the early 1900s [10].

The Third Industrial Revolution began in the 1950s [11], highly accentuated by the invention of semiconductors, leading to the invention of computers and culminating with digital tools and the internet. These developments came after more series of pandemics, such as the Asian flu (1957–1958 [12]) which caused millions of deaths worldwide, closing factories and causing a global recession. Epidemics, as such, have supported the need for automating factories and inventing ways to make machines operate more independently of humans.

Certainly, pandemics as well as wars and other conflicts, provoke socioeconomic consequences. The direct connection between disease and the First and Third Revolutions can be argued to be tenuous, as there is a much stronger link to the other conflicts that preceded them. However, it is clear that the Second Industrial Revolution was propelled by the need for improvements in public health due to diseases. In a similar way, the isolation strategy of COVID-19 throughout the world has had a great impact on the way countries operate. With the virus rapidly spreading worldwide, several countries have enforced quarantine and closed their borders, establishing rules of social distancing and self-isolation. This has forced people to find ways to work, consume, study and socialise through the internet, creating economic chaos in the outdoor market and hastily transforming our ways of thinking, acting and being.

The arrival of the Fourth Industrial Revolution has been announced before by many historians and technologists [13–15]. Yet, there was no event like the pandemic that could accelerate technological advances and immediately turn the market over. The cause of such a revolution is not the coronavirus per se; all this was expected to develop to this stage. However, the pandemic has caused an abrupt market change from physical to online, where society has had to completely reconfigure itself. The educational sector, for example, has had to rethink how to educate children and adults through dedicated technology platforms that are easily accessed from homes. The demand from businesses, now operating from homes, for easy communication, has been pushing further technological development favouring conferencing software relatively unheard of prior to the pandemic and massive 5G adoption, something that had been under question due to the use of hardware developed by the Chinese State Telecoms Company and scare stories around spying [16]. This certainly marks a revolutionary change. For this reason, now we believe we can officially declare: The Fourth Industrial Revolution has begun, and its starting point is 2020, the 'Corona Decade' (Fig. 1).

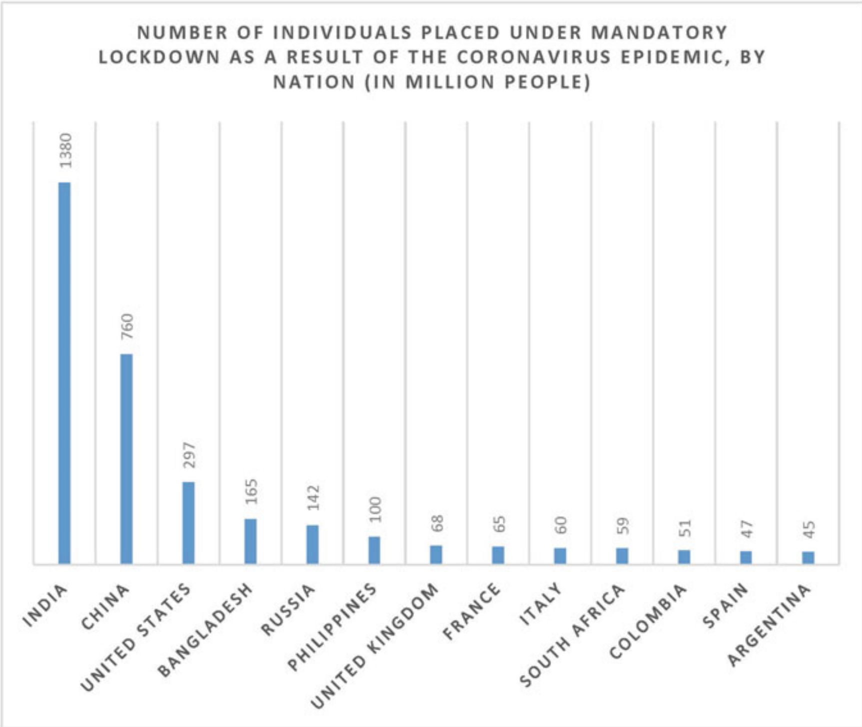


**Fig. 1** A graph that depicts the size of coronavirus lockdowns

## 3 Philosophy of a Transformative Chaos

Our society has suddenly become isolated and many have seen their jobs in danger. The solutions for those who are not key skill workers (e.g. medical or social services) seem limited to two main options: Work at home online or work for the warehouse and delivery industry. Who are the people losing their jobs? All workers who require physical structure and dealing directly with customers, which includes a great part of the arts and entertainment sector (artists, galleries, performers, etc.), the education sector, sales representatives, hospitality, the whole tourism sector including airlines and hotels, personal service workers such as decorators, plumbers, hairdressers. The list continues extensively, addressing all industry sectors [17]. If there is dependence on mobility, the job is at risk. A report from the UN estimates that up to 24.7 million jobs could be lost [18]. However, society carries on, with services and products that require to be delivered. Therefore, there will always be those who will keep old patterns alive. We are living through a dramatic reshaping of society consisting of online work and study. If drones were more ready to be utilised for delivery, human activity could be even more suppressed.

For those people forced to go the route of an online business, skills for acquiring specific tools and managing online marketing are indispensable. This has provoked new technological demands; faster connection services (leading to rapid 5G adoption), faster computers and webcams. Those items, among others, increased their market value following the crisis. As an example, the shortage of protective masks was soon followed by a shortage of webcams [19]. The education sector suddenly relies on this technology, and thus thousands of teachers around the globe will benefit from investing in new digital equipment. Yet, to compete in a saturated online market, high-quality media and internet speed are crucial, which means consuming equipment and services that are not always affordable.

The chaos opens the curtains on the 20 s decade; announcing a drastic shift in our common way of living. The steep increase in internet traffic is further proof. It is evident that this data has increased exponentially since the first quarantines. Digital streaming platforms such as Netflix and Disney Plus are limiting high definition content in Europe so that bandwidths can cope with increased demand [20, 21]. We are now noticeably more financially dependent on the internet and its digital tools. Cash is history. It holds the risk of virus contamination and, now, more complicated, physical, distribution. The total shift online has been predicted many times over but until now had been slow to come about. It has been a key strategy of capitalism: Multinational online companies such as Amazon taking over physical shops, supermarket chains improving their delivery services, online banking, and the arrival of 5G. Despite the predictions, the change hadn't quite happened, until now. The transition has taken place with no warning and all digital resilience has been suddenly lost. One example concerns the elderly population, those who did not have a connection to the online world, who still paid bills by visiting the bank and post office. By unfortunate coincidence, the elderly population seems to be the most affected by this virus. These are thousands of senior citizens who are getting excluded from the digital turn of society as they no longer comprehend how it works. In isolation, people who have ignored digital platforms such as WhatsApp and social media see little choice but to reconsider adopting new ways of communication. All of the extra expenses that can be attributed to the digital shift of home supply, compared to all jobs at risk, point to a global recession [22]. However, it goes beyond that, we are seeing a societal shift to a single economic model of online work, especially for the tertiary industry. The coronavirus situation will be a temporary one as solutions and vaccinations are brought forward, but the changes are bound to remain. Who will invest in an offline business after such an event? This virus is going to be contained or eradicated soon, however, the risk of similar threats in the future remains and this calls for more preparation globally. Whereas the digital dependence can be reversed after recovery, it is unlikely it will return to the same state it was before the pandemic (Fig. 2).

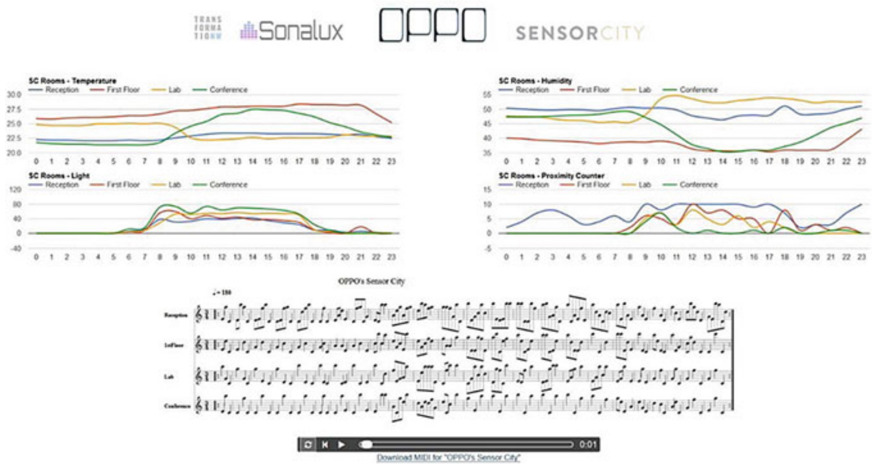


**Fig. 2** OPPO: the web-based version translating live data from four sensors in four different rooms onto a musical score

## 4 Global Cocoons and the Worldwide Transition

As many countries adopt quarantine strategies and the global society adapts to online solutions, we see a stage of change and transition. The worldwide strategy dilemma has divided the priorities between economy and health. This decision can drastically change the current economic position of all affected countries. Governments that better respond with economic tools to protect employment, income and demand, who are providing effective methods, guarantee a better economic future after the outbreak. However, prioritising the economy is not a straightforward option, especially for countries with public health systems that cannot cope with large or concentrated influxes of cases, as a weak public health system during a time of chaos can also profoundly impact the economy.

What is essential here is to include in the mitigation strategies the strengthening of the digital infrastructure. Quarantining the population means an increase in the use of digital tools, from production to consumption. Although countries have been adopting different measures, most countries in the world have encouraged remote working and the closing of schools. Financial support for online working has been provided in Italy and Japan [18]. In other cases like Greece, a proposal for developing digital skills—customer service, technical support, etc.—was considered at the onset of the pandemic but eventually not applied [23]. Nevertheless, this makes the need for training and transition more evident, moving individuals from not using or using some digital tools to becoming efficient in operating daily chores and vocational responsibilities remotely and online.

Media reports data [24] that shows a great part of the world's population has entered a lockdown state, where the tendencies are to socialise and work online. As the event prolongs for longer than a month, the likelihood of having a new structuralisation of socio-economic patterns on a global scale is high. However, it is important to consider that a restructure is not possible for all parts of the world at once. Countries or regions that lack digital infrastructure and technology have more difficulties confronting COVID-19, and as such, many countries will not participate in such a transition as described here. Yet, this event reinforces investments and developments in digital technology, which then leads to the same paradigm shift in harder to reach regions. It is important to remember that the previous industrial revolutions did not exist in all parts of the globe concurrently [25]. However, in the current scenario changes are happening in all industrialised regions through several means of communication and international relations.

We, here, take into consideration the concept of ‘revolution’ as the hasty and precipitous restructure of a society, which happens for almost urgent reasons. Countries that responded with immediate measures for encouraging online working and that already had a high-end digital structure in place are likely to be transiting towards revolution. According to the Harvard Business Review, countries on the frontline of digital business are the US, the UK and the Netherlands [26]. The list ranks countries for their digital capabilities such as banking, retailing, media and skilled freelancers. These are countries that can function through a wide range of online services and have efficient delivery services. At the bottom of the list, we see Indonesia and Russia, countries that struggle more to find digital solutions and thus will not operate similarly in this historical shift (Fig. 3).

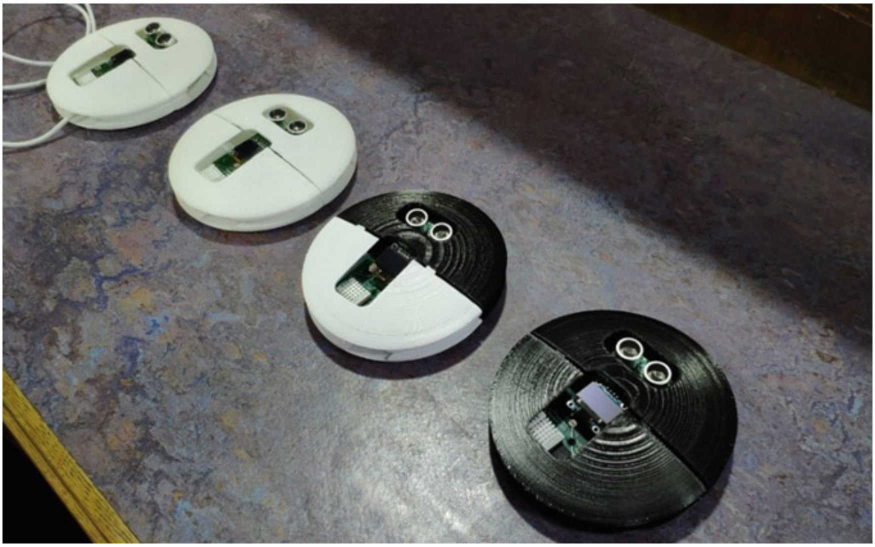

**Fig. 3** Customizable sensory devices for the OPPO system

## 5 Hyperconnectivity and Possible Futures

During this period of rapid transition brought by the Fourth Industrial Revolution, workers will become more accustomed to flexible working. Through the realisation that workers no longer need to waste time on the daily commute, and perhaps a greater appreciation of their homes, there is a high possibility of having more creative pursuits and a return to the old adage from the Second Industrial Revolution: 8 h for sleep, 8 h for work and 8 h for play. A change to the week/weekend dichotomy is another future scenario. Even prior to the house-isolation measures, services such as groceries or product deliveries were already in place throughout both the weekdays and weekends with normal working hours. However, these services have now received a significantly higher demand, consequently changing the habits of many shoppers and attracting new customers. This has substantially increased the number of people connected to the online market.

As the world is counting the weeks in the work-from-home setup, there are certain changes in human behaviour regarding work and leisure to be considered. These changes relate to aspects of flexibility, overtime, management and motivation. We are seeing that people tend to keep a more flexible and loose working schedule. This is to cope with responsibilities at home as they occur (home-schooling children, career responsibilities, household emergencies). While they may compensate with the time gained from not commuting, this, in turn, requires certain skills of self-management. This also requires a new approach to arranging meetings, making deadlines and tracking excess working times in the hierarchical levels of different professions. Online services are now becoming more frequent and accepted. As a result of the imposed quarantine measures and the new rules for supermarkets, which include long queues for grocery shopping, more consumers are registering online [27]. It is likely that after the pandemic crisis people will continue to online supermarkets for groceries. Video conferencing tools have become crucial since the beginning of quarantine and there has been a boom in previously underused platforms such as Zoom [28]. Without cinemas, restaurants, cafes and clubs for socialising, online platforms such as cloud clubbing and film/music sharing have been in higher demand [29]. Digital tools and skills are becoming critical for career development in all sectors. In the entertainment business, for instance, many artists have experimented with online performances, and funding is being offered to create computer-based experiences. Online platforms have expanded their capabilities for audience interaction and have improved features to assist digital concerts. It is possible the new decade will have an increased number of YouTubers as the profession becomes more valued and competitive. The digital culture of micro-celebrities will rise further and will be levelled with other media channels. The online shift has also increased interest in joining VR platforms to experience virtual tourism through online galleries and museums [30]. There has been a surge in connectivity as more people have joined the connected world since the start of the pandemic; we can say now we are 'hyper connected'.

There is another consideration to be made. The limitation of personal services during quarantine and the longer stays at home have an impact on domestic affairs.

**Fig. 4** These are energy data image captures that have been transformed into an interactive graphical set of spheres that follow the relevant audio levels based on the obtained data

As people settle into life at home, we see a return to old skills; craft and repair projects that have been growing dusty on shelves will suddenly look appealing once all the streaming content has been consumed. The internet is replete with sites to help us to repair and create, and older relatives might delight in the chance to demonstrate cooking, sewing or woodworking skills, for example (while possibly learning about video making themselves). In Europe, as this crisis is developing during the start of spring, many people will make attempts to grow their own food in light of the supermarket shortages and inevitable supply chain disruption. This has also coincided with parents being forced to educate their children. Parents are now looking for easy, home-based activities, which will result in a generation of people with traditional skills that were almost lost to the generations before them (Fig. 4).

## 6 The Architectural Practice

As previously described, COVID-19 has a huge influence on nearly every business on the planet. The architectural field has been no exception. As soon as the epidemic struck, initiatives were either cancelled or postponed until a later date. Every significant epidemic throughout history has resulted in a large-scale architectural shift. While architectural projects may have been cancelled in the early months of the pandemic, they could be crucial in the long run in combating COVID-19.

After contact, viruses and illnesses have been shown to survive and grow on a variety of surfaces across an interior setting. Many organizations are adding temporary "contact-less" features throughout their offices and services, so many of these features are likely to become commonplace in the future. Ventilation systems that remove potentially polluted air, automated doors, and elevator buttons linked to smartphones, voice-controlled lighting, and a slew of other contactless technologies might become the norm in interior areas across the country. Those who are reluctant to change and regard these new trends as transient may be left behind, while those who comprehend the changes and their influence on society drive architecture ahead.

## 7 The Industry 4.0 and Data

Together with COVID-19, the architectural field was already pushing its boundaries with technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT). Considering the effect of the "contact-less" safety measures against the coronavirus within the AEC industry, there is an opportunity to apply AI and data-driven systems in order to boost the potential of computational design. This is particularly effective when it comes to monitoring the in-use energy performance of an edifice and computers play a crucial role in a better understanding of the energy levels of a building after its construction.

Prior to the use of computers and software for design, the practice of architecture developed by depending on experienced architects' design judgments and assumptions. Architects create and accumulate building design knowledge via their work. Their knowledge progressively transforms into a personal intuitive design technique. Most other architects are unaware of this particular intuition since the gathered data is kept in their heads. Eventually, the building and its package drawings are all that is left as tangible evidence of that knowledge.

The use of computers has sped up the process of creating and documenting data in architecture. Around the mid-1960s, computer-aided design (CAD) became popular, making it easier to store both graphical and non-graphical project data. Architects were able to optimize their productivity by switching from manual drafting to a more integrated and automated generation of package drawings in the late 1990s, thanks to technological breakthroughs in software programs brought on by the Third Industrial Revolution. Traditional design procedures were also automated, allowing architects to organize their workflow with other engineers around a single basic digital model. This fundamental model serves as a primary structure for collecting and arranging the project's data by combining the varied perspectives of all project partners. This is also referred to as Building Information Modelling (BIM).

When examining how organizations in the AEC industry handle data, it becomes evident that companies now have digital design tools that create and document information in a complete and interoperable manner while constructing a structure, thanks to advances in computing technology. The essential aspect of this improvement is that construction knowledge can now be transferred without relying entirely on personal experience. BIM has been evolving since the 1970s and it is currently becoming a prerequisite for the delivery of public buildings in a number of countries, including the United Kingdom, and architects are using it for private projects as well.

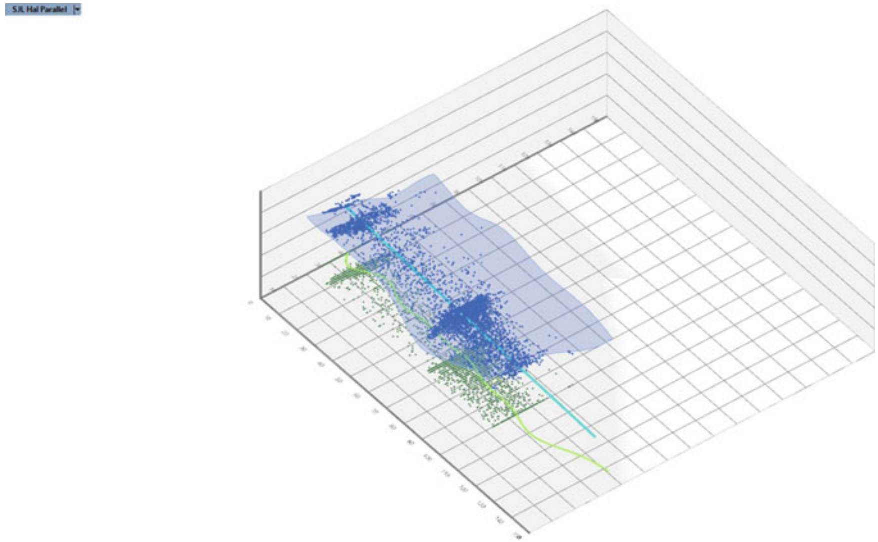

**Fig. 5** A 3D machine learning graph of energy data from Sydney Jones' library reception area

Companies who are first in line to take advantage of Industry 4.0 and the Internet of Things' ability to capture in-use performance data will expand even faster. It is critical to design policies that link performance analytics apps to benefits, duties, and liabilities in this case. Aside from rules relating to industry interoperability, there is also a demand for targets for designing and managing buildings using in-use energy data. There is an opportunity here to address the UN's position in the building industry in terms of its sustainability goals. With live energy data, aside from the automated HVAC system, there is the possibility of more creatively conveying the building's energy levels. Such an initiative is described in the following case study (Fig. 5).

## 8 Ad-Hoc Energy Gathering System

The position of the UN's goals toward a brighter future, in addition to fighting climate change, is also to make cities and communities more sustainable. Examining the energy levels of a structure is a step in achieving that aim. The UK's Secretary of State for Business, Energy and Industrial Strategy has also said that the Net Zero Strategy would be used to achieve that aim. They indicate in their white paper that they will seek suggestions on regulatory measures to increase building energy efficiency. Here, the flow of project data is an essential part of this efficiency. Certain protocols (IFC, COBie) have been established in the AEC sector to simplify the flow of project information among the many collaboration stakeholders. These transfer procedures appear to place a strong emphasis on the stages that span conception through delivery. However, there is no feedback loop in place once the project is completed to optimise efficiency or monitor changes in usage. Projects will be established and managed more effectively with the availability of performance data combined with the goals of regulating bodies and AEC industry data validation in the design process. This is when design computerization comes in handy. Having real-time updates of a building's physical properties, in addition to its fixed digital representation, will change the way architects develop and deliver their projects. This will be a BIM-driven transition.

As a case study, a system was designed to enable the creative and practical collecting and sharing of energy data while recognising how the Internet of Things technology includes changing real things into smart devices. The technology, which is part of a project called Oscillating Personal Places Occurrences or OPPO, uses an audio-visual medium to transform raw numerical data into valuable information. The goal here has been to improve our understanding of a building's energy behaviour by using working tools from both the fields of architecture and music. While we humans are visual beings, our cognitive ability to hear is greater than that of sight. Our hearing sense is not only the quickest, but it also has the ability to calculate minute variations in sound strength. With this in mind, and because communication is so important when it comes to transmitting information, the project examined the visual and audible translation of numerical energy data.

The OPPO project entailed the development of sensor boxes and an Internet of Things system that can collect data (light, temperature, humidity, and proximity) from a building and convert it to another, editable format. It was installed from February 2020 to July 2021 at two libraries simultaneously at the University of Liverpool and investigated how a large collection of energy data may be used in the predictive modelling process using artificial intelligence techniques. Specifically, the *LunchBox* software plugin was used to employ a method known as regression analysis. This method of prediction is widely utilised, and it has a lot in common with machine learning. The approach, based on Adrien-Marie Legendre's least squares method, displays a curve that best fits a set of data points, such as a set of energy values, on a Cartesian system by minimizing the sum of the offset points from the projected curve. By extending the curve, which displays the relationship among specific data points, it is possible to get a sense of the future relationship of the points that are still to be generated.

The project used computation to develop novel methods for gathering and processing real-time energy data. The speed with which these complex data sets were acquired was very fast and large databases formed quickly. These databases will be impossible to manage with standard data processing software. However, these vast amounts of data could be used to solve a number of previously unsolvable challenges in the industry. Big Data, or large, complex data sets, could help the architectural profession with information visibility and process automation. When Industry 4.0 and additional BIM levels are implemented in small increments, new working methodologies and rules for accessing, validating and processing open data in a standard format will emerge.

## 9 Conclusion

Through this paper, we have proposed the COVID-19 event as a historical mark. One that is reshaping society by motivating a number of industrial sectors to move to fully online operations and changing the face of work for millions. We have compared this to previous industrial revolutions, elevating the current crisis to a catalyst for a fourth revolutionary phenomenon; an event that has the potential to characterise the whole next decade. The current state of quarantine of several countries has been seen as a transitional phase which can have profound socio-economic consequences and a large impact on global society. Estimated changes in society have been expressed in possible futures, as the digital market and technology continue to be impacted by the pandemic. The decade of the 2020s will greatly differ in many aspects from the previous two, spawning a whole new cultural generation that functions through live virtual interaction. As an example of such interaction, it was demonstrated how in the architectural practice there is an increasing interest and benefit for having a system that can keep a virtual record of the building information gathered as well as display it remotely. As a result, rather than a segmented survey, a broader perspective is possible. The immersive outputs make it easier to interact with data using various representation approaches. The case study's ambition has been to show a way of adding another layer of data to cross-reference a physical entity rather than creating a model capable of precisely predicting outcomes. Moreover, data that are collected using open-source sensor technology such as OPPO, can be subsequently translated using design tools for use in a more creative visual and audio communication context.

## 10 Discussion

Besides the architectural case study, the aspect of harvesting data and storing them holds a lot of implications. It can have benefits in promoting a more efficient way of understanding our world but it can also become a tool used for partial purposes. This delicate balance between the two sides became clear when measures against the coronavirus were created based on personal data. Hence, the steps that governing bodies consider taking to tackle this pandemic can also endanger public privacy and new concerns will continue to emerge as governments seek to prevent future pandemics. However, there is the potential for research into skills acquisition and actions towards self-sufficiency during this time, which can be complemented by research into a phase in experiments in governance and social welfare models.

**Acknowledgements** This article takes the view of technologists members of the Transformation North West cohort working with the industry in the UK'S North West. We acknowledge the sponsorship of the AHRC and NWCDTP as a contribution to our doctoral research.

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# Quasi-Decentralized Cyber-Physical Fabrication Systems—A Practical Overview

**Ilija Vukorep and Anatolii Kotov**

**Abstract** Building an effective cyber-physical system is difficult due to the overall complexity of technologies on their own, challenges with the interaction between all parts of workflow and applicability issues. This makes the real-world application of complex cyber-physical systems only available to the big industry parties or high-tech startups, leaving small and medium-sized businesses behind. Therefore, the democratization of such applications is a reasonable goal to achieve. Cyber-physical systems of this kind are in the experimental stages and incorporate robotics, IoT, materials science, visual and 3D-scanning techniques, and machine learning (ML) tools all under the heading of Industry 4.0. This paper covers specific practical approaches in several application fields using robotics and IoT. We use custom-built hardware and software setups together with standard frameworks and the MQTT protocol for different applications. Due to the practice-driven approach, the paper will illustrate both positive and negative effects. We describe the use of our systems in several case studies: Multi-layer automated robotic concrete spraying using ML, IoT spatial awareness via sensors (such as Lidar, Kinect), robotic multi-axis milling and quasi-autonomous robot movements. A unifying issue is a decentralized approach of modular IoT elements that we grouped to achieve specific tasks. The paper illustrates how these elements exchange data and communicate, and all services are controlled on each computer instances, connected to an IoT network to ensure a high level of system stability.

**Keywords** Cyber-physical system · Digital fabrication · Industry 4.0 · Decentralized digital services

**United Nations' Sustainable Development Goals** 9. Industry Innovation and Infrastructure · 12. Responsible Consumption and Production

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_12

## 1 Introduction

Our paper discusses practical approaches to robotics and Internet of Things (IoT) in several application fields. In order to increase the reusability of such cyber-physical setups, a combination of custom hardware and software, as well as standard frameworks and protocols are used for different applications. We implement principles of Industry 4.0 paradigm by using several architecture defining principles such as microservices, applied robotics and ML. There are several examples of similar setups of using industry 4.0 principles in robotic fabrication [1, 2]. Micro-services allow us to isolate key services and machines, enabling us to create decentralized, modular IoT elements that can be grouped together to achieve specific tasks. Furthermore, microservices are used within the software and hardware domains, allowing for better communication and data exchange between different segments. This further enhances the integration of our cyber-physical systems, allowing us to achieve greater levels of automation and efficiency. This concept embodies one of industry 4.0's main strengths, which is the democratization of complex tools.

We are discussing some typical services in detail used in our applications and providing links to some own developed libraries and components on GitLab [3]. Our system is demonstrated in several case studies: Multi-layer automated robotic concrete spraying using machine Learning (ML), IoT, spatial awareness using sensors (such as LiDAR, Kinect), robotic multi-axis milling, and in teaching scenarios. A common theme is a decentralized approach of modular IoT elements that we group to achieve specific tasks. One of the tasks is the concrete spraying case study that is aiming to reduce the weight of produced elements and increase the potential design space through its capability to produce free-form shaped parts. Its production incorporates a wide range of machine control, space observation and data processing segments. The paper will describe how these segments exchange data and communicate with each other. In the quasi-autonomous case study section, we will cover the interaction of a pair of robots, where one robot is performing target action, while the second is following the first one via dynamic observation. Micro-services are used both in a software and hardware sense—both key services and machines are isolated. We start by defining the problem statement, which discusses the use of Robot Operating System (ROS), a leading system for developing cyber-physical systems. The following chapter is about categorizing various types of cyber-physical systems in terms of their internal organization and communication of processes.

## 2 Problem Statement

There are several systems that can help in developing automatized and robotic applications. One of the most popular and robust is ROS—robot operating system, a framework for various robots founded 2007 at Stanford University. It is suitable for heterogeneous clusters with a highly developed messaging system with low latency. Its publish-subscription communication management is even near real-time in the new ROS 2 version. Furthermore, its services run decentralized, so demanding processes can execute remotely. ROS' lively community is providing libraries for all kinds of hardware. Communication with external non-ROS clients is possible (Websockets, mqtt). The ROS-industrial is an extension of ROS and provides open source industrial general and vendor specific libraries in an industrial context. The drawback of such a powerful system is that the implementation can be very complex. In a typical academic scenario, where experiments are performed with light and atypical configurations, setting up ROS with its enormous overhead can be extremely time-consuming. Although ROS covers a big range of hardware and allows implementation of one's own libraries, installing unsupported sensors and actuators inside of ROS proved to be unrealistic in our context of projects.

The setup of a construction-related robotic system requires the creation of several services that can work robustly and independently and have a clear way of interacting. As most robotic setups are different, those services should operate in different constellations. The software can be written in different languages, and the services can run on completely different hardware. With this, to distribute the development of single parts to a wider range of people is easily possible, in our case to students and academic researchers. When working with parametric geometry, such as connecting Rhino 3D Grasshopper results to a robotic setup with many sensory inputs and complex actuator control, this flexibility is especially important. Another important feature is also the ability to work remotely, via VPN, when needed, with visual feedback.

## 3 State-of-the-Art

In the architectural and construction context, most academic experimental robotic setups are very narrowly and pragmatically tailored to solve some specific scientific problem. The majority of related research papers do not detail their technical setup, but a few of them mention their software equipment and this has been analyzed. Generally, we can divide architecture- and construction-oriented robotic setups into several groups:

1. **ROS as a central unit**. ROS is often used for its integrated and decentralized service platform and communication protocol. In [4] research, a collaborative human–robot construction system is developed around a ROS computational core and its ability to communicate with virtual reality in Unity, sensor data, and the robot. In the work of [5], ROS is exchanging data with MATLAB Robotics System Toolbox for path creation. In [6] ROS is used together with MoveIt for trajectory planning of the robots. In [7] Choreo is used along with ROS-industry and Move-it to plan motion and choreography.
2. **ROS as one of several parallel services**. The work [8] involves modeling in Rhino, kinematic modeling in the COMPAS FAB package, and ROS as a robot controller with communication via Roslibpy. This library was developed

at the ETH Gramazio. Kohler and is based on WebSockets and bridges between services. For [9] GH/Lunchbox ML services, as well as serialized data in JSON format, are implemented.

3. **Decentralized system with heterogeneous communication**. The work [10] uses individual services for scanning (python), ML analysis (Tensorflow, python), modelling (GH/Rhino) and path planning (RoboDK) without a specific communication protocol. In this study, [11] Rhino for modelling, GH to simulate robotic processes, Unity for VR-visualization, DynamoDB at Amazon Web Services (AWS) for data handling and data storage are used and heterogeneously connected.
4. **Decentralized system with specific server communication**. Described in [12] is a robot setup controlled by a self-written python server (XML, TCP/IP Ethernet) that transmits data between services (clients: Python algorithms, Rhino visualization, camera, and robot). In [13] the communication is arranged through Java in Processing and an UDP protocol exchanging data with the Scorpion plugin in Rhino/GH for path creation and transmission to the robot.

These categories each have their own advantages and impact on scalability, modularity, and reusability. A decentralized system with a Message Queuing Telemetry Transport (MQTT) protocol is described in this article based on experiences gained in a variety of scenarios. The protocol serves as a basis for IoT development, as all clients and services in an IoT system communicate via the web. These services will be described in more detail within the following chapters.

## 4 Components/Services

Our system uses a modular microservices architecture. Most commonly, this term describes the organization of software complexes and information systems. Contrary to a monolithic approach where all the code is merged together, the microservices concept divides a program into several independent components (services) that can run on multiple/divided platforms and have a unified communication vocabulary. If one subsystem fails, the whole system will be less likely to crash, what improves stability. Another advantage is a possible update/change of individual components inside the system without having to rebuild the entire system. There are currently many distributed online systems with millions of users using it. As a basis for further development, this approach was chosen due to the need for stability, modularity (reusability), and scalability.

## 4.1 MQTT Broker—Infrastructure Server

The core element of this decentralized cyber-physical system is the IoT data exchange protocol (MQTT). In contrast to *XML* over *TCP/IP*, *Websockets*, *UDP* or other previously mentioned communication protocols, is that it can deliver messages with requested quality of service (QoS). This includes fire and forget, at least once and exactly once. QoS can help when connections are unstable or we have critical command execution procedures (as running a robot). It's supplying sufficient speed and it's lightweight. The principle of subscription and publishing over topics is similar to ROS' handling messages. The issues of security around MQTT are not explicitly handled in this article and need special care by using client identification rules. The broker runs in the background inside a network. In our settings, we ran a *Mosquitto* broker (mosquitto.org) on *Raspberry* Pi 4 that automatically activates the service on booting. It can run on any OS system with a known IP address to the clients. For testing purposes, we provide a self-developed MQTT server on localhost running inside GH/Rhino as a component. Furthermore, we wrote a MQTT subscription and publication component for GH/Rhino [3].

## 4.2 Dashboard

To manage all processes, we could theoretically use any MQTT-browser like MQTT-lens [14] but this will not give us a good overall overview of incoming and outgoing information. For visualization and administration of all processes, a central dashboard is necessary. Fig. 1 is showing an example of such a dashboard with several pages. The best method of a dashboard that is compatible for diverse use cases is to keep it growing as services are being added. This means that services that are not used are automatically disabled in some applications. This can be done by internal checking if services are available (online).

Key features of a dashboard are:

- Robot control, with some predefined robot positions or movements, manually loading robot scripts or others,
- System observation, key vital data of robot TCP position, availability of hardware and program components,
- Visual observation from connected cameras,
- Control of additional machines as scanners, grippers,
- Database connection with data presentation and editing options.

Our dashboard is built with *Python* and *Flask* backend programming framework that can easily be scaled as it uses templates and sophisticated data interaction. These packages can run on Raspberry Pi 4 or any other computer (also together with the broker) in the network and can be reached at the local network.

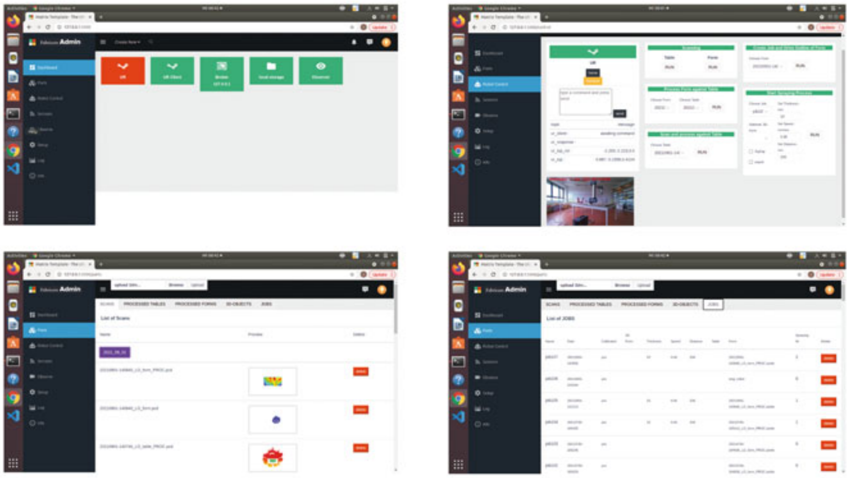

**Fig. 1** Dashboard pages: status, robot control, scan data view and info page

## 4.3 Robot—IoT Interface

One central part of the IoT robotic setup is the connection of the robot to the rest of the system. For this connection, we use an interface service that is transferring incoming data directly to the robot over an Ethernet/Lan connection and vice versa, publishing information like robots joint and TCP positions data. As this interface is embedded in a wireless network to other clients, huge flexibility of robotic control is provided, which means we can control the robot without being directly connected to it.

As every robotic company has got its own I/O solution, this interface has to be tailored individually to robotic families. We tested this setup with *Universal Robots* running the interface on a Raspberry Pi 4 and written in Python. All outgoing information about the robot is read by the IO Modbus protocol of the UR robots and broadcasted over MQTT.

Additional machines connected to the robot are also accessible through this interface as part of the script that is transferred to the robot. This transfer incorporates also some extra features such as comparing the robot position with the target position or relative and absolute movements and some special positions, like home, self-test or tool changing position.

## 4.4 Data Management

Data management is not organized as a single service but can be found in all other services and processes. In our cyber-physical arrangements, we have four data streams that handles: Configuration files of the setup, incoming (i.e. sensor) data, processed data and logging data. Configuration files are actual settings (home position, special robotic positions, broker addresses, storage credential data) stored as JSON-files. Besides this, we also have environment and tool data stored as Rhino 3 dm-files. Both types are inside the folder structure of the *dashboard*.

Incoming data are files made by sensors and are mostly of high volume. Those are saved in a project folder with a time-stamp and additionally automatically processed or triggered by incoming commands. Those processed files are then saved in additional folders like thumb views of scanning or images, automatically generated scripts or other project specific data. All processed data that are part of closed procedure, are saved in the job-folder. This decentralized database-free approach is working well in closed networks but there are security issues when we expose them in open networks. For this usually some professional data handling services can be used like AWS S3 services that is also handling user-right-management and some data processing through APIs. In our setup we used a *Resilio* Sync—*BitTorrent* protocol for data synchronization as this proved to be fast.

Logging is an important step toward error tracking and statistical analysis. Some of the services in our cyber-physical system are logging their processes. Advisable would be a central logging device, even organized as an own service, that is collecting logging data from other services with the capability of analytic display in dashboard or other viewer.

## 4.5 Vision

Cameras can be used for tracking movement, security control, position diagnosis or simple documentation purposes. The application will define if camera stream will be recorded or not, if the processed image will be directly processed or high computation is necessary (i.e. OpenCV postprocessing). Any stream data client can be connected to the network and then retrieved from the dashboard. Based on streamed data it's possible to detect movement, risk situations (and use MQTT for signaling) or incorporate customized recognition of elements. In our case we have used the camera for finding edges of the scanning area. For simple low resolution processing, a camera can be connected to a Raspberry Pi 4, which can run OpenCV4, and transfer the data over Wi-Fi. For higher resolution data streams an Ethernet connection is necessary. Remote control of the system is also facilitated by vision.

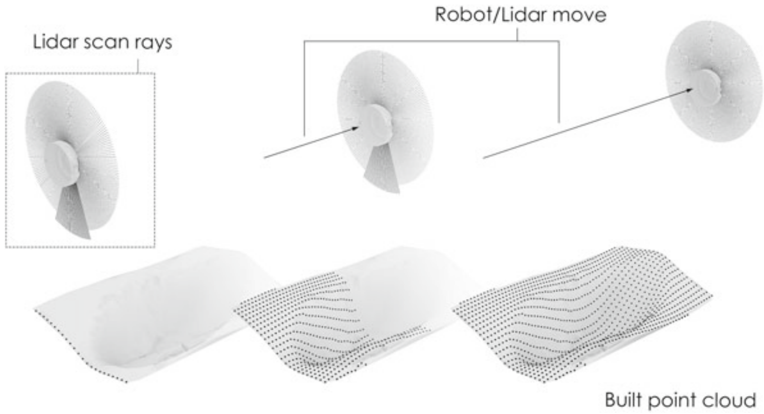


**Fig. 2** Illustration of the scanner movement over the observed object

## *4.6 Sensing*

The complexity of the task and models meant that we had to use different scanning systems in our project. We did tests with *Kinect*, *azure Kinect DK* and *RPLidar* scanners. All three have different capacities and options of sensing the environment.

### 4.6.1 Rotation Lidar Scanner

Rotation lidar scanner like is measuring distance to an object at some specified angle. As it rotates, it can only measure in slices, meaning if we want to measure distances in all 3 axes, the lidar scanner has to move. In combination with a precise movement of a robot we can have a very effective scanner that can, in some cases, make better scans of areas that are obscured, deep objects or with cantilevers (Fig. 2). We connected our RPLidar A2M8 scanner to a Raspberry Pi 4. Together with the UR-robot, both were triggered by an MQTT command [3]. Scanning results grouped with the coordinates of the scanner positions were saved in the incoming data folder and automatically further processed. This data processing usually depends on the application and in our case it consisted of deleting the unnecessary data and transforming the rest into a 3D point cloud.

### 4.6.2 Azure Kinect SDK Scanner

For certain tasks, such as real-time scanning for object presence and control, a moving lidar is not the best solution. Therefore, a depth camera coupled with a RGB-camera seemed like a good option [3]. We chose an *Azure Kinect SDK* scanner that is connected to a computer with the *Ubuntu OS*. Even though the hardware and software requirements are high, the scanning process worked well because we needed a high level of precision without a high resolution. As the RGB-stream can be read separately, we use the camera also for documentation purposes. Several MQTT commands are running the scanner: RGB-single shot, RGB-stream, hi-resolution scan, low-resolution scan. The results are stored in the incoming data folder and are automatically processed like creating thumb views of the point clouds or detecting objects.

In our case we mounted the scanner above the active zone of the robot, see Fig. 5. In the usage examples described later, the scanner serves for sensing the actual state of robot production. For this, every process step is scanned and the object scan are compared after the process step is finished. Before the process starts, a calibration scan is executed that marks the clean table and initializes the process.

### *4.7 Point Cloud Processing Service*

When scan data is stored in the incoming folder, several application dependent processing steps are necessary. Usually object have to be detected from out of a messy point cloud and for this the following functions are executed: (1) the empty table scan detects a plane, (2) the object scan is been cleaned against this plane, (3) the result is clustered so some flying points eliminated, (4) the outline of the object is found, that all further scans can use for the eliminating unnecessary point data. Although this service depends on the application we wanted to develop, it as a module that can be reused in other applications. The algorithms are triggered by MQTT-commands from the dashboard. Most processing work is done in the background while the dashboard lists the objects in the browser views. Fig. 3 shows a 3D scanned mould after the point cloud cleaning procedures.

### *4.8 Grasshopper Components*

Since the wide adoption and the abilities of Rhino/Grasshopper, it was essential to create viable MQTT components for Grasshopper. During different development phases we also used GH/Python connected modules, but that was not offering enough scalability, since one has to install and configure a Python environment for any new machine. GH components are simpler to use and also better in terms of response of the GUI since they're natively compiled from C# and Grasshopper is built on.NET technology. The components for Rhino 6 and 7 can be downloaded from GitLab [3].

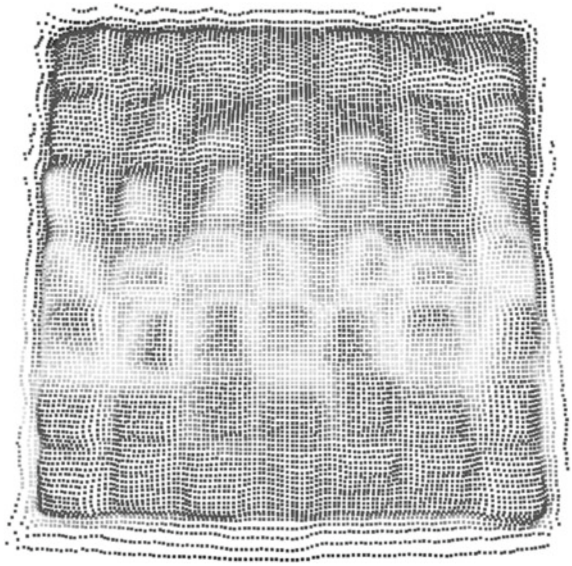

**Fig. 3** Mold 3d scan example automatically subtracted from the surrounding environment

## *4.9 Path Planning Service*

The goal of the path planning service is to provide a viable adaptive trajectory over a given surface keeping in mind execution of additional tasks. Those tasks are the execution of actions or activating hardware connected to the robot depending on path and/or surface properties. The path planning are then combined with action augmentation. This means, in certain positions or areas robot activates connected hardware (e.g. use gripper or run the concrete pump).

A naive path planning approach can be defined as a *zig-zag pattern* based on a given shape (Fig. 4). However, such an approach is ignoring the curvature of the target surface. In this case it is not adaptive, and this can cause problems with complex shapes and where actions require precision. We calculate simple patterns based on the previously mentioned outline form without any usage of additional 3D programs.

An alternative approach would be the use of ML methods with the aim to be adaptive to any form and be compatible with imperfections of the scanned object. We use a *Multi-Objective Optimization (MOO)* strategy in conjunction with other ML methods. These methods are proven to be useful as one of the tools in architectural production [14]. However, to apply those methods, the transformation of several stages of data is necessary. The path planning between different zones can be also formulated with the *Travel Salesman Problem* (TCP), which enables us to find the optimal path. To solve it, we're using internal Grasshopper components with custom Python processing. Thus, we're solving the problem of uniform distribution of the points over the given surface with desired in-between distance (a derivative of action radius and distance between TCP and surface). As a result, a waypoint graph with equal edge length based on the surface of any curvature is generated. Using the

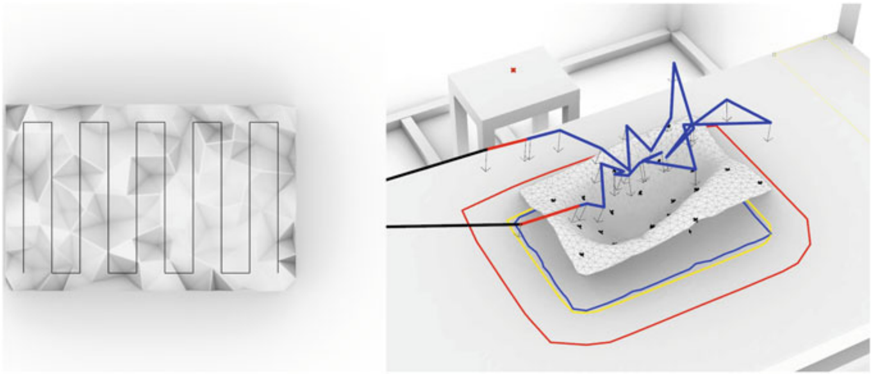

**Fig. 4** Left: naive zigzag approach, right: ML approach with the determination of the working area for the path planning algorithm as well as for dynamic hardware control settings (e.g., we stop air & concrete pumps while the robot is travelling outside/between red and blue line, and enable it over islands/inside blue line)

previously generated graph and applying TCP guided local search algorithm, we're able to find the optimal path. In our examples we are using different script generation software like RoboDK (robodk.com) and Robots (github.com/visose/Robots) running in Rhino/GH instances. Those are activated by MQTT commands that sends the number of the job so the identification of the files in the job folder is possible.

To ensure that the robot movement is safe, the path is being simulated in a duplicated virtual environment where the virtual robot and all the robotic movements are synchronously simulated prior to the machine execution. Thus, we're testing that the given path can be executed, that all points can be reached, that there are no singularities and collisions (and signaling an error over MQTT). As a final part of the program, the resulting script is being augmented according to the target setting for acceleration and speed of the robot's linear and joint movements' settings.

### 4.9.1 Digital Twin

During the implementation of certain use strategies we found it very useful to implement a digital twin of the URs that we use in the lab. This can help us to prevent singularities or collisions with itself, other robots or the environment. The difference between a digital twin and a simulation is that it simulates the setup in real time and with all possible MQTT inputs that is streamed over the *Robot—IoT interface*. Each simulation is using individual UR calibration files, so we can be sure that it's 1:1 to the real setup. The other benefit of using digital twins is the fact that one can develop programs for robots without the physical availability of the systems (e.g. develop robot control system not from the robot lab, but from home office). Later, the algorithms and models tested on digital twins can be propagated onto real hardware. For implementation we are using Python for MQTT-side communication and control, sharing part of the codebase with a *Robot—IoT interface* and RoboDK, all running on a windows machine inside a Rhino/GH instance. The limitations lie in limited sensor (vision and scanning) data or the simulated production process that can be complex.

# 5 Applications

## *5.1 Adaptive Robotic Concrete Spraying*

Concrete spraying is one of the promising technologies that aim to reduce the weight of produced elements and increase the possible design space through its feasibility in producing free-form shaped parts. Even though thin-formed concrete shells production is efficient for many situations, a variable thickness would increase applications. First situation is resulting from the inconsistent process of spraying. It often suffers from an interruption in concrete feeding that the pump is pushing through the tube. As these interruptions are happening during the robot movement, the applied material unintentionally varies in thickness. The second situation comes from the structural properties of the element that sometimes demands to have ticker or slimmer areas depending on its structural needs.

Using ML methods this system offers different spraying strategies: Using target thickness or matching the target form. The spraying is done automatically using 3d scanning and adaptive robot path planning (Fig. 5). The software subsystem consists of several parts:

– Point-cloud scanning of mould and scanning the processing phases,
– Form comparison/matching—comparison of the given form to target goals,
– Robot path planning component—optimal robot spraying trajectory,
– Robot—IoT interface for execution of desired spraying path, controlling pump and air valve.

While there may be simple forms, the high curvature forms' surfaces present a challenge. This requires a complex path plan strategy as the mechanical movements of the robot should not collide with the mold during the spraying process as well as to follow the goal parameters of the target concrete shape. The outcome of the research can be found [15].

## *5.2 6-Axis Milling*

Traditional CNC-milling is usually limited to milling in 3 axes. However, attaching a milling machine to a 6 axis robot arm allows to achieve much more versatile milling.

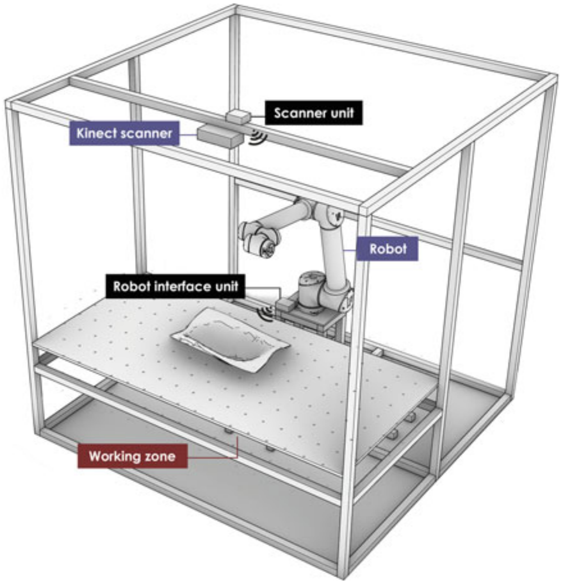


**Fig. 5** Hardware and software elements of a cyber-physical concrete spraying system

One of the key abilities is so-called "undercutting", the movement when a robot drill goes under an already existing form without destroying it (Fig. 6).

In our setup the robot was controlled via a Raspberry Pi with our software. The most challenging part of this application was the software that forms the movement trajectories in 6 axis movements, to check if the form is feasible to milling and the robot arm and milling drill will not collide with the milled model itself. Furthermore, there are also issues of visibility of milling paths on the target surface in case of sophisticated target form. Despite the proof-of-work state, developing a full-scale application seems challenging due to the complexity of robot path planning and challenges with fine milling of complex curvatures.

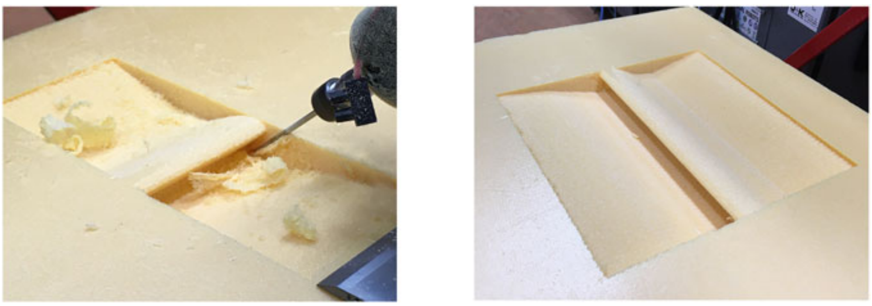

**Fig. 6** Left: undercutting maneuver, right: resulting mold

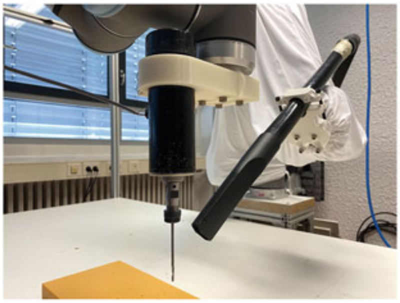
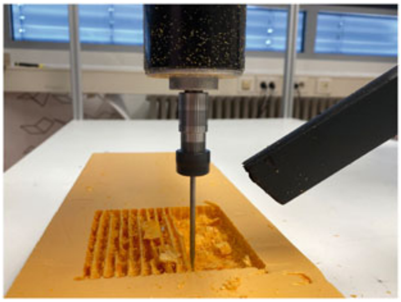

**Fig. 7** Left: system setup, right: milling-following-vacuuming

### *5.3 Milling with Real-Time Relative Robot Movements*

Milling produces a lot of dust, which is a problem. In this instance, we are solving this with a robotic IoT toolset. Next to a milling instrument attached to one UR, we added another actor; a new UR with the vacuum nozzle that is designed to follow the milling TCP of the first UR robot to vacuum all dust generated during the milling process.

Hardware setup consists of UR robots each connected with Raspberries. During the implementation of this solution we found the need to create the 1:1 digital twin of the acting robots in the environment due to the fact that it was more convenient to debug controlling algorithms in a digital way. UR1 is milling, while UR2 is following UR1 TCP via constant reading real-time position and axis data (Fig. 7). Using this data UR2 is correcting its position.

### *5.4 Teaching*

Teaching digital design methods in universities often involves the use of robots. The robots are usually housed in cages and separated from the workshop area to minimize injury risks. Several groups of students can work with the robot and develop experimental setups. We found that the possibility to wireless control the robot over MQTT can help in the workflow as there is no need to always re-switch the cable to the robot control unit. Still, as everybody can control the robot from their computer and if the right MQTT topic name and the broker's address is known, this can increase the risk of uncontrolled sending commands to the robot. This type of dangerous interference can be reduced with strict rules in robotic workshops (time-slots for groups) and vision-based recognition to signal, when the robot area is free of people.

## 6 Results and Future Work

In this paper we described a decentralized cyber-physical setup based on services that can be easily reused for various applications. As the main communication protocol is MQTT with good remote capabilities it can serve as a classical IoT example. Due to security and latency issues, the described setup has still no direct industrial potential but as the system is modular, elements can be evolved towards professional use cases. It is perfect for academic workshops where a lot of task-driven pragmatic and quick development is possible.

All presented services can be improved, especially where real-time is necessary (i.e. controlling safety measures is high risk environments). We noticed 300–500 ms latency when controlling the robot with a gamepad or in the milling-following-vacuuming application example. Also the data management can incorporate industry-grade data handling services such as AWS S3 services, Azure or Google Cloud to avoid exposure of data with a safe user-management. Logging can be incorporated as a single central service together with a good analytic visualization. This setup was tested only with the UR robot family. The interaction with other robots should be further developed and tested. Some of the libraries and GH components are publicly available at GitLab [3].

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# Latent Design Spaces: Interconnected Deep Learning Models for Expanding the Architectural Search Space

**Daniel Bolojan, Shermeen Yousif, and Emmanouil Vermisso**

**Abstract** This work proposes an adoption of Artificial Intelligence (AI)-assisted workflow for architectural design, to enable the interrogation of possibilities which may otherwise remain latent. The proposed design methodology hinges on the "systems theory" consideration of architectural design, expressed in Christopher Alexander's "systems generating systems", offering an alternative to the reductionist and complexity-lacking structure of design processes (Alexander 1968). This logic is pursued through the integration of DL models into an "open-ended" workflow of interconnected Deep Learning strategies (DL) and other computational tools, rather than treating it as a closed "input–output" cycle (single DL model). While a closed cycle risks flattening architectural layers, ending up with a reductionist encoding of design intentions, an open-ended workflow can inquire into an expanded design search space and augment creative decision making. This way, chained model strategies can simultaneously address design intentionality within discrete architectural layers (i.e. organization, composition, structure).This system enables three distinct modes of collaboration: *human–human, human–AI,* and *AI–AI*. Understanding the contribution of human and machine agents within the workflow offers a re-evaluation of designers' processes. The proposed nested workflow reflects the transition from 'expert systems', which rely on hard-coded rules, to 'learning systems', which are inspired by the human brain (DL) (Hassabis 2018). This allows architects to approach design problems which are not fully defined (Rossi 2019) and helps avoid over-constraining the search in creative domains like architecture. Furthermore, the design investigation is strengthened by accessing a search space that is otherwise beyond the designer's reach towards an expanded design creativity.

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_13

**Keywords** Computational creativity · Deep learning · Human–machine collaboration · Architectural design space · Human–machine collaboration · Augmented intelligence

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote sustainable industrialization and foster innovation · 11. Make cities inclusive, safe, resilient and sustainable

## 1 Introduction

### *1.1 Generative Design Systems*

The 4th industrial revolution, or "4IR" [4] is projected to influence a wide range of white-collar jobs in contrast to prior industrial paradigm shifts in history, which directly impacted the blue-collar workforce [5]. This disruption manifests through introducing new problem-solving approaches using, for example, Artificial Intelligence (AI). The design and realization of buildings during the twenty-first century is increasingly informed by computational tools which enhance performance and enable the emergence of a new kind of aesthetics. Data-driven design can address more criteria than before, breaking down levels of complexity which were difficult or impossible through analogue processes alone. Taking advantage of large amounts of available data and corresponding algorithms like Artificial Neural Networks (ANNs), designers can access additional layers of information, which can potentially augment their design thinking. The adoption of AI-assisted working protocols in the architectural domain can enable the interrogation of otherwise latent possibilities. These protocols complement traditional rule-based "expert systems" which use hard-coded rules for problem-solving (input + rules → results), with learning systems (i.e., deep learning models) which learn by example and can generate rules from the ground up (supervised: input + results → rules; unsupervised: input → rules). Instead of depending on pre-programmed answers, learning systems develop solutions from first principles. ANNs are examples of learning systems, inspired by the structure and function of the human brain, as well as the way humans acquire specific types of information. The capabilities of learning systems to generate creative outputs can be attributed to their non-linear and unknown synthesis, and lack of rule determination in the learning process [6]. Expert systems such as algorithmic and parametric models involve rule-based and/or performance-driven algorithms that evolve design as a product of a parametric exploration, with specific parameters and constraints, often to satisfy a set of objective functions [7]. Such deterministic systems require a set of input parameters to examine a feasible search space, offering a reductionist approach to design approach and confining the design space to pre-programmed solutions [8]. By integrating learning systems, a recent second generation of GDSs is emerging, marking a shift in design, towards an expanded exploration of the design space.

### 1.2 Design Complexity

Existing literature demonstrates that current applications of AI in architectural design occur at the representation level, without addressing other important design layers. The progressing line of research on AI for architectural design remains experimental with a limited scope of investigation, due to its infancy [9]. Current approaches employ a single AI model to tackle multi-faceted design problems. “Design is probably the most complex of human intelligent behavior” [10], therefore, the capability of a discrete AI model to address all design levels is questionable. Rather than using one AI model for a single design task, a new AI-assisted design workflow of multiple connected models can tackle multiple systems. This echoes a “systems theory” consideration of architectural design, expressed in Christopher Alexander’s “systems generating systems”, offering an alternative to the reductionist and complexity-lacking structure of design processes [1]. In this multi-step workflow, this work initiates a thorough investigation of recent generative machine capability by looking at designer agency and mode of collaboration with the machine.

This work examined a new human–AI collaborative framework (“Deep-Chaining”), where multiple chained deep learning (DL) models were deployed in a sequential logic with feedback from multiple designers to address specific architectural systems and design tasks. Our method is based on task separation to minimize the complexity inherent within AI-assisted workflows. Different strategies were examined: *(1) fully-chained supervised, (2) fully-chained unsupervised and (3) partially-chained hybrid networks*, trained on a specific scale (urban or architectural), and architectural task (e.g. Fig. ground, envelope, structural system, etc.). A case-study was implemented in a workshop format for computational designers/architects. Strategies for chaining results from multiple neural networks enabled assessment of discrete design tasks from human agents when necessary. The primary objectives include assessing the proposed generative framework of human and artificial agency by identifying and evaluating the interactions among the involved agents (Human–Machine; Human–Human; Machine–Machine). In addition, the work interrogates a new type of “Augmented Architectural Intelligence”, leveraging the potential of AI-assisted workflows to be computationally creative [11]. The authors have adopted a “process” approach for assessing creativity defined by neuroscience [12], to discuss and evaluate the quality of the proposed strategies and overall framework. This novel framework contributes to innovation in the architectural sector in line with UN Sustainable Development Goal #9 and #11.

The manuscript is structured in seven sections: 1. Introduction; 2. Theoretical framework; 3. State-of-the-art and DL Application in Architecture; 4. Research Methodology; 5. Discussion; 6. Conclusions & future work.

## 2 Theoretical Framework

### *2.1 Intelligence and Creativity*

Our proposal stems from an interest to enhance the designer's creative faculty, so we present here a brief discussion of *intelligence*, *creativity* and the emerging concept of "*computational creativity*", in order to frame our subsequent discussion. Architectural design thinking is an inherently creative act. Understanding the relationship between human and computational creativity (AI) is essential to develop AI-assisted computational procedures which encourage creative results while introducing reliability and efficiency.

Our current understanding of intelligence is focused on two properties—which, combined—may help frame the discourse between human and AI: "*Intelligence measures an agent's ability to achieve goals in a wide range of environments*" [13]. This definition identifies two aspects of intelligence, the former referring to task specificity and the latter to context specificity (generality).

In contrast to intelligence, creativity is harder to define, because its study spans across disciplines. Experts identify novelty and utility among manifestations of the creative process: "*Creativity is the ability to come up with ideas or artefacts that are new, surprising and valuable*" [14]; "*Creativity can be defined as an idea or product that is original, valued, and implemented* " [15]. Creative insight is thought to emerge either by sudden perspective shifts or non-incremental solutions reached through logical analysis [12] and can be classified into three types of increased rarity and difficulty: *Combinational, Exploratory* and *Transformational* [14]. Furthermore, everyday creativity (P-creativity: Psychological) is distinguished from less common, and more impactful H-creativity (Historical) in terms of prior precedence.

The recognition of human creativity is slightly more complex, and has been known to fluctuate over time-unlike intelligence, which has a consistent benchmark. Professor Csikszentimihalyi argues that it is important to ask not only *what* creativity is but also *where* it is found; according to the "systems model "*…creativity can be observed only in the interrelations of a system made up of three main parts: …the domain, …the field …and the individual"* The domain consists of "*a set of symbolic rules and procedures*" and the field "*…includes all the individuals who act as gatekeepers to the domain*" [15]. Creativity typically occurs when the symbols from a particular domain are used to generate a new idea which is in turn adopted within the domain by the existing field, or occasionally, new domains can be formed altogether. The systems approach expands common regard of creativity as an endeavor associated with a single person and considers external factors as a catalyst for creative achievement: *"...whatever individual mental process is involved in creativity, it must be one that takes place in a context of previous cultural and social achievements, and is inseparable from them"* [16]. An interesting example of creative output lying beyond the individual sphere is Renaissance Florence, where the timely co-existence of appropriate socio-political conditions enabled the civic encouragement of intensive artistic creation during a short period of time (1400–1425) [15]. Accepting the likelihood of creative production as a result of collective interactions among agents and processes, we speculate herewith on the advantages of using multiple designers for curating inter-connected design workflows.

## 2.2 From Computational to Augmented Creativity

As a result of recent technological developments in AI a new kind of creative output has been observed: the new field of Computational Creativity (CC) "*...is an emerging branch of artificial intelligence (AI) that studies and exploits the potential of computers to be more than feature-rich tools, and to act as autonomous creators and co-creators in their own right...The CC field seeks to establish a symbiotic relationship between ...scientific and engineering endeavors, wherein the artifacts that are produced also serve as empirical tests of the adequacy of scientific theories of creativity*" [11].

It is important to note that computational creativity should not be equated with AI, as the former incorporates facets of the latter. According to research studies, intelligence is "a necessary-but-not-sufficient condition of creative ability, creative activity and creative achievement" [17]. While a certain intelligence threshold (120IQ) is required for creative thinking, other conditions are also necessary. Nevertheless, the correlation between creativity and intelligence is not exponential; incremental increase in intelligence beyond this threshold does not necessarily favor creative achievement [15]. As creativity is inclusive of intelligence, our mention of "architectural intelligence" in this paper will henceforth refer to design creativity, because we believe it encapsulates the requisite properties for successful design decisions.

Our discussion will argue that creativity is intertwined and related to design agency and authorship within AI systems; collaboration between human and artificial agents depends on human intellect, AI-produced solutions, and their relationship and modes of interaction. This can increase our creative design capacity by leveraging AI's ability to explore a large range of possible successful solutions, establishing a kind of augmented architectural intelligence within a robust and flexible framework. There are several approaches identified by neuroscientists to assess creativity, focusing on person; product; process; press(ure)/place [12]. Our discussion will focus on the "process" approach to establish qualitative benchmarks for increasing creative thinking in design, as we think evaluating the logistics of the overall method is more beneficial than a discrete consideration of outcomes. The significance of crafting "hybrid" processes which leverage on human intuition and machine (AI) has been highlighted by several experts, like Gary Kasparov. 'Kasparov's law' indicates that a "*...weak* *human + machine + better process was superior to a strong computer alone and, more remarkably, superior to a strong human + machine + inferior process*" [18].

## 3 State-of-the-Art AI Technologies and Background Literature

In this section, a background literature is offered to situate the research within current research on AI and architecture. In order to identify related work, and our research methods, state-of-the-art concepts and approaches that are most relevant, and employed in our work need to be explained. Those methods include DL methods, Generative Adversarial Networks (GANs), and types of GANs (Pix2Pix: supervised learning; CycleGAN unsupervised learning), explained in the following subsections.

### *3.1 State-of-The-Art: Deep Learning*

Ian Goodfellow et al. discuss the potential of machines to learn and develop a hierarchy of interrelated concepts. In this type of framework, humans curate the formal knowledge needed for the machine [19]. The challenge for an AI lies in acquiring knowledge on its own, extracting and interpolating patterns from datasets. Specifically, it is difficult for the machine to select particular features for extraction, to successfully perform the determined task. This indicates a need for applying Machine Learning (ML) towards representation learning versus representation mapping. In a DL approach, AI can adapt to new tasks and discover features, performing complex tasks not possible for humans [20]. We predict that Computational Creativity can greatly impact the ecology of architectural design.

#### 3.1.1 Generative Adversarial Networks (GANs)

Developed by Goodfellow et al.'s, GANs are defined by two deep neural networks (DNN) which compete against each other: a discriminator network (D) and a generator network (G) [20]. The two networks engage in an adversarial learning process of generating synthetic samples that are incrementally more realistic (Generator) and a process of distinguishing synthetic samples from real samples (Discriminator). While the generator network tries to predict features given a certain category and learn how to improve its output to resemble reality, the discriminator network tries to perform a correct classification (*real* or *fake*), given an instance of data. The objective is to minimize the distance between the two sample distributions.

#### 3.1.2 Unsupervised GAN (CycleGAN)

CycleGAN models represent an innovative approach to image-to-image translation where learning occurs in a process of translating an image from a source domain (X) to a target domain (Y), without image pairing. The objective is to learn how to map (X) to (Y) coupled with an inverse mapping of (Y) to (X), performed by introducing a cycle consistency loss to enforce consistency. In other words, the DL training is targeted towards achieving successful image translation within the cycle, where (X) is translated to (Y) and (Y) should be translated back to (X) accurately [21].

#### 3.1.3 Supervised GAN (Pix2Pix)

Pix2Pix models are a conditional sub-category of GANs for synthesizing images in a supervised logic where pairing is necessary to reconstruct images after learning from a paired dataset. Pix2Pix networks use a loss function to train their mapping from an input image to an output image. This makes it successful at synthesizing images from labeled datasets such as maps, reconstructing parts from edge maps, in addition to other tasks. The method showed success when used in wide applications, and became popular for artists in particular [22].

### *3.2 Deep Learning Application in Architecture*

The research on AI contributes beyond the advancement of machinic or robotic intelligence, additionally providing descriptive and analytical understanding of how human intelligence operates. According to Hiroshi Ishiguro "*the robot is a kind of mirror that reflects humanity and by creating intelligent robots we can open up new opportunities to contemplate what it means to be human*" [23]. AI has been modeled on the human brain's neural networks, and can perform tasks which include image recognition, classification, clustering, etc.. In recent ML developments, Google researchers observed that if an AI can recognize an image, that meant it had understood the structure and representation of that image. As a result, engineer Alex Mordvintsev reversed the direction (flow) of the image recognition network, resulting in a network (DeepDream) which can generate images [9]. In "Machine Hallucinations" (2019) Refik Anadol, combined AI and media art, utilizing 100 million images of New York City for training a StyleGAN. These networks produced an AI-generated future vision of the city [25]. This strategy showed a good example of directing the data generation process to create a creative artistic expression [25, 26]. Early architectural work generated by AI includes a design process developed by Japanese architect Makoto Watanabe. His process applied AI for "Induction Design" in the project" Tsukuba Express/Kashiwanoha-Campus Station" designed in 2004–05. The objective was to retrieve unpredicted "magic-like" aesthetics without pre-determined conception of "what good is". The workflow involved exchanges between the designer and the machine, starting with sketches and allowing the program to infer the design intent and propose other sketches; evaluation occurred repeatedly until satisfactory design results were reached [24]. More recently, Matias del Campo argued for generating an AI sensibility that goes beyond formal aesthetics [27]. He questioned the interpretation of AI as *Style* and the multi-dimensional interpretations it entails, arguing for the use of ML to examine stylistic features [28]. In the work of Güvenç Özel, *"Interdisciplinary AI"*, ML was employed to classify and evolve stylistic approaches borrowed from artistic references. The human's role becomes limited to input dataset curation and selection of ML-produced iterations. His underlying argument is that AI is certainly capable of design creativity when calibrated and customized to do so, opening possibilities for external aesthetics [29]. The work of Immanuel Koh used an AI model to extract spatial patterns for generating new configurations with associated semantics [30]. Another example of applying GANs, in particular Pix2Pix, to optimize the process of generating a diverse set of architectural floor-plans can be seen in the work of Stanislas Chaillou [31]. His research showed AI's potential in automating floor-plan design while still producing high quality design options, in a creative process where AI is sensitive to site conditions, building footprint, spatial configuration, and furnishing.

It is important to note that the scope of the investigation in most examples from current AI research in architecture, is often limited to representational and artistic exploration. Representation has been traditionally identified as a generally challenging and important aspect of this research field even in earlier AI models [10]. Apart from representation, in our exploration of AI's potential, we seek a process-driven approach where AI is employed to tackle multiple architectural systems (Fig. 1).

Motivation for this research stems from a need to investigate and redefine interactive modes between AI and human agents in workflows using multiple interconnected neural networks. A primary objective is to identify strategies to expand the possible solution search space. This capacity of DL models has been demonstrated during applications of AI to solve games like Go. The AlphaGo algorithm used a system composed of a Policy Network, a value Network, and a Monte-Carlo tree search to expand and refine the selective search of potentially successful scenarios [2].

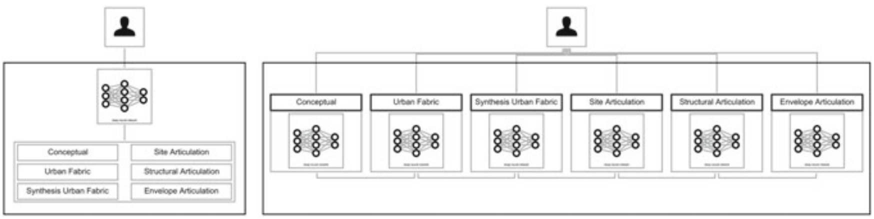


**Fig. 1** A sequential design approach vs a parallel design approach

## 4 Methods

The scope of our research is to investigate the application of AI strategies through a holistic approach to design processes. Adopting John Gero's schema of 'design prototypes' [32], a new framework to architectural design was pursued, employing interconnected DL models and strategies for 2D and 3D. To demonstrate the framework and test its functionalities, a prototype was formulated through a series of experiments at a discrete architectural and design intention level. Our proposed methodology hinges on "systems theory" consideration of architectural design, which involves a "*… shift from the view of architecture as a material object to architecture as a system comprised of and working with a series of interrelated systems*" [33].

Architectural design thinking is by no means linear. The designer negotiates several parameters to find a solution accounting for all criteria in terms of certain hierarchical preferences. Rather than thinking of AI as a "closed" loop of "input–output" in relation to the design process, the authors propose a framework (Deep-Chaining) consisting of (1) a single vs a multi-designer approach; (2) a series of complementary DNNs to examine the potential of logical continuity in AI-driven workflows for a new mode of generative computational design.

### *4.1 Single Versus Multi-designer Approach: Agency and Feedback Loops*

This approach is expected to challenge yet augment the designer's agency, to work in an interactive mode of collaboration with the machine. Computational creativity is exploited and coupled with humans' creativity, in a back-and-forth exchange of design input and feedback, progressively, towards finding new design solutions, aesthetics and higher performance.

When adopting a single-designer unidirectional strategy, the designer determines the architectural task, which is the driving force of the project. Thus, the initial tasks in the design process affect subsequent ones, while the opposite is not true (e.g. Urban Fabric → Street Layout → Building Footprint). The strategy is inherently linear, allowing design intentions and sensibilities to be only forward-propagated in the process. This strategy's unidirectional nature limits the emergence of unexpected solutions and back-propagation, thereby preventing self-organization of designers' intentions.

A multi-designer bi-directional strategy is therefore regarded as more appropriate for creating an open "input–output" loop (the meta level). Within each layer (at the infra level): this strategy manifests as (a) a process where *human and AI agents* interact through self-organization and (b) a process where *multiple human designers* formulate their design intent through self-organization. Therefore, the strategy enables three distinct modes of interaction: designer–designer, designer–AI, and AI–AI (chained networks). It also allows for bi-directional propagation

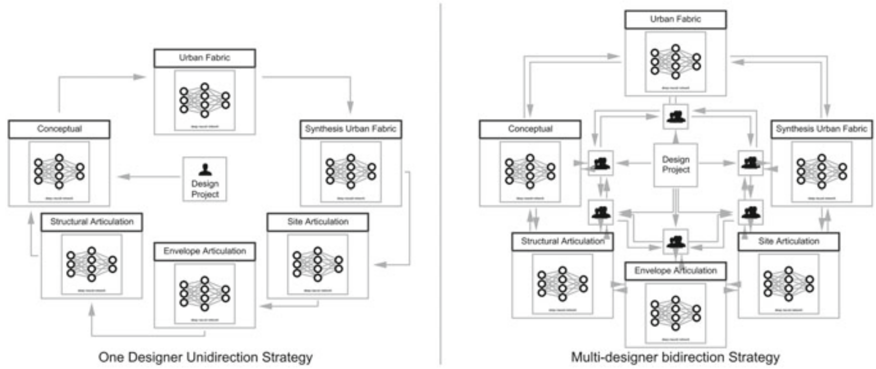


**Fig. 2** One designer unidirectional and Multi-designer bidirectional strategy

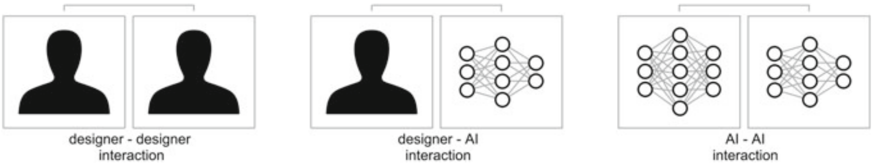


**Fig. 3** Modes of interaction between agents (Human–Human; Human–AI; AI–AI)

of designers' intentions and sensibilities, therefore becomes inherently nonlinear, governed by local rules of interactions (Figs. 2 and 3).

### *4.2 Complementary DNN: Case-Study*

An application of the prototype was carried out to demonstrate the developed framework, test its strategies and evaluate its findings. It was structured in the format of a long workshop offered to 24 architects. Participants were clustered in 6 groups (4 people each). Group 1–3 and Group 4–6 focused on urban and architectural scales, respectively. The workshop aimed to reconsider the Architectural Design Cycle, proposing nested generative AI design processes. Implementing an interactive designer–AI feedback loop, a number of complementary DNNs was employed in collaboration with the groups, to examine the potential of a logical continuity in AI-driven workflows for architecture. The workshop structure consisted of a range of DL models deployed to tackle a variety of urban tasks involving *learning from natural patterns*, *urban fabric encoding*, *urban fabric synthesizing*, and architectural tasks of *site articulation*, *tectonic articulation*, and *envelope articulation* (Fig. 4). Each group implemented strategies ranging from fully-chained to hybrid. The chained network combinations can interrogate the potential of supervised versus unsupervised models. The resulting strategies were (1) Fully-Chained Supervised; (2) Fully-Chained Hybrid (Supervised and Unsupervised); and (3) Partially-Chained Hybrid (Supervised and Unsupervised).

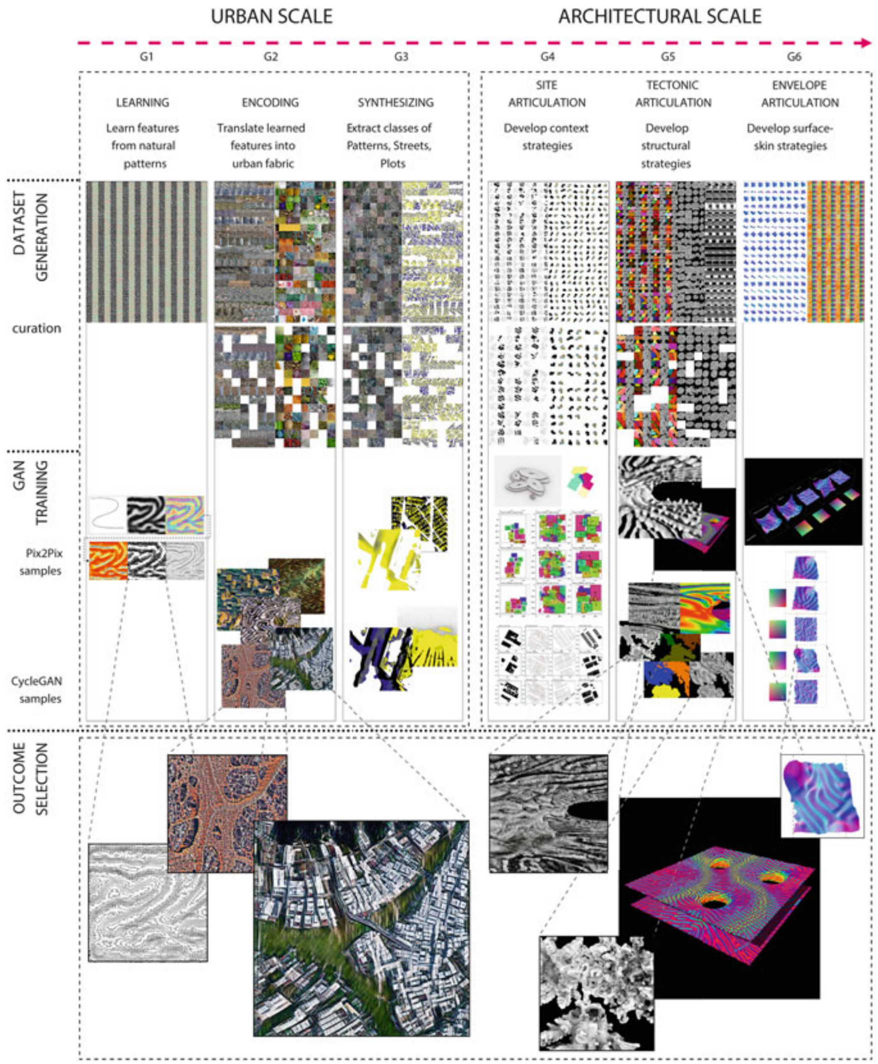


**Fig. 4** Implementation of various NNs for discrete tasks, divided into two sections: urban and architectural. The urban scale was divided into three processes: learning, encoding, and synthesizing; the architectural level was divided into site, tectonic, and envelope articulation

### 4.2.1 Strategy 1: Fully-Chained Supervised

Group 1 used a fully-chained strategy, using supervised Pix2Pix models for image-to-image translation. The work followed a sequential logic to chain all the models (Fig. 5), where an "intuitive curve" can lead to a corresponding urban settlement scheme. The workflow was targeted to assist designers in planning urban settlements which were informed by environmental conditions (i.e. solar radiation) and topographical features. The training set was produced from simple initial sketches—representative of landscape formation intuitions—which mapped a Gray-Scott Reaction–Diffusion pattern to a synthetic topography, which was then analyzed for cumulative solar radiation. Based on local cumulative radiation and topographical features, a settlement was generated. The designers curated the dataset for training the following DL models:

1. **Sketch-to-Pattern**. The first network was trained with a paired dataset of intuitive curve (sketch) and Gray-Scott Pattern, to enable pattern prediction from a sketch.
2. **Pattern-to-Displacement**. The second network used the Gray-Scott pattern prediction from the first network to generate a displacement mesh.
3. **Displacement-to-Radiation Analysis**. The third network used the displacement mesh to generate Solar Radiation analysis predictions.
4. **Radiation Analysis-to-Settlement Strategy (Plots)**. The fourth network used the Solar Radiation Analysis and contour gradients to deploy the settlements into the landscape.
5. **Settlement Strategy (Plots)-to-Settlement Strategy (Roads)**. The fifth network used settlement plots to generate road predictions.

The logic of fully chained supervised networks (Fig. 6) is to establish a continuity for impacting i.e. a pattern or system in systematic manner, by certain contextual factors which allow design scenarios to emerge. Once a change occurs in the beginning of the chain, all the corresponding conditions adapt and update automatically to reorganize the evolving system. It is a hierarchical workflow, where each part (DL model) depends on the previous model. The objective of this strategy is to guide how information impacts early design conceptualization. Once the model is trained, it can simulate an interaction with a human designer, within the learned range of design intentions. This strategy can be applied retrospectively to early design stages as a means to update design solutions. The clarity of this process allows the automation of a given task, which in turn can enable human agents/designers to interact with, and explore the design space in a more open-ended fashion. The economy of

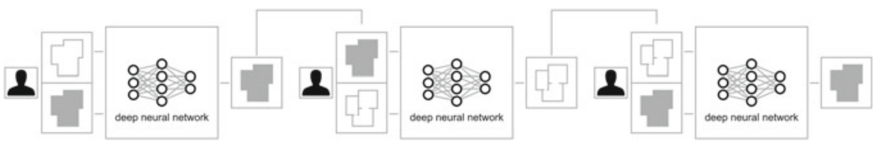


**Fig. 5** Diagram of strategy 1, fully-chained supervised DL models

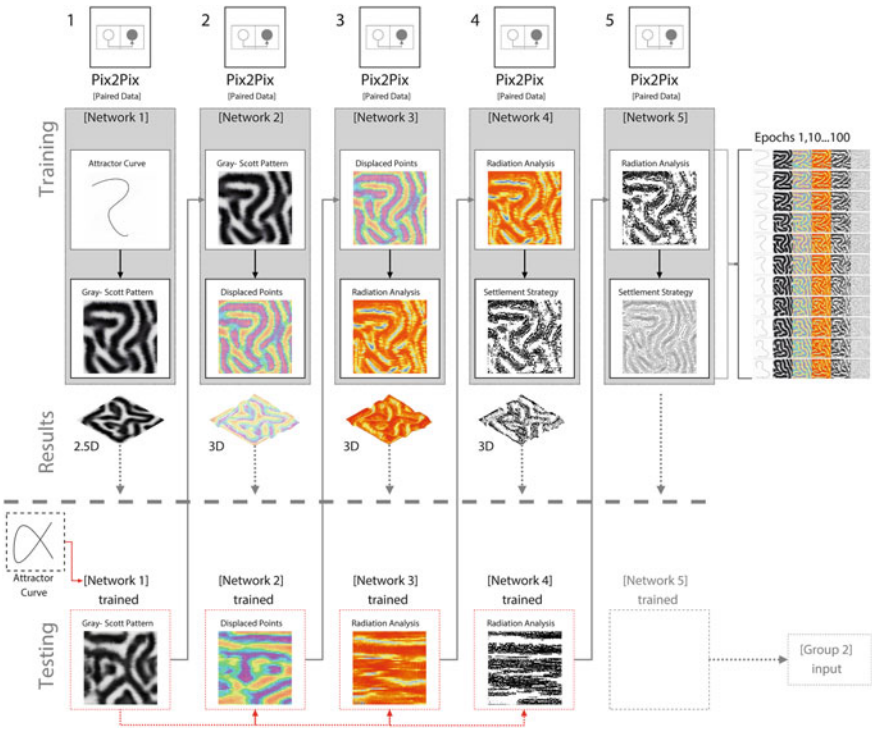


**Fig. 6** Strategy 1, Fully Chained Supervised, using sequential logic in connecting four Pix2Pix Networks

time and effort incurred through certain automations can increase the probability of risk-taking in the design ideation, leading to unconventional, possibly more creative decisions in far-reaching areas of the design solution space.

### 4.2.2 Strategy 2: Fully-Chained Hybrid (Supervised and Unsupervised)

In a fully chained hybrid strategy, (Group 4) unsupervised CycleGAN models were combined with Pix2Pix supervised models. The workflow targeted a design proposition that was responsive to its context (surrounding built environment) and was tailored to a process of multiple fully-chained AI models (four CycleGANs and one Pix2Pix) and parametric translation (Fig. 7). The fully-chained models started with Alpha-plot images and finished with a simple abstract mass model. In between, the models were trained to generate the following sequence of outcomes: (1) Alpha Plots to Plot Outlines; (2) Plot Outlines to Subdivided Plots; (3) Subdivided Plots to Plots with Buildings; (4) Plots with Buildings to One Plot/One Building; (5) One Plot/One Building to Floor Plan Generation; (6) Floor Plan Generation to Colored Floor Plan and Colored Floor Plan to Mass.

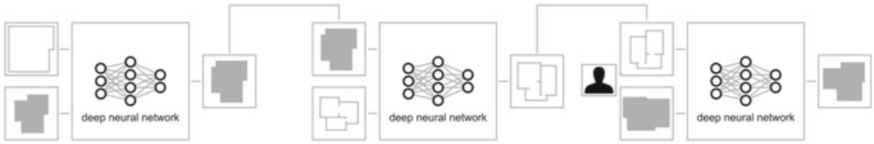


**Fig. 7** Diagram of strategy 2, fully-chained hybrid DL models

This strategy suggested an approach where design evolved from physical conditions, surrounding built structures, and responded to those conditions in a less constrained manner, compared to the fully chained supervised strategy. The results demonstrated a higher degree of freedom in design exploration, leading to new or unexpected results in terms of building footprint relative to plot outlines. In general, this strategy facilitates exploration of design ideas that can be vague, latent, and cannot be easily described i.e. when design intentions are qualitative and undefined, opening the chance for reaching solutions outside the original dataset (i.e. through accidental discovery). Additionally, the chaining with supervised models at some step offers designers the benefit of partial automation which can prompt higher risk-taking in design thinking, as already mentioned (Sect. 4.2.1). This approach can be applied as a suggestive method for possible design scenarios in early phases of design conceptualization (Fig. 8).

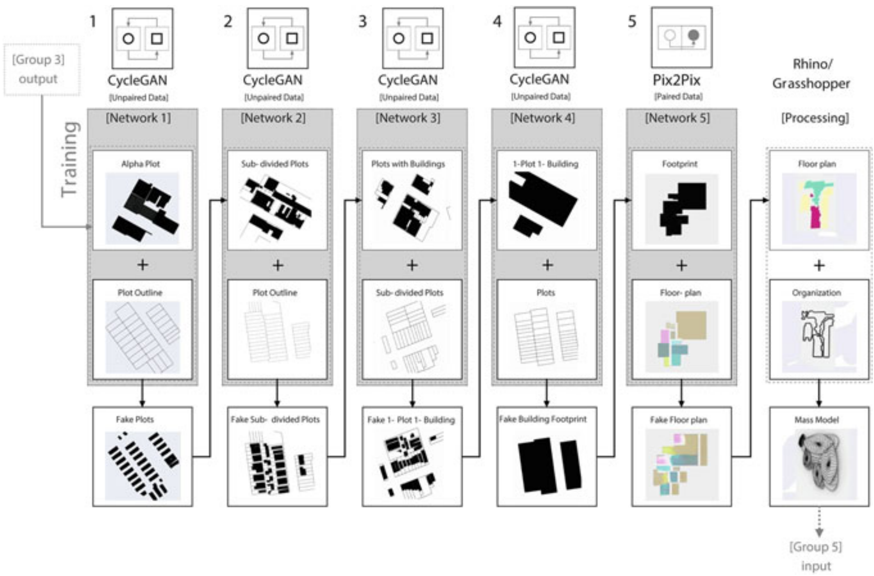


**Fig. 8** Strategy 2, fully-chained unsupervised workflow with five CycleGAN Networks, and one Pix2Pix model in the process

### 4.3 Strategy 3: Partially-Chained Hybrid (Supervised and Unsupervised)

This strategy incorporated a partially chained approach with a combination of supervised and unsupervised networks (Group 5, 6) (Fig. 9). The partial chaining allowed a different workflow; parallel DL training allowed simultaneous experimentation with supervised and unsupervised networks, in a hybrid mode (Fig. 10).

Group 5's workflow comprised four Pix2Pix networks and two CycleGAN networks to produce a spatial configuration of three-dimensional topologies with morphological qualities inspired by natural systems. The process began with a three-dimensional coral model and tried to map differentiated coral patterns on a spatial model, according to surface curvature and color distribution. The experiments included a transition from color swatch to corresponding coral pattern, and subsequently, a transition from color silhouette to coral pattern. Group 6's workflow (Fig. 11) illustrates another example of this strategy, using two DL models, one supervised and one unsupervised. Results from the latter were used as input for the former in testing mode, and then processed in Rhino/Grasshopper for translation into 3D geometry.

This strategy ultimately encapsulates the advantages of the aforementioned strategies, by combining both supervised and unsupervised models, with the flexibility of chained and parallel operation. As a result, designers can capitalize on selected automated tasks, leaving them free to explore in more high-risk search spaces, without precluding the possibility for accidental discovery available through the flexible problem definition with unsupervised networks.

It is important to note that the other groups followed slightly different strategies; Group 2 used unsupervised DL models (CycleGANs) in a parallel, disconnected logic. Group 3 followed a partially-chained unsupervised strategy. All groups' networks were intended to be inter-connected, so the output of the preceding group became the input for the following one, when running the networks inference mode (a neural network infers things about new data it's presented with, based on its training). The workshop resulted in a less linear and more complex workflow, where Group 3 used output from Group 1 and Group 4 used output from Group 5. In addition, early workshop planning specified two or three DL models per group, while some groups ended up training up-to six DL models. This demonstrates the need for experimentation with multiple AI networks to calibrate the workflow. Finally, the case-study reinforced the effectiveness of multi-designer bi-directional approach, discussed in Sect. 4.1.

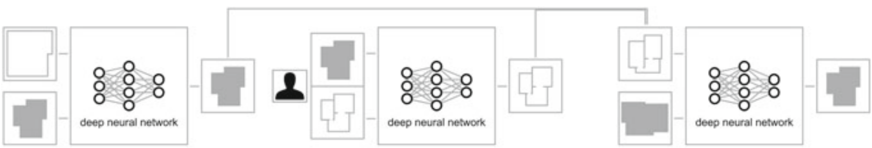


**Fig. 9** Diagram of strategy 3, partially-chained, hybrid DL models

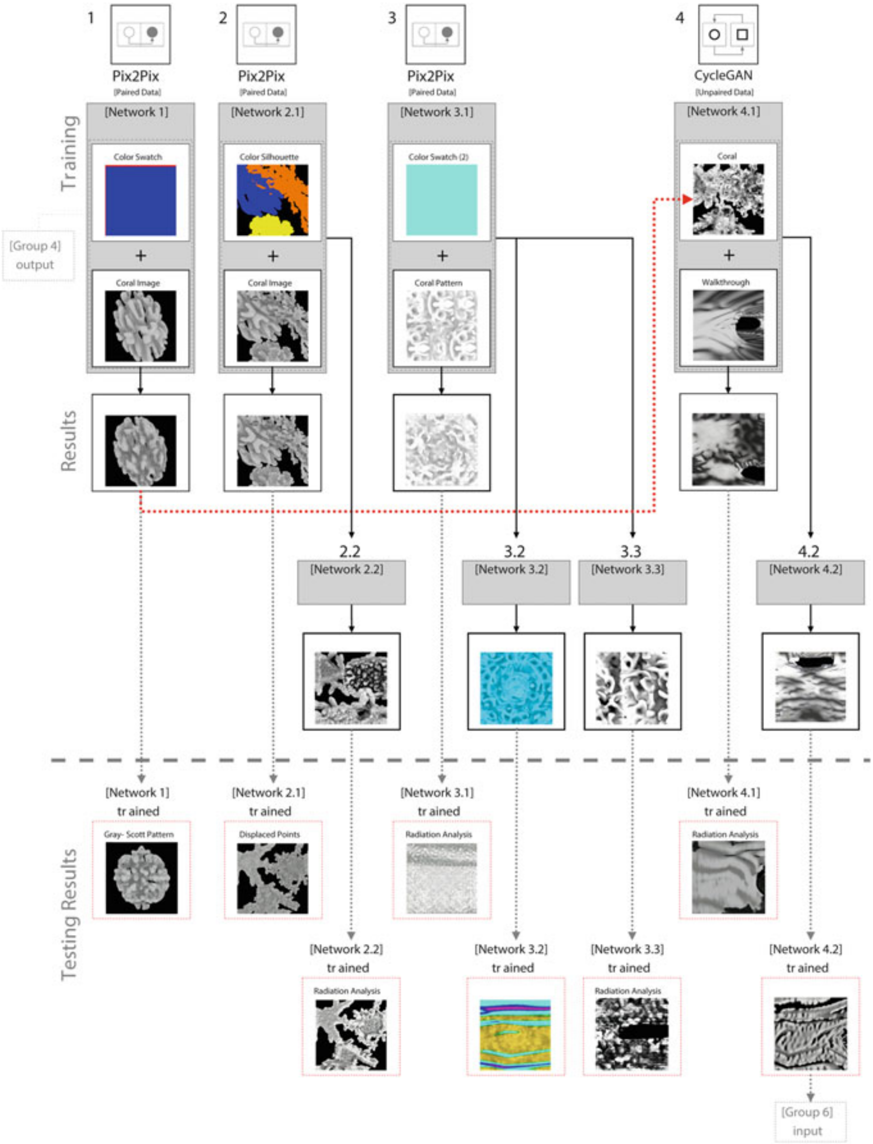


**Fig. 10** A similar approach to Strategy 2, partially-chained hybrid workflow with four Pix2Pix and two CycleGAN

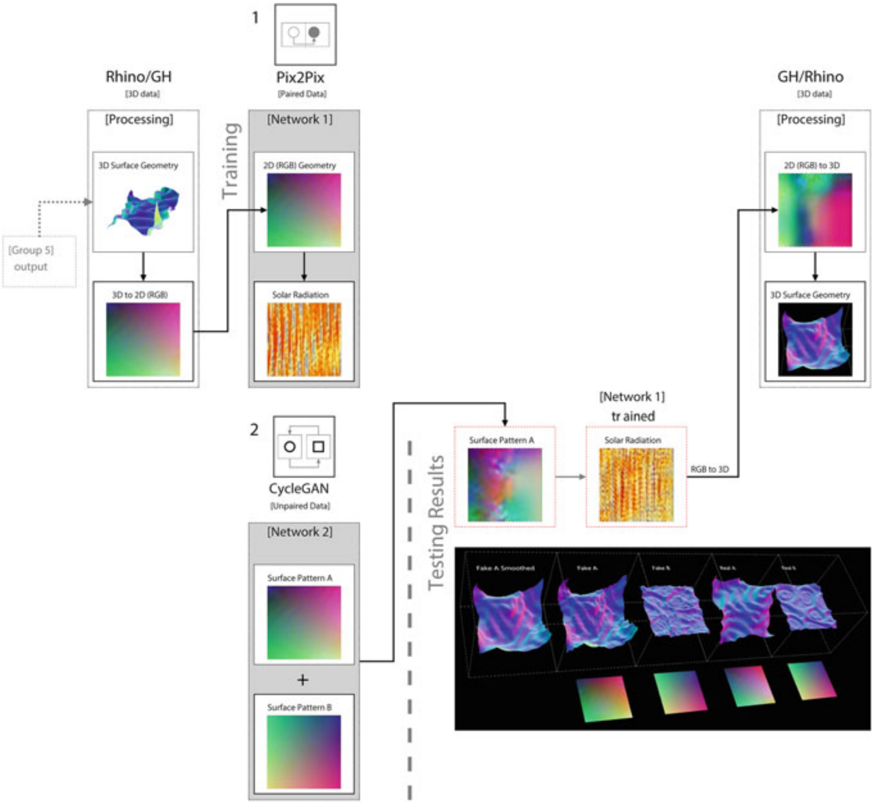


**Fig. 11** Partially chained Pix2Pix and CycleGAN process

## 5 Results Discussion

Our discussion of the case study outcomes focuses on the potential of design strategies to establish a useful *human-machine* agency which assists architectural creativity. A specific examination of the interaction between human designers and ANNs (*human–human, human–machine, machine–machine*) is used to make this assessment. We identify a couple of important things to situate this discussion.

### *5.1 Design Search Spaces*

The design space is an ever-expanding or contracting area of possible solutions. Every decision results in an expanded or constrained search space. Depending on the design objectives, certain domain-specific AI models can facilitate narrowing down the designer's options, expediting and facilitating design exploration [2]. Within our

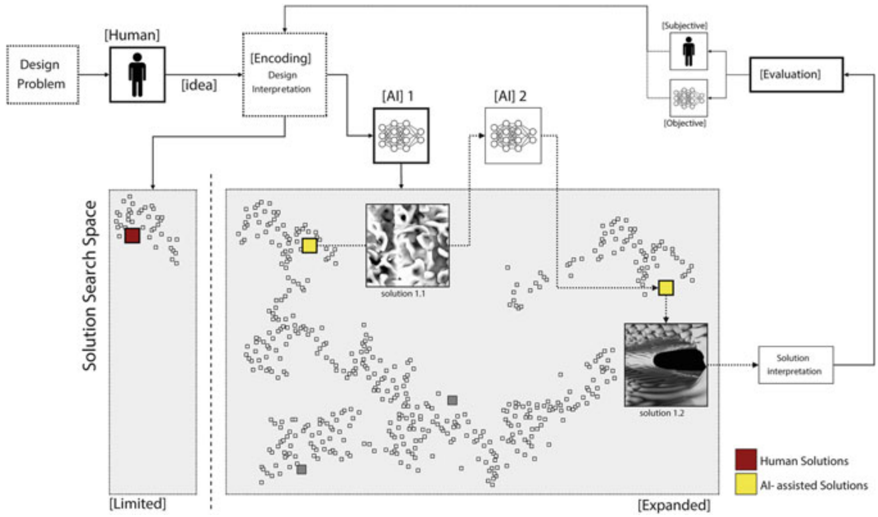


**Fig. 12** Introducing AI models for ideation expands the design space of possible solutions. Results can be plugged into further AI models, thereby progressively re-directing the designer to alternative areas in the latent space of solutions

comparison of human and machine cognition, it is worth noting that humans might not tend to explore a certain range of solutions (either because of bias, habit or other unintentional factors), while the DL model can implicitly and explicitly help human designers expand their solution range. For example, the use of AI (DL models) as an assistive tool for selected task automation can encourage the human designer to assume a higher degree of 'risk', considering options which might otherwise not be explored. Furthermore, in spite of the advantage of human cognition with respect to immediate recognition and synthetic ability of reading data [34], human agents are not able to examine a design space at the same resolution and breadth as a DL model, processing, for example, domain translation (Fig. 12).

## *5.2 Frame of Reference for Measuring Design Creativity*

We have considered focusing our assessment either, on the agents involved in the workflow (human agent; artificial/computational agent) with respect to their distinct contribution (~person. agent), or towards the overall process by way of its outcomes. In the former case, it may be difficult—if at all necessary—to make such a distinction between agents, because both human and AI agents are meant to assist each other. As a result, we prefer to focus on the process, and identify the agents' optimal function within it (order of use for each agent; way of interaction between human–machine; selection of single versus multiple human agents to coordinate the A.I. process).

By extension, the evaluation of outcomes is facilitated by the nature of the proposed workflow, which examines the distinct parts of the process; this allows regular assessment of the design criteria at various nodes of the workflow. The evaluation of any creative process which includes AI-assisted steps, requires human input, according to experts: The use of AI can help target the second category of creativity, per Boden: "*Exploratory creativity is the type best suited to AI.*" (This does not exclude AI's potential to contribute more profoundly in the creative process) "*There are countless examples...However, even exploratory AI depends crucially on human judgement. For someone must recognize—and clearly state—the stylistic rules concerned*" [35]. Boden acknowledges the necessity for collaboration between human-machine in the final part of a design process, the evaluation, and potential re-calibration. Although the computational power of neural networks is useful for heuristic search, human input is still required for evaluation, as available objective metrics like "SSIM" or "Perceptual Similarity Index" used by AI to assess "successful" outcomes may not be coincident with the subjective evaluation humans perform (and which can include other qualitative factors beyond the network algorithm's performance metrics). For instance, visual transfer can be approached through both style and domain-transfer networks; assessing the results of the former may be harder from a human standpoint, as the qualities are transferred visually, not by semantic association, so any due preference would remain very subjective. Assessing the overall process seems to be a more inclusive way to evaluate the proposed design framework and relies on the understanding of relationships among design agents.

### 5.3 Supervision of the Process by a Singular Versus Multiple Designers

Creative achievement can be situated and discussed as a kind of output which takes place within a specific domain, or sub-domain. Nevertheless, bridging across more than one domain is also important because it presupposes creative thinking. Popular perception of creativity usually reflects one of two situations: either significant contribution to one domain, or contributions to multiple domains [36]. Although the second instance is considered less feasible, it is important because it can direct our attention to the benefits of specialization and polymathy as they relate to our earlier comparison of one-directional and bi-directional design strategies for this project (Sect. 4.1).

Following the design strategies discussed earlier, the expected outcome was a sequential approach between groups, where each group used two or more networks, testing their trained models with input from the previous group, while providing their output for testing the trained model of the following group. However, the implemented workflow of each group produced more than two–three networks, and sometimes exceeded six networks. In practice, some parts of the workflow proved less sequential than expected, and required the use of parallel (simultaneous) training.

The presence of multiple human designer-agents established a bi-directional workflow structure which encouraged the self-organization of design intent through its back-propagation to earlier stages and networks. At the same time, different agents presuppose different qualitative backgrounds which, combined, may lead to original insights for updating the task parameters among the various networks. In some sense, the combinational presence of multiple domain-specific agents (multi-designer strategy) could allow for a "simulation" of *domain-general* understanding which is present in polymaths, but is quite rare to find.

## 6 Conclusions and Future Work

The methodology described in this paper tackles the application of AI in a process-based workflow. Early DL applications targeted experimental results by focusing on representation; our work utilizes ANNs to handle the complexity and multiplicity of the architectural design process, avoiding a reductionist handling of design decisions by stand-alone ANNs, through the proposed framework ("Deep Chaining"). This type of design approach increases the chance for creative design thinking because it focuses on iterative collaboration, where semantic relationships among the explored design features are not fixed, but can adapt to influence from other features. Furthermore, using a chained process, the designer(s) is able to exploit AI's capabilities to tackle multiple layers of design simultaneously. The idea of creative production through collective synergy has long been proposed by scientists, as Professor Csikszentmihalyi reminds us of Dr. Jonas Salk, who believed interactions among individuals from different domains could help new ideas emerge, which would otherwise have not: "*I find that that kind of creativity is very interesting and very exciting—when this is done interactively between two sets of minds. I can see this done in the form of a collective mind, by a group of individuals whose minds are open and creative and are able to bring forth even more interesting and more complex results….this is in fact part of the process of evolution, and ideas that emerge in this way are equivalent to genes that emerge in the course of time. I see that ideas are to metabiological evolution what genes are to biological evolution* " [15].

Our approach favors clarity of architectural intentions, thereby acting as *objective* benchmarks for evaluating the AI-generated outcomes, unlike otherwise heuristically pursued design exploration by the authors [37]. The method facilitated the breakdown of the architectural design process into systems and tasks with specific layers, allowing more control over local decisions and result evaluation, in contrast to employing an overall AI model for a complex multi-layered task like design.

The "Deep-Chaining" method augments current Human and Artificial Intelligence, by incorporating three modes of interaction: *human–machine, machine–machine* and *human–human.* A case study tested the proposed framework, using a structure of variable architectural systems (i.e. *concept, tectonics, envelope*), applied to both architectural and urban scales, within a workflow of multiple designers collaborating with a series of DL models. Three primary strategies of connected networks were explored, including ***fully-chained supervised, fully-chained unsupervised,*** and ***partially-chained*** hybrid models. The case study findings demonstrate the effectiveness of the framework to tackle the two scales at multiple phases, leading to a new design process.

The research limitations involve the complexity of enacting, and more importantly, assessing the creativity of Human-AI collaboration, (*process*) as well as the assessment of AI-produced work (*product*) within this still-experimental research phase of AI in architecture. One problematic issue involves the assessment of the "perfect" or successful mode of interaction of human and artificial agency in generative strategies by identifying the interactions among the involved agents (*Human–machine; Human–Human; Machine–Machine*). Another issue is the complexity of coordinating multi-agents, which can be more challenging compared to a single-designer.

Recent work by the authors has elaborated on this framework development through the integration of more types of GANs (i.e. StyleGAN; StyleGAN nada) which are not addressed here, with other ANNs which are based on natural language processing (NLP) like DALL-E, VQGAN + CLIP and Diffusion Models [38]. Current and future work by the authors may address minimizing the top-down supervision of the chaining; allowing multiple agents to self-organize beyond their local environments and further testing the adoption of further language-based AI models in light of recent advancements in diffusion models (i.e. Midjourney, DALL-E 2).

**Acknowledgements** This work proposes a new research framework, introducing the notion of "deep chaining", connecting multiple artificial neural networks within an architectural design workflow, and originates on earlier work by the authors, which enabled testing of an experimental design workflow. This was first implemented in 2020, during the *Digital Futures 2020* online conference and workshops event. An online workshop, offered by Daniel Bolojan, Emmanouil Vermisso and Shermeen Yousif, allowed the implementation of a design workflow, advancing a number of strategies from the workshop's teaching structure. The authors would like to thank the participants in the "Creative AI Ecologies" workshop taught during "Digital Futures 2020": Maider Llaguno-Munitxa, Khaled Nahas, Manoj Deshpande, Anuj Modi, Weiqi Xie, Vlad Bucsoiu, José Roberto Arguelles Rodriguez, Danny Osorio Gaviria, Yunling Xie, Parvin Farahzadeh, Daniel Escobar, Ian Fennimore, Shaoting Zeng, Andrei Padure, Heba Eiz, Kaihong Gao, Behnaz Farahi, Pooya Aledavood, Sarath Raj Sridhar, Frank Quek, Ahmed Hassab.

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# From Technology to Strategy: Robotic Fabrication and Human Robot Collaboration for Increasing AEC Capacities

**Dagmar Reinhardt and M. Hank Haeusler**

**Abstract** This position paper unpacks the relationship between intangible pre- and post-production and tangible production processes under an Industry 4.0 framework for architecture and design to mitigate the Architecture Engineering Construction (AEC) sectors' contribution to climate change and investigate potentials for SDG 9 (industry, innovation and infrastructure). As Industry 4.0 is describing a business model or strategy foremost that utilises and incorporates technology via a cyber-physical system, we investigate how robotic technologies and human robot collaboration can enable methods, frameworks, and systems for the AEC sector; and what opportunities and challenges outside the tangible production floor can be considered to tie in architecture and construction. By reviewing state-of-the-art tangible production processes, robotic fabrication, and robotic interfaces, we aim to outline potential research domains in intangible pre-and post-production towards Next Gen Architectural Manufacturing. We conclude with objectives for reducing architecture's resources appetite using computation and modern manufacturing strategies and a strategic framework to enable this in the AEC sector. This investigation, its proposed hypothesis, methodology, implications, significance, and evaluation are presented in this chapter.

**Keywords** Cyberphysical systems · Robotic fabrication · Human robot collaboration · Data-driven design strategies

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure · promote sustainable industrialization and foster innovation

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_14

## 1 Introduction

The building sector contributes significantly to the current climate crisis on a global scale by using the largest amount of natural resources (~60%), producing excessive emissions (~50%) and waste production (~50%)—all of which are related and interlinked [63]. A discussion of Industry 4.0 in a context of the Architecture Engineering Construction AEC industries must thus have at its centre a reduction of use of resources, a reduction of emission, and a reduction of waste. Consequently, in this position paper, we discuss and outline a strategic approach for Industry 4.0 geared towards enhancing collaboration amongst various departments to increase efficiency and productivity [4] and so assist in improving the AEC industries carbon footprint. We align with two critical comments. As Adams notes, 'the technology of Industry 4.0, while important, is less important than the business model that utilises and incorporates' [3]. Moreover, as MIT economists argue, 'digital is not about technology but strategy' [69]. Section 2 opens the discussion with an overview of second machine age general purpose technologies and cyberphysical systems and continues towards reconsidering production values via intangible pre- and post-production processes. Here we see an important role and contribution of the architectural business sector. Section 3 reviews a case for current AEC with research and knowledge in robotic fabrication as tangible production floor. Section 4 overlays the AEC sectors version of intangible pre- and post-production processes; *synthesis* (creative process), *management* (business process), and *analytics* (data process) and outlines pathways for an integrated, cross-disciplinary framework as strategy to address the building sector's climate problem. Section 5 concludes with overarching objectives for an industry 4.0 framework in AEC sector and potential SDG9 contribution.

## 2 Smile Curve for AEC Industries, a Development Space

Referred to as a descriptor for developments and advancement of information technology in the German economy in 2011, the term 'Industry 4.0' was rapidly adopted by the Architecture Engineering and Construction industry (AEC). The continued high interest in this concept—of industry, research and academia—is evidenced by recent web discussions, with a keywords search ('Architecture' AND 'Industry 4.0') yielding in Scopus 25,903 document results: and with an exponential rise in the years 2014–2020 (access data 5. July 2022). While this provides by no means a qualitative insight, it clearly presents the growing interest that exists in architecture and construction for the concepts, methods, tools and adoption for an Industry 4.0 framework.

## 2.1 Industry 4.0 and General Purpose Technologies

The interrelation of technologies that facilitate the emergence of the 'Smart Factory' is a base concept that is highly valuable for architecture design practice and adoption into the construction industries. Design principles that can inform the design to construction workflow and thus enable implementation to Industry 4.0 scenarios include *interoperability* (ability of systems connection); *virtualization* (data-based models, digital twin); *decentralisation* (ability for local decision making); *real-time capability* (data collection, analysis and evaluation); and *modularity* (flexible adaptation through modules) [35].

The fact that new approaches in architecture have become available results from new general-purpose technologies such as digitised and social data analytics, sensors, machine learning, or robotics which allow the automation of cognitive tasks and offer human and software-driven machine substitutes [12]. Similar to electricity or the combustion engine that rendered labour and machines complementary in the First Machine Age, these general purpose technologies are identifiable as single generic system or equipment; recognizable over a lifetime; have scope for improvement, and will be used and enable uses with spill over effects [45]. Significantly, IT driven changes in manufacturing systems are expected to affect product- to service-orientation even in traditional industries (Lasi 2021).

Key advanced technologies associated with Industry 4.0 are manifold, ranging from the Internet of Things (IoT)/Internet of Services (IoS), Cloud Computing, Big Data, Smart Factory, 3D-Printing, Mobile Computing and Radio-Frequency Identification (RFID), the Cyber-Physical Systems (CPS) or Embedded systems, Augmented Reality (AR)/Virtual Reality (VR)/Mixed Reality (MR) and the Human–Computer-Interaction (HCI) [43]. Their adoption brings benefits for design-to-make production processes alongside digital technologies within industrialised construction, which are much needed for certainty of cost, schedule, and scope in the AEC industries [51].

As Fig. 1 shows, methods that become thus available include processes and strategies that enable digitisation and integration of work and construction processes at different stages, where this work alongside Building Information Modelling (BIM) and manufacturing concepts such as Product Lifecycle-Management (PLM) and Modularisation. Out of the range of these general-purpose technologies, as this chapter argues, robotics holds a particular significance, as this enables computational data to being seamlessly integrated with work processes and thus bridging between digital/virtual realms and the physical/real. At the core, robotics opens different strategies in terms of how to approach data and labour. Beyond management (data capture, simulation analysis), robotic applications as part of Industry 4.0 enable connectivity and interoperability between human workforces, data, material and machines, in the domains of robotic fabrication and human–robot interaction (HRI) or collaboration (HRC), as will be further discussed in Sect. 3.

Ross et al. [69] propose in 'Designed for Digital—How to architect your business for sustained success' that the true impact of the digital stems not primarily

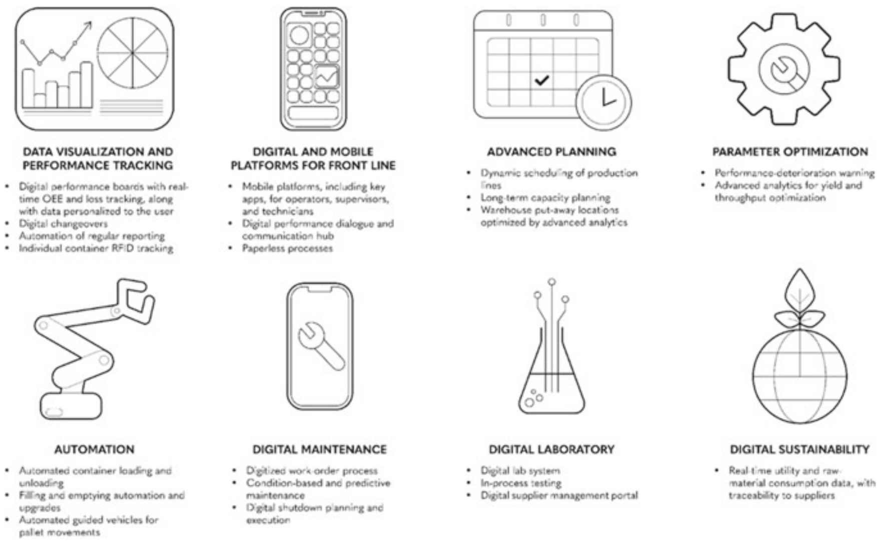


**Fig. 1** Available technologies and methods for a context of architecture and construction (after McKinsey report) [53]

from application as a technology but considering these as a strategy. This is important when reviewing existing challenges in the AEC industry [15], which include field-level barriers for strategic innovation; fragmentation as a barrier for collective action; limited understanding for business models and use of digital transformation; investments not driven by strategies; lack of orchestrated or common approaches; and lack of knowledge and skills for digital transformations. Consequently, we need to move towards better discernibility for all phases of plan to production to support companies' productivity increase and add value for design, production and services.

## 2.2 *Increased Productivity Through Cyber-Physical Systems*

Internationally, the AEC industry is one of the least digitised and least efficient industries [18, 54, 55]. A growing list of performance and productivity problems are directly linked to the sector's failure to embrace advanced technology [26, 52, 72]. The current divide between advanced manufacturing's move towards Industry 4.0 and architecture's stagnation on a status quo suppresses opportunities to improve cost competitiveness and value differentiation.

In this context, cyber-physical systems (systems linked to computation) present an alternative pathway for architecture and construction; by providing an increased potential for data capture and integration [54]. Cyber-physical systems can further adopt a concept of *digital twin* (a highly complex virtual model that is the exact counterpart of a physical condition, object or entity, process or service). Benefits arise from data being continually updated and mapped against it, which can then be simulated, analysed and evaluated to trial different scenarios and enable decision-making. Such accessibility of future scenarios allows investigating systems performance—and consequently being able to operate, maintain and repair systems with no physical proximity and affordance. Importantly, by bridging mechanisms for communication, control and sensing via sensors, cyber physical systems further enable collaboration between design and manufacture, and interoperability through open-source libraries and hardware. The integration of cyber-physical systems into construction workflows via data processing techniques and inter-device communication allows fabricators, manufacturers and constructors to overcome process fragmentation and directly link physical production processes to computational processes [76]. Cyber-physical systems for coordination play an increasing role in construction and are adopted for surveys, task planning and networking control systems. The introduction of sensors informs on required ad-hoc changes, and enables direct, responsive, intelligent and interconnected workflows through continuous online monitoring on the basis of data acquisition. In opening for diagnostic protocols and adjustments, this allows for overcoming stereotypical, standardised or modularised building methods and construction processes. Yet despite the adoption of Industry 4.0 technologies and ongoing research and development, there remains a considerable gap between research, industry and practice collaborating for manufacturing and construction [17]. There is a strong focus on production activities, yet there is limited exploration on how Industry 4.0 principles could be applied across different phases. Hence, we ask: In which way can opportunities and challenges outside the tangible production floor and beyond CAD/CAM and robotics digital manufacturing technologies enable an Industry 4.0 framework for the AEC sector?

### *2.3 Smile! Lifting the Pre and Postproduction process for AEC*

Implementation of Industry 4.0 solutions empowers manufacturing companies by enhancing collaboration: effectively providing relevant information for people on a real-time basis [4]. We argue that a close look into the distinct and successive phases in manufacturing holds the key to opportunities in the AEC industry in a context of Industry 4.0. Linking three core phases is essential, the pre-production phase with R&D, design and logistics; the production activities with the 'actual' production; and the post-production phase with distribution, sales and service. Since failing in one would sabotage and hinder success in the overall production process, all must be considered for Industry 4.0 as changes affect the entire supply chain, not only the tangible production activities. However, improvements in productivity become more accessible by coupling tangible production activities to include in-tangible pre- and post-production phases. As the so-called 'smile curve' in Fig. 2 illustrates, value can

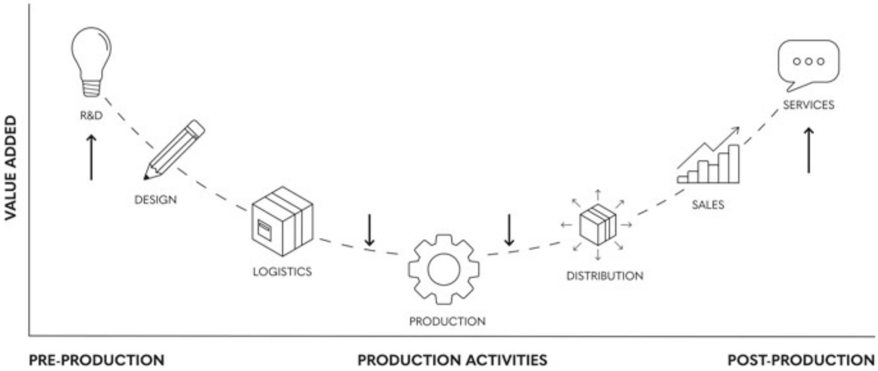


**Fig. 2** Value added in a 'smile curve' for manufacturing context, embedding phases of pre-production (R&D, design), production (logistics, production and distribution) and post-production (sales and services)

be added across the different stages of bringing a product on to the market in an IT-related manufacturing industry (Industry Insights).

Daniel Chuter, CEO of the Innovative Manufacturing Cooperative Research Centre (IMCRC), refers to value increase as 'moving up the smile curve' [46], where production (including logistics and distribution) can be largely enhanced by introducing focus (resources, investments, knowledge) to pre-production (R&D, design) and post-production (sales and services). In a context of AEC industries, ignoring phases outside of core production creates a bottleneck for manufacturing industries; and a similar bottleneck exists in the form of architecture and building practices that model and manage design and construction data, used to establish, and later maintain building stock, infrastructures and services. For example, architects provide phase-based information for builder/manufacturer through design and documentation. They are thus external and as a result usually unavailable for partnering in pre- and post-production with advanced architectural manufacturing and construction. Architecture's digital practices, systems and platforms can significantly support the AEC industries (with advanced architectural practices on the basis of advanced computational modelling and scripting and fabrication knowledge, development of Artificial Intelligence, Machine Learning, and Big Data approaches to digital twins) as core technologically intersecting domains and phases via methods and processes, and so connecting parts and sectors of the building industry which are central to improving efficiency and competitiveness and increasing innovation and ensuring direct links to manufacturing [6, 53, 52]. A collaborative workflow through taking cyber-physical systems in full advantage, and early integration of R&D with a focus on modelling within the machining/manufacturing framework can raise the value of architecture and construction equally—a Next Gen architecture manufacturing approach.

Figure 3 illustrates a framework for three systemic lenses: *synthesis, management* and *analysis*, interrelated through new cybersystem technologies, digital twin and digital business models that allow for interoperability. Each of these lenses holds specific potential to align capacities and knowledge in architecture with manufacturing processes. *Synthesis (creative process)* accommodates pre-production (R&D/Design) through advanced computational scripting, parametric modelling (PM) and machine learning (ML) enhances understanding, optimisation and automation of complex, repetitive tasks and 'workflows' in practice. As a result, the creation of more efficient, reliable and machine-readable manufacturing instructions would enable manufacturers to complete new product designs and achieve operational productivity gains for small scale production [13, 60, 18, 33]. Furthermore, this phase is core for integration of industry competencies with architectural design and planning. *Management (business process)* addresses post-production (sale) and targets commercial advantages and risks of 'business as usual' models in architectural business. Changes in a combination of consumer spending patterns, economical, ecological, and external political pressures can support the AB sector to reconsider business models towards new digital 'XaaS' (Anything as a Service) models, thus redirecting towards design (synthesis) and innovative manufacturing [15, 18, 27, 70] Colins et al. (2016).

Analytics (data process) incorporates post-production (services) for simulation, analysis and evaluation of existing and new data (from CAD to BIM to PM) across the architectural service industry [43]. AI, Machine Learning, Parametric Modelling and Big Data can be adopted to establish digital twins of buildings as extracts from architectural data to use for services. Equally used for describe-for-production, these digital twins can be employed to maintain and repair their physical counterparts and increase operational efficiency [7].

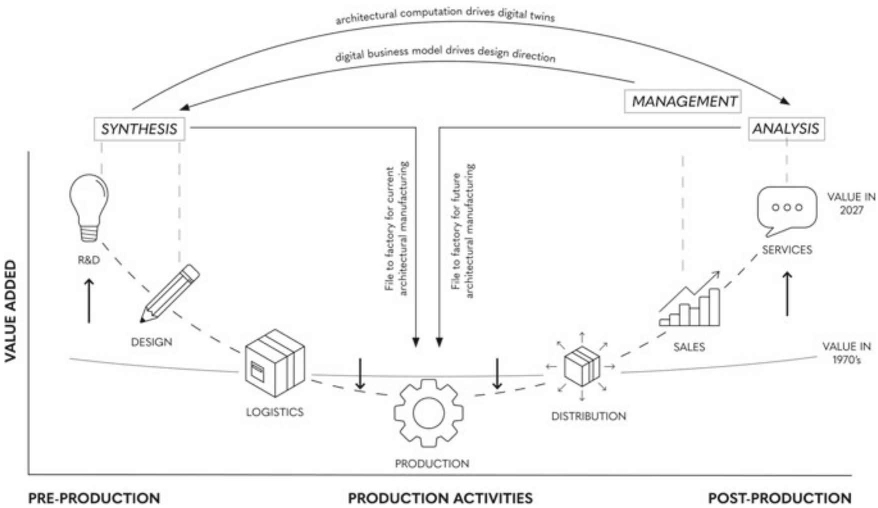


**Fig. 3** Co-opting the Australian Government's Modern Manufacturing Strategy's (AGMMS) 'smile curve' [30]

Importantly, knowledge for processes and agency through technology can be increased between research, architectural practice, and industry, by closely reviewing potential intersections for architecture along the manufacturing curve. These systemic lenses inform the ‘smile curve’ and add greater value from architectural services both in pre-and post-production including ongoing maintenance, specifically for architecture to construction. Consequently, we argue for two ways to increase the potential for architecture and construction to work better together within the technologies of Industry 4.0. Firstly, by enhancing and enabling the core phase of production (ie human labour, machines, data workflow, for example robotics and AR as is discussed in Sect. 3). Secondly, by delivering a targeted approach to intangible and tangible production activities such as robotic fabrication, collaborative robotics and interfaces for architecture.

## 3 Industrial Robotic Fabrication and Human Robot Collaboration

The AEC industries continue to be slow in integration of six axis industrial robotic arms and defining robotic tasks due to perceived barriers including safety, costs and skill applications [62]. Yet six axis industrial robotic arms, robotic fabrication technologies, sensor systems and haptic interfaces can change the way in which architectural design practice, manufacturing and construction are conducted, through robotic fabrication methods and technology; mobile and onsite robotics; and human–robot collaboration, as is discussed in the following.

### *3.1 Robotic Fabrication for Architecture Development of Material Applications and Construction Methods*

Digital fabrication tools (CAD, CAM) have continuously risen in popularity for manufacturing and fabrication, with articulated arm robots that are reliable and flexible; can effortlessly execute an unlimited variety of non-repetitive tasks, and which have become increasingly affordable, accessible, and usable. Initially adopted for high precision, autonomous workflows and independent locomotion in the automotive industry, robotic applications are now considered a catalyst technology that leverages mass customisation to a more elaborate and even architectural scale. Current robotic system providers include ABB, UR, KUKA, Boston Dynamics, Fanuc, with a large range of differentiated robot specifications and types. These industrial robots provide the ideal combination of human and machine labour, connect to a wide bandwidth of general-purpose technologies of Industry 4.0 (AI, ML, Data, AR/VR) and consequently can support the AEC with a potential for further developing/customising a wide variety of existing building and construction materials. It can

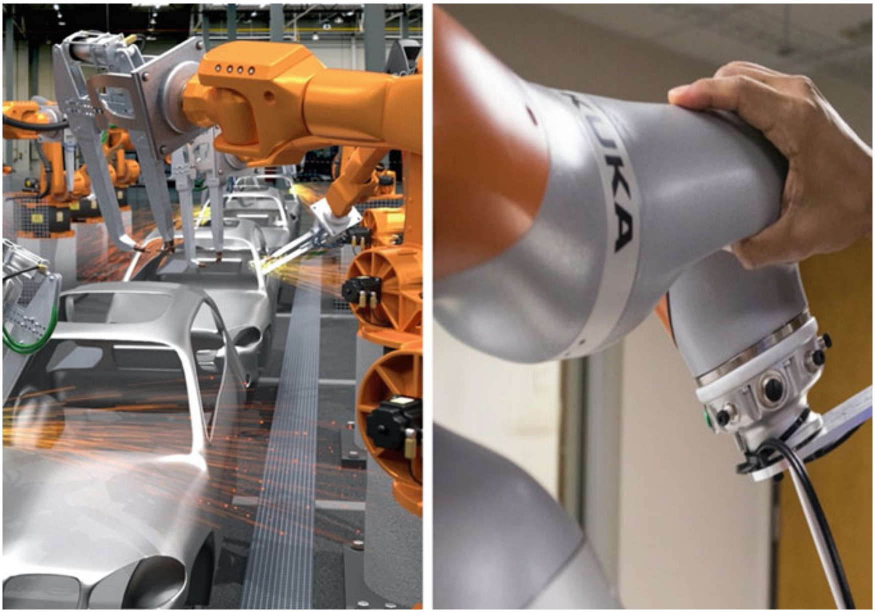

**Fig. 4** Development of robots from automotive to architecture: task and workspace restrictions (left) towards intuitive haptic interfaces (right)

already be observed that construction automation technology, STCR approaches, service robot systems, and other microsystems technology are merging with the built environment, becoming inherent elements of buildings, or building components [8] (Fig. 4).

Global research into robotic applications has been developed between multiple partnerships (variably with industry, research, academia, software and robot developers, or architectural practices). Designing for robot production (architecture) and operating robot setups (fabrication) has become accessible through multiple programming languages such as C/C++, Python, Java, C#/.NET, or directly intersect with architectural modelling and scripting data (on the basis of McNeel Rhinoceros and GH plugin), Robot Operating System (ROS); robot programming coupled with motion simulation such as KUKA|prc; or KUKA|crc: Cloud Remote Control.

In the last decades, research on robotic fabrication with six-axis industrial robotic arms has been thoroughly investigated with new potentials for processes, systems, materials, construction methods [31, 16, 74, 78]. This laid the foundations for an enormous spectrum of potential applications for bespoke and customizable fabrication processes and robotic control protocols and has been widely disseminated through bi-annual proceedings [10, 52, 1] and across journals (Springer Construction Robotics; Automation in Construction; Robots in Construction). A non-exhaustive overview for research robotic applications between 2012 and 2018 shows:

- Robotic brick laying [31, 78, 21]

- Robotic modular timber assembly [31];
- Robotic wood processing [64]
- Robotic assembly (Gandia et al., 2018; Snooks Jahn, 2016)
- Robotic subtractive cutting/milling (Clifford McGee, 2011; Clifford et al., 2014; Feringa McGee, 2014)
- Incremental sheet forming (Kalo Newsum, 2014; Nicholas et al. 2016; Ficca 2017);
- Robotic bending (Culver et al., 2016; Tamre et al. 2013);
- Robotic 3D printing (Johns et al. 2012; Oxman et al. 2017; Hyperbody/Bier/Mostafavi, 2015; Dubor 2016; Branch technology, 2015; Feringa, 2017; Huang et al., 2018; Alothman et al. 2018; Battaglia et al., 2018; Gaudilliere et al., 2018)
- Robotic (carbon fibre) weaving (Yablonina, 2016; Doerstelmann et al. 2016; Witt, 2016; Reinhardt et al., 2018).

As a consequence, research on robotic fabrication protocols, systematic applications of a variety of end-effectors that can inform standard construction processes (assembly, positioning, punching, drilling, cutting, sawing, fixing, plastering) and non-standard productions (3D printing, wire cutting, weaving/threading) together with an understanding for workspace scenarios, workflows and operative has been widely disseminated. However, several challenges remain, including (a) knowledge and skill transfer from research to industry applications for methods and techniques of robotic protocols; (b) upscale to industrial building processes and building site; and (c) increased human–machine or human–robot interactions with intuitive feedback and interfaces.

### *3.2 Onsite Robotics-Large Scale Construction*

While the construction industry has not kept up with manufacturing in adopting robotics despite the promise of improvements in quality and enterprise performance and a shortened time-to-market for products [11, 58] this is partially due to underlying conditions that differ strongly in the two sectors: manufacturing uses closed work settings, construction is produced in multi variant, unstable and uncertain environments. Standard construction sites pose challenges for operating industrial robots due to complexity as a consequence of unstructured environments, and thus limiting transfer and direct adaptations to this sector. Other typical characteristics of construction industries impede the adoption of robotics such as a high volume of manual operations, inconsistent deviations and variability of the construction site over long periods, large and heavy building structures, and in general limitations resulting from outdoor operations [50]. Other barriers exist due to scalability—robotic arms and thus workspace and range are restricted to the systems in which they are mounted, for example on a crane, track rail or gantry system, and so robotic reach and work scale is determined by the platform. However, significant achievements to date include gantry based modular components (Sequential Roof, Gramazio Kohler), integrated robotized construction site [28], or mobile robotic construction units [21].

An exert overview of industrial robotic applications with large-scale construction and buildings includes: HadrianX's FastBrick (2018, Australia) demonstrated in a commercial application for a mobile robotic system for construction of block structures from a 3D CAD model in unstructured environments with construction of a residential unit in three days. Odico Construction Robotics (2021, Denmark) developed Factory-on-the-Fly as a platform technology for mobile on-site robotic construction, driven by Sculptor® operating system for constructing with a robotic cell through intuitive interface programming (iPad). DFAB House by NCCR/ETH researchers (since 2016-, Switzerland); a 1:1 demonstrator for implementation of novel robot driven construction methodologies, including In Situ Fabricator (an autonomous on-site construction robot), Mesh Mould (a formwork-free, robotic process for steel-reinforced concrete structures), Smart Slab (integrated ceiling slabs fabricated with 3D-printed formwork); and Spatial Timber Assemblies (robotically fabricated timber structure). SQ4D Inc. Autonomous Robotic Construction System (ARCS) (USA); Robotic 3D printed residential house with use of sustainable materials (mold and fire resistant) and assumed 70% reduction of cost and labour. MX3D/Laarman MetalXL (Netherlands [18] combines a standard industrial robot and power source for 3D metal printing, showcased with a 3D printed steel bridge.

On a smaller scale, robotic technologies that aim to assimilate conventional construction approaches for building construction represent a larger percentage of the developments. These often focus on singular construction activities, tasks or components, such as protocols developed for a single, formatted and modularised material (bricks and blocks), for fluid-controlled material deposition (concrete and clay printing), or for customised protocols (steel-welding), preparation for masonry walls (marking, fixing), plaster deposition or tile laying. Principle knowledge exists in research for robotic fabrication, yet this does not extend to actual knowledge for AEC industries, nor does it connect to performance criteria or values (use, location, cost, durability, performance, materials, construction method), or to business models (integration, service, maintenance). Only recently research has moved from closed robotic protocols to knowledge-based systems [23], which originate with workers' embodied expertise. More research is needed to streamline construction workflows, such as innovative use for robotically processed construction materials, adopt improved robotics interfaces and hardware, to achieve sufficiently versatile, on-site, and human-interactive robotic systems.

### *3.3 Cyber-Physical Pathway for Robotic Fabrication*

Commercial building processes are commonly conducted by multidisciplinary teams (architects, engineers, consultants, and on-site/off-site contractors) and consequently the way in which construction information can be successfully communicated to builders or contractors is highly relevant. Data feedback on issues of material affordances, labour and production protocols, or unpredictability and uncertainty across construction sites through cyber-physical systems thus represents a huge potential for connecting human workers, robots, machines, materials and control devices (tablets, computers) for collaborative workflows [75]. Importantly, while this can enable architects to create, test and build in a virtual environment and so support evidence-based collaboration and inclusive decision-making, this also enables architects to connect to data controlling design to fabrication processes inclusive of resource data; enhancing existing building information models with operating data; and overview of lifecycle demands comparative analysis.

Whereas the full control of the computational or building information model, fabrication method, and assembly can be affordable, a highly specialized workflow and customised robot setups in industrial or commercial projects can present challenges related to economics and time. In this context, the adoption of robotic fabrication, and recent developments for human–robot collaboration hold significant potential to change in construction industries. In the last five years, increased efforts have been made to connect robots to the bandwidth of cyberphysical systems with the aim to move beyond static systems, closed operations and linear protocols (Fig. 5).

Coupling digital monitoring, sensor feedback and haptic interfaces with physical robotic manufacturing methods enables robots to sense, analyse and respond to changes in movement, tasks, material resources and thus gives access to new possibilities for production. This includes the potential for startups and entrepreneurship, whereby industrial robotics allows new manufacturing technologies to gradually evolve from initial tests and pilot studies to industrial processes—a new generation of construction [22]. Here, the raw production capacity of industrial robotics brings 'design and build' approaches to construction into view. Robotic startups revisit the

**Fig. 5** Cooperation to Collaboration: human support of robotic fabrication process for robotic carbon fibre winding (Reinhardt et al, 2017, left), versus data capture for fabrication techniques and knowledge of motion, force and material resistance (Reinhardt et al, 2016, right).

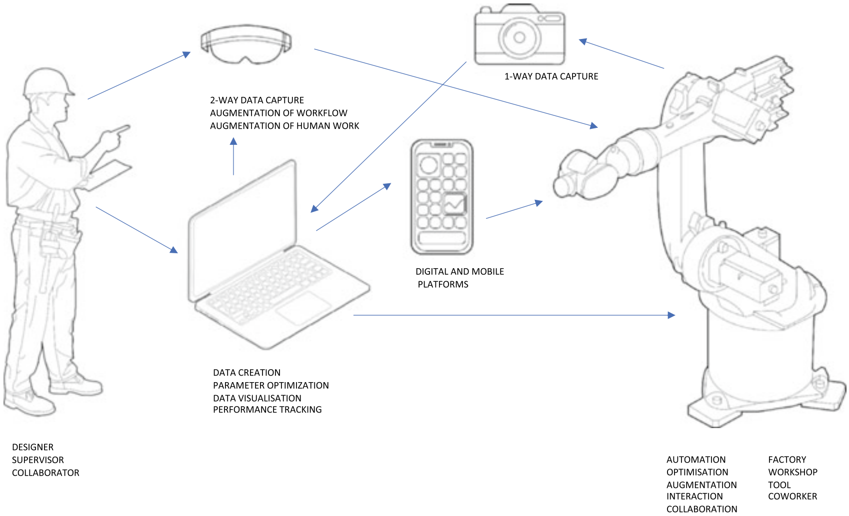


**Fig. 6** Network for Human–Robot Cooperation across cyberphysical systems, digital twinning and intuitive interfaces in onsite conditions

idea of an architect-builder through computational design knowledge coupled with the means of production thus opening new career paths and in fact new professions for the AEC industries (Fig. 6).

### *3.4 Human–Robot Collaborations*

The fourth industrial revolution changes the role of humans in operations systems, and so integrating human work contributes towards a successful digital transformation [58]. Whereas industrial robotic robotic arms were previously confined to factory settings with strict safety controls [25] and regulated in standard manufacturing environments by the ISO 15066 safety standard [66] with explicit limitations to robotic work environments to prevent accidents and injuries to human operators, this has opened with the concept of Human–Robot Collaboration (HRC), introduced by Colgate and Peshkin [14]. Collaborative relationships allow human(s) and robot(s) as one of the most important modes, where humans and robots have intersections in space and time domains through the shared work/tasks. This translates to shared working environments and shared working time for human–robot collaborations, with shared non-fenced zones and direct physical interaction. Approaches of human-centred and creative methods, user interfaces and machine learning have started to be developed in recent years, so that more direct access and control over processing of data to machinery—and with that, more direct interaction between human–robot processes—become available [29], with systems and methods for better understanding the human as active agent in the workflow with robotics.

Instead of fully autonomous or automated robot setups, collaborative robots (CoBots) in partnership with humans are the future of construction work: robots can perform tasks that are repetitive, dangerous, harmful, monotonous, or even physically impossible for a human worker while the operator would manage the more skilled work that required more finesse and experience. Instead of using industrial robots as 'human' substitutes, robots can be used intuitively and actively in an immediate interaction between design and motion. The current (r)evolution in human–robot interaction shifts the procedural/prescriptive programming of robots (typically via 'recipes' written in industrial robot languages) towards declarative/if–then scenarios and criteria based robotic protocols.

### *3.5 Lifting the AEC Smile Curve Through Robotic Interfaces*

Human Robot Collaboration (HRC) recenters building and manufacturing processes from the product towards a human or user-centric process. Emergent interactive strategies explore sharing of tasks and actions where humans and robots have intersections in space and time and here, the concept of coexistence manifests as a shared working environment and shared working time. Importantly, this means that the smile curve can be significantly lifted through direct integration of production knowledge at the early stages R&D and Design, as a direct and iterative loop for logistics and production. To achieve this, the integration of data, but more importantly interactions or collaborations between human and machine, digital twinning in the form of data visualization of workflows, positions, and reconsiderations of robot workspace and movement protocols in relation to human co-workers is crucial. This means that robot-specific software that couples particular robot programming with robot products, such as aforementioned RobotStudio, ABB robots or KUKA|prc software needs to be expanded to directly and intuitively interact with the user—and thus bringing trained/skilled/embodied knowledge systems from the factory floor/construction site to the architect's office. While these distinct robot languages commonly require a specialist to operate the software and create robot instructions, this is about to change. Recent research explores Java programming via KUKA LBR-iiwa, using seven axes with integrated force-torque sensors to safely safe interact and further enabling entirely new applications that use hand-guiding and utilize the force-sensors to compensate for high tolerances on building sites, like manual assembly tasks [9]. Other alternative methods of interacting with robots that reach beyond previously required complex bus systems or industrial data interfaces include vision-based safety systems for human–robot collaboration [34]; haptic programming approaches where a collaborative robot physically manipulated/taught a movement based on feedback loops between the robot controller and its associated force sensors [19], vision systems [49], application of alternative robot programming through tablet [60] and augmenting robot processes through AR via Microsoft Hololens [42], fologram; [37]. The collaboration for the same goal [5] and research into classification of collaboration levels [40] changes the directive of human–robot collaboration from subservient strategies or a confined placement. Distinguishing between the different levels is important because of the requisite safety issues and for the purpose of designing and evaluating the worker aspects of human–robot interaction (e.g., acceptance and workflow), but moreover, for facilitating best practices to implement future human–robot collaboration on the factory floor [2]. The organisation of industrial robots in a human–robot team approach [78] frees interaction space considerably, where human and robot have agency, task sets and are single, team or multiple constellations (for example a singular robot, a robot-human team, or a multiple robot-multi operator setup). This includes turn-taking, handover, or multi-party and situated interaction [73]. Current developments for defined relationship frameworks include reference models for human–robot interaction [20, 18], and systematically define interactive intention between human and robot [75],with models of 'leader–follower' (human to robot), or status descriptions for both agents including 'active' (leader status), 'inactive' (rest), 'supportive' (following prompts/external control) or 'adaptive' (changing roles). Moreover, this requires a different form of robotic interaction and entails a move from robot to control a process segment, towards development of a communication language with task content, specified interactive nodes, and task process transition between agents (and here is where haptic interfaces are extremely useful in instructing the robot through discrete visual systems adaptation with special symbols and prompts).

## 4 Discussion

In the following, we discuss the potential of robotic fabrication and human–robot collaboration for new strategic prompts in Industry 4.0, core objectives for the AEC sector, and the Big Picture Thinking for better integration for SDG 9 (industry, innovation and infrastructure) and Climate Change.

### *4.1 Moving Robotic Technologies Forward*

Robotic fabrication, as has been discussed, has solvers for applications in advancements in the construction industries. The increasing need for agile production equipment can be addressed by collaborative robots in dynamic environments, working alongside human workers, and while this require reconfiguration and agile control methods, plug and produce frameworks are currently developed with exchange of hardware modules coupled with agent-based system extending the robot operating system [69]. Consequently, multiple pathways for production chains could be orchestrated, and applications that are highly customised to serve the special user needs, solve specific issues and tasks can be optimised through multi-agent reinforcement learning [24]. What is required are frameworks for integration, collaboration between construction trade and architecture practices to enhance synthesis (creative process) and production processes. A focus on the construction of hardware (sensing technology, end-effector design, etc.) and software (programming AI algorithm) needs to implement tasks and balance exploration and innovation for human–robot collaborations, and methodology and system configuration, to achieve a coordinated development of AEC.

### 4.2 Developing Core Objectives for Industry 4.0 Frameworks

In addition, core objectives can be outlined for the AEC sector, given the technological advancements available through robotic technologies, cyberphysical systems and digital twinning for tangible production. Firstly, training, upskilling and transfer of process knowledge between architects and manufacturers needs to be increased, to make them fit to deliver complex, high value-add architectural manufacturing. The integration of both business operations between intangible and tangible production will be extremely valuable and further fuelled by population growth and increased demands on the industry. Secondly, contributing to digitalise architecture and engineering firms can increase productivity and potential speed of project delivery, by creating manufacturing-specific design tools and frameworks. The World Economic Forum estimates that full-scale digitalisation has the potential to generate 12–20% in annual cost savings in the construction industry. Thirdly, establishing the methodological foundations for a profound rethinking of the design process in the AEC sector. This chapter has presented a new paradigm, adopting an integrative and cross-sectoral approach encompassing digital business models, computer science, architecture, and engineering for architectural manufacturing. It consequently works toward a future industry where organisations, products, and services are arranged around specific projects or problems rather than distinct disciplines. Fourth, research is required into how to remove the bottleneck between design as an intangible pre-production process with tangible production activities, where cross-lateral training between architects and manufacturers will make construction and production cost effective, feasible and innovative. Lastly, we aim to contribute to accelerate digital transformation in AEC businesses by developing industry and organisational interventions. The digital transformation investigation will include business models (e.g. platform models), future scenarios, ecosystem collaboration (e.g. open innovation) and processes that will enhance organisational efficiency, agility, growth, and profitability.

### 4.3 Investing in SDG 9 to Counteract Climate Change

Industry 4.0 and circular economy knowledge can radically transform waste management [51], reduce resource consumption in a manufacturing context [45], or contribute towards achieving the Sustainable Development Goals. Understanding opportunities in the tangible and intangible pre- and postproduction in the architecture business sector and enhancing collaboration between different stakeholders is an immediate and important means of systematically connecting technologies available through Industry 4.0–with the larger scope of moving construction towards better resource management, circular economies, and increased building performance. Computational architecture practice coupled with advanced manufacturing and robotic fabrication strategies can unlock opportunities for AEC, when instrumentalised not merely as a technological pathway, but as strategies that can inform and change the way in which we operate. If the AEC sector plans to unpack via computational methods, strategies, and tools, quantity and type of resources in buildings and by applying modern manufacturing strategies—to build less, with less and with new materials and material systems—to mitigate resource demands of the building sector—then we need to develop a strategic framework first for upskilling all parties involved. To this extent the development of integrated, cross-disciplinary, innovative training frameworks from technology to strategy will address the building sector's request for advancement and at the same time provide pathways for answering the current climate problem.

## 5 Conclusion

This position paper has explored the utilisation of technologies for Industry 4.0 towards advancement of AEC industries, with a focus of applications of cyber-physical systems, digital twins and architecture robotics. We have discussed state-of-the-art tangible production processes in the domains of robotic fabrication and manufacturing, and ways in which these systems impact on challenges and opportunities outside the tangible production floor, with contributions in the form of a framework that integrates pre-and post-production phases and so uplift the manufacturing/construction smile curve, adding value for the AEC sector. We have outlined potentials for increased knowledge integration between architecture practice and the construction sector and defined objectives and potentials for the digital as major change agent in the AEC sector's role and impact in a climate change context.

Increasingly buildings will have a digital twin, a virtual model designed to accurately reflect a physical object. Building file to factory capabilities within architecture will help manufacturers to viably engage in design-led production via file to fabrication, so a pathway to develop sector-specific IP and training for AI-driven specialised architectural manufacturing out of digital twins will be an important aspect of architecture in a context of Industry 4.0. Data on building performance under changing environmental conditions will enable a deeper understanding for individual buildings but more importantly of larger building groups and their interferences, enabling better overview of complex data for building collectives and urban scapes that can respond for subtle and extreme changes, such as increased heat, floods and bushfires of the past years. In that scenario, digital twins could not only pass data back to manufacturing, but robot fabrication could be continued into robotic maintenance, human–robot collaboration embedded in buildings, and extend to different robotic ecologies—including industrial arms, drones, robot swarms and augmented support through interactive and haptic interfaces.

**Acknowledgements** The authors acknowledge parts of Sect. 2 are aligned with the research and thinking of the Australian Research Council (ARC) Industry Transformation Training Centre for Next-Gen Architectural Manufacturing' (IC2220100030). Findings published under Sect. 2 are the result of research towards the grant application and are the result of the team effort of the applicants.

Funding. Sections (Sect. 2) of this research was funded by the Australian Research Council (ARC) Industrial Transformation Training Centre for Next-Gen Architectural Manufacturing (IC2220100030).

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# Overview on Urban Climate and Microclimate Modeling Tools and Their Role to Achieve the Sustainable Development Goals

**Matteo Trane, Matteo Giovanardi, Anja Pejovic, and Riccardo Pollo**

**Abstract** The role of the fourth Industrial Revolution enabling technologies is pivotal if the paradigms of data-driven, performance-based, and optimized design have to become standard practice. Urban climate and microclimate models are increasingly likely to support the design for adaptation, resilience, and mitigation of the heat island in cities. In this context, the objective of this chapter is to emphasize the role of urban climate and microclimate modeling tools to achieve the Sustainable Development Goals at the local level. To this, firstly the authors screened the Agenda 2030 official Targets and Indicators and the European Handbook for Voluntary Local Reviews' indicators, highlighting how they deal with environmental quality, urban climate and microclimate issues. Interlinkages and possible trade-offs were identified among goals and targets, too. Secondly, a robust overview on the main software for climate modeling is provided. Tools were clustered, according to the domain of application, into scale, statistical, numerical, and dispersion/air quality models. Thus, the authors focused on numerical models, identified as proper tools for architects and planners to support urban and micro-urban scale design. A final matrix compares the most used numerical models at a glance, highlighting main features, fields of applications, environmental parameters simulated, and interoperability options.

**Keywords** Climate models · Computational fluid dynamics · Urban microclimate · Agenda 2030 · Sustainable development goals · ENVI-met

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_15

**United Nations' Sustainable Development Goals** 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 13. Take urgent action to combat climate change and its impacts · 3. Ensure healthy lives and promote well-being for all at all ages

## 1 Introduction

Open public space is crucial when talking about quality of life within urban environments. It reflects the identity of a city in an aesthetic, ecological, and functional sense, thus providing environmental, social, economic, and health benefits and fostering the sense of community [58]. Moreover, redesigning the space between buildings has the great potential to both adapt cities and mitigate the causes of climate change, which, in turn, is the most promising strategy to cope with ongoing climate crises [11]. The role of open public space is also promising in attenuating the effects of the Urban Heat Island (UHI), as designing by combining strategies to cope with both climate change adaptation and mitigation has immediate effects on microclimate, thus quality of life and health [52]. Specifically, the role of greenification—i.e., the use of green infrastructure (green areas, roofs, and façades and vertical vegetation)—benefits the local climate conditions and has a direct impact on human thermal stress and mortality [29]. Indeed, heat waves accounted for 68% of natural hazard-related deaths in Europe in 1980–2017 and many climate models still project a global rise in climate hazards [59].

In such a scenario, the quality of public space is definitely a key element to convey sustainable development, and the Agenda 2030 put specific emphasis on access to safe open public space for all, good air quality, and environmental comfort. As a consequence, modeling the behavior of urban elements—both natural and artificial—is essential for decision and policy making, data-driven urban planning and climate projection-based scenario assessment. The rapid spread of enabling technologies, with the consequent increase in computing capabilities, redefines design practice in favor of computational approaches, which require interoperability, modeling, 'simulability' and connectivity [55] to finally boost the 'generative process' of an optimized design [14]. Specifically, the use of numerical models and tools may support domain experts (e.g., urban planners, architects, landscape designers, environmental engineers) and non-technical professionals (e.g., decision-makers, public and civic stakeholders) [29] in the early stage of a performance-based design process (*ex-ante*), thus allowing better monitoring of the effects of design and policies (*ex-post*). Nowadays, many software and solutions exist, enabling urban climate and microclimate simulations with different spatial resolution and grid size (from less than one meter to hundreds of kilometers) for different purposes (from urban streets to regional modeling).

In the perspective of an increasing full 4.0 awareness for architects and planners, i.e., shifting from a computer-based design to a computational one [3], the purpose of this chapter is to provide a detailed overview on the most used tools for urban climate and microclimate modeling, highlighting their role to ease the transition towards a sustainable development. Moreover, this chapter will focus on how these tools may support the achievement of the United Nations' Sustainable Development Goals (SDGs) at the local level. Indeed, it should be taken into consideration that 65% of SDG targets could not be achieved without a decisive commitment of cities towards the implementation of local sustainability agendas [40], possibly aligned with the UN Goals. In this context, computational design plays a crucial role in shaping cities' transition towards carbon neutrality, combining several dimensions: mitigating the UHI, reducing the resource consumption, promoting the user's comfort, and boosting the resilience to climate change. Indeed, planning for the adaptation claims for a combination of data and scenario assessment, that is, the results of knowledge exchange and contamination among disciplines, to eventually provide policy makers with consistent and sound 'environmental synthesis', grounding on predictive modeling and supported by research [4]. Thus, the role of the 4th Industrial Revolution enabling technologies towards the achievement of the SDGs is fundamental if the paradigms of data-driven, performance-based, and optimized design process must be universally pursued.

This paper is structured as it follows. After the introduction, Sect. 2 describes the methodology adopted. In Sect. 3, the authors map the recurrence of the urban climate and microclimate-related issues in the Agenda 2030, giving emphasis to possible interlinkages and trade-offs among them and their utility for progress measurement. In Sect. 4, the authors clustered urban climate and microclimate tools according to their features and scale of application. Section 5 specifically focuses on numerical models, providing an overview on the ones most frequently used and quoted by the literature. In Sect. 6, the results are discussed by a matrix summing up the main features of the software and providing some insights on how they may further support the Agenda 2030. Finally, in the Conclusions, the authors open up to the possibility of both integrating data from climate simulations into GIS environments and providing more and more local climate-specific boundary conditions, based on extensive sensor networks, time-series and climate projection data for future scenarios simulations and assessment.

## 2 Materials and Methods

The first objective of this chapter is to put into correlation climate analysis with the Agenda 2030 Sustainable Development Goals. Specifically, the authors highlight how models and tools for climate and microclimate simulation could assist to reach the SDGs (Sect. 3). To this, the authors screened the 17 goals, 179 targets and 239 indicators of the Agenda 2030. Correlations, both positive and negative, are made evident by means of several Sankey diagrams. First, it has been analyzed how Agenda 2030 deals with urban climate and microclimate issues, finding interlinkages with seven goals and eighteen targets. Second, the authors emphasized how urban climate and microclimate models may specifically help measuring progress towards some of the selected indicators, coming from both Agenda 2030 and the *European Handbook for Voluntary Local Reviews* (VLRs) [49]. Third, interlinkages and possible trade-offs both among the selected targets and between them and other Agenda 2030 targets are presented. To this, the European Commission's Joint Research Centre (JRC) *SDG Interlinkages* tool from the *KnowSDG Platform* was used [7]. This tool helps visualizing the cumulated interlinkages from a set of publications, to quickly see and understand for which interlinkages there is strong agreement in the literature. It should be noted that, at the time of finalizing the outputs and figures for this chapter (May 2022), the first edition of the *European Handbook* was available and a previous version of the tool, with less analyzed papers on the SDG interlinkages, was consulted.

In the second part of this chapter (Sects. 4 and 5) a robust overview on the software available for urban climate and microclimate modeling is provided. First, by screening the scientific literature, the authors clustered them into scale, statistical, numerical and dispersion and air quality models (based on [15] and according to the scale of applications (meso- and micro-scale). Second, by screening manuals, websites, and literature providing information on the main commercial solutions available, the analysis focused on numerical models only, identified as the main tools for architects and urban planners to assess the effects of local-scale design options. Third, in the Discussions (Sect. 6) a matrix offers a complete figure to compare the most used numerical models, highlighting their main features, scale of applications, and environmental parameters that can be simulated.

# 3 Urban Microclimate in Light of the Agenda 2030

## *3.1 An Overview: Urban Microclimate, SDGs, Targets*

The 17 Sustainable Development Goals (SDGs) were adopted by the United Nations in September 2015 as part of the 2030 Agenda for Sustainable Development [57]. They replaced the previous Millenium Development Goals by defining a path towards sustainability fitting to all countries. The concept of genuine quality of life for all, to be ensured in respect of the planetary boundaries [50], stays behind the Agenda 2030's vision. Although not legally binding, SDGs have been setting up a normative framework by which cities, as major actors towards climate neutrality, may boost sustainability. However, many challenges remain in fully localizing the SDGs, mostly due to lacking data, the need to establish local priorities in light of policy regulations and a complex framework of highly interlinked targets, and capacity building [54].

Although the term "microclimate" is not explicitly mentioned within Agenda 2030, at deeper look connections among the topic and the SDGs exist and are strong. As recalled by [58], the potential of quality public spaces to contribute to sustainability involve five SDGs (3, 5, 8, 11, 13) and eight targets (3.4, 3.6, 3.9, 5.2, 8.8, 11.7, 13.1, 13.2). In a broader perspective, the authors argue that efforts towards

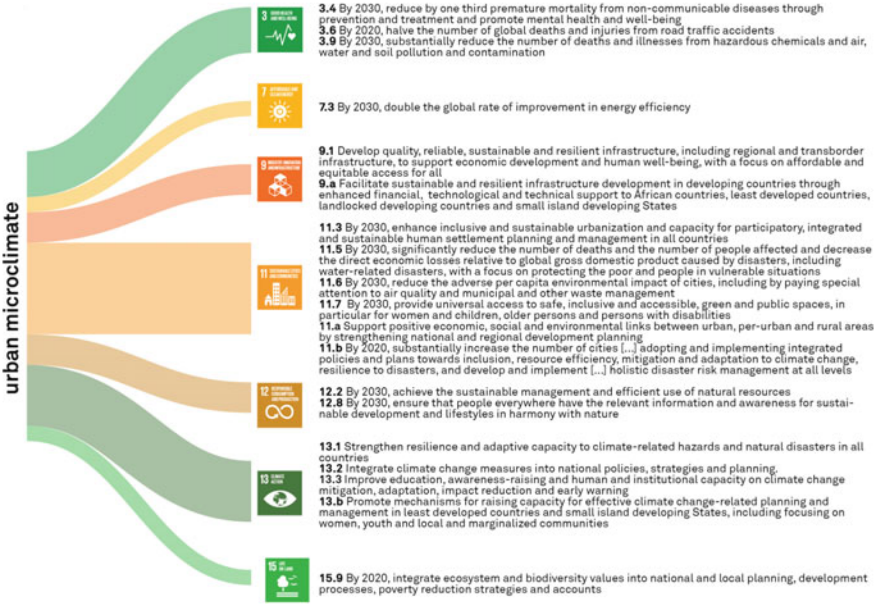


**Fig. 1** Interlinkages between mitigating Urban Heat Island and SDG targets

urban microclimate mitigation by public space redesigning may imply benefits in achieving SDG 7.3 ("By 2030, double the global rate of improvement in energy efficiency"), as lowering outdoor temperatures turns into reducing energy demand for buildings [44]. Besides, it may still have positive effects on SDG 9.1, 9.a, 11.3, 11.5, 11.6, 11.a, 11.b, 12.2, 12.8, 13.3, 13.b, 15.9 (Fig. 1).

### 3.2 *Urban Microclimate: Models and Tools for SDGs' Indicators*

In the context of the Agenda 2030, climate and microclimate modeling tools may assist to measure progress towards the achievement of SDGs, fulfill the lack of intra-urban scala data by simulating, and analyze the effects of policies and design *ex-ante* and *ex-post* [53]. Specifically, among the target interlinkages identified, climate models may provide a strong support to indicators 3.9.1 ("Mortality rate attributed to household and ambient air pollution") and 11.6.2 ("Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)"), when it comes to models able to assess air pollution concentration. However, major contribution of climate modeling approaches is linked to SDG 13 indicators, which can benefit the employment of modeling approaches when it comes to assess national policies facing disaster risk mitigation, local strategies for disaster risk reduction strategies, adoption of national adaptation plans, and the communication of risks arising from climate hazards (respectively, indicators 13.1.2, 13.1.3, 13.2.1, 13.3.1). Finally climate models are still central in contributing to the measure of target 11.7.1 ("Average share of the built-up area of cities that is open space for public use for all, by sex, age and persons with disabilities"), 11.a.1 ("Number of countries that have national urban policies or regional development plans that (a) respond to population dynamics, (b) ensure balanced territorial development; and (c) increase local fiscal space") and both 11.b.1 and 11.b.2 ("Number of countries that adopt and implement national disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015–2030", "Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies") (Fig. 2).

SDG localization is highly challenging: scholars, practitioners, policy makers and practitioners are committed in measuring progress at urban and local level by framing and implementing indicators needing high data granularity. The *European Handbook for SDG Voluntary Local Reviews* (VLRs) [49] provides a "fundamental instrument to monitor progress and sustain the transformative and inclusive action of local actors towards the achievement of the Sustainable Development Goals" in the specific European Union (EU) context. The structure of the *Handbook* (first edition—2020) is lighter than the 2030 Agenda framework and tailored to the EU cities needs: it comes with 72 indicators, each of which is related to one or more SDGs targets. The use of climate models may provide effective support in assessing indicators 49 and 53 (if a pollution concentration module is embedded in the software), 48, 58, 61 (Fig. 2).

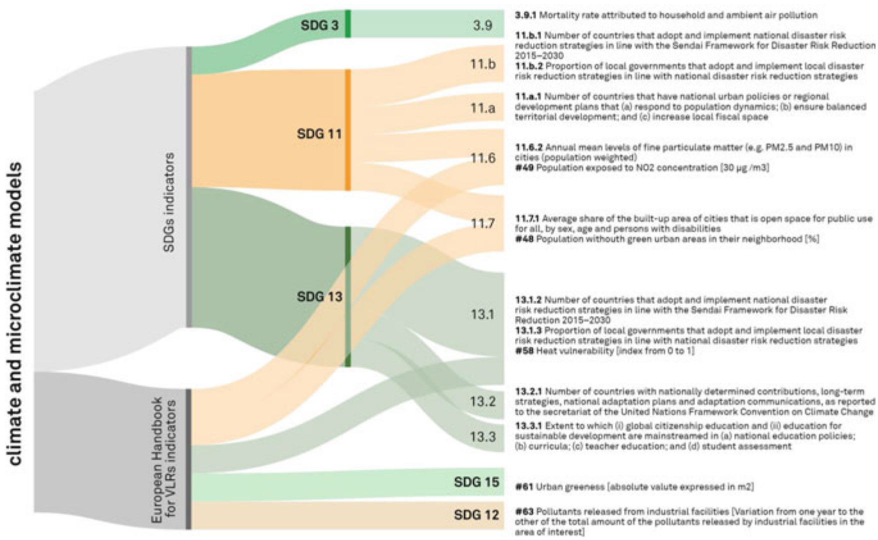


**Fig. 2** Climate and microclimate models in support of SDGs indicators measurement

### 3.3 Mapping SDG Interlinkages and Trade-Offs

The analysis of the potential contribution of climate and microclimate models in achieving the SDGs confirmed that major benefits could be registered in progressing SDG 11 and 13. However, boosting sustainable development in all dimensions (social, economic, environment) implies a systemic approach, assessing interlinkages and possible trade-offs among targets to eventually minimize them [54]. Indeed, according to scholars the general lack of progress in effectively reaching the SDGs [19] is also due to poor understanding and addressing of interactions between goals and targets. As stated by [9], "the challenge lies in identifying and countering inherent conflicts (trade-offs), while harnessing and building on potential synergies (co-benefits) between the 169 targets", to finally unveil the "invisible" nature of Agenda 2030, i.e., enhancing interlinkages among targets to achieve them faster and with minimized drawbacks.

Coming back to highlighted targets, according to the *Interlinkages Visualization tool* (version: May 2022) 11.6, 11.7, and 11.a manifest eight positive interlinkages; among them, strong support to target 3.9, 13.2 and 12 could be provided (Fig. 3). No trade-offs are detected among SDG 11 selected targets and other targets. Moreover, fifty-two positive interactions exist among targets 13.1, 13.2, 13.3 and other targets. Target 13.1 is one with the greatest number of interlinkages (twenty-six), especially with SDG 9 and 11. On the contrary, target 13.2 is the one with major possible trade-offs, especially with goal 14 ("Life below water"). However, no trade-offs are detected among SDG 13 targets and the ones related to urban climate and microclimate (from other SDGs). To conclude, although trade-offs exist and SDG 13 implementation should be managed "with care", no specific drawbacks exist among the selected targets, implying that the targets to which climate modeling may provide support could be achieved independently and eventually providing benefits to other Agenda 2030 targets.

## 4 Climate Analysis Models: An Overview

### 4.1 Clustering Climate Models

**Scale models**. Scale models have mainly been used for the simulation of urban flow, turbulence and dispersion phenomena in wind tunnels and water flumes or outdoors over type-arrays of building-like obstacles. They have been using a range of experimental facilities, maquettes and techniques for measurement of urban canyons that have deeply contributed to the understanding of the urban atmosphere [15]. The development of Computational Fluid Dynamics (CFD) models was also possible thanks to high resolution datasets produced in laboratories. Scale studies were able to demonstrate that small-scale features such as roof shape or tree placement can significantly impact street canyon ventilation rates (Kastner-Klein and Plat 1999).

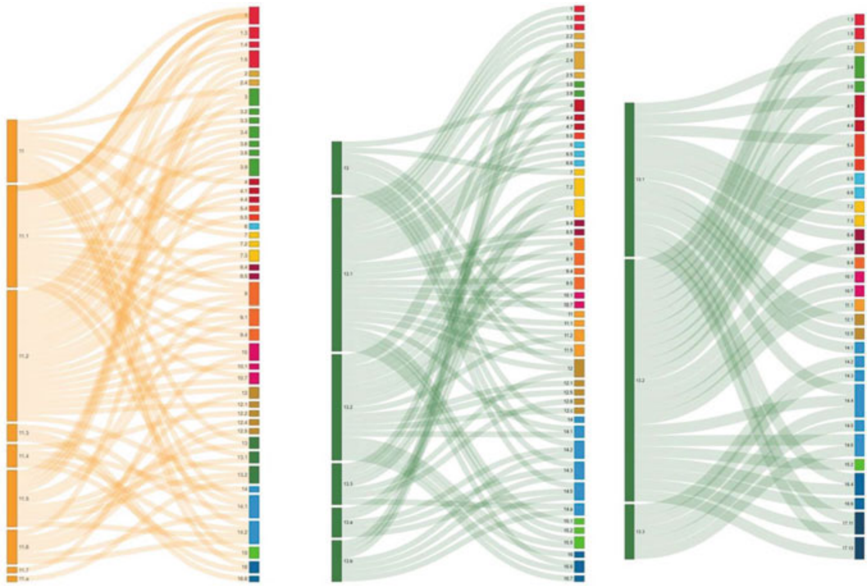

**Fig. 3** In orange, the interlinkages among SDG 11 targets and the Agenda 2030. In green, interlinkages (left) and trade-offs (right) among SDG 13 targets and the Agenda 2030 (*Source* JRC's Know SDG Platform—Interlinkages visualization, https://knowsdgs.jrc.ec.europa.eu/)

Only a few studies used city-scale models, demonstrating that building height has a strong influence on the Urban Canopy Layer (UCL) [15]. One of the limitations of scale models is the size, because of the typical size of wind tunnels allowing only a small range of model scales to be evaluated.

**Statistical models**. Statistical models estimate the effects of cities on climate. Among their main advantages, they usually produce realistic results, require low computational features and input parameters. The disadvantages of certain statistical models imply long observation periods, lack of physical basis and data from many different locations [15]. Their main field of application is the study of the UHI and most of them are simple linear (multiple) regressions of temperature differences between the center of the city and the surrounding area ($\Delta$T), where temperature is calculated as function of several meteorological variables (e.g., wind speed, rural lapse rate, etc.) [22]. More advanced statistical models use spectral analysis, eigenvectors or neural networks to predict risks related to UHI [46]. Statistical relations have been also used for assessing the normalized evolution of UHI, allowing fast forecasts of city temperatures and helping predict future climate conditions [15].

**Numerical models**. Numerical models allow 3D simulation of urban thermal environments to assess the interactions among (vertical and horizontal) surfaces, solar radiation and wind. They mostly deal with the governing equations of the flow (e.g. Navier–Stokes equations). The use of numerical tools is becoming practice at meso- and local scale to assess multiple design alternatives, informing urban planners, decision makers and designers [29]. They are able to provide information about any evaluated parameter in all points of the computational domain and conduct comparative analysis based on different scenarios [6]. Numerical methods are used to predict impacts of different microclimates and design options on the urban environment. The most used numerical simulation approaches are Energy Balance Model (EBM) and CFD [51].

**Dispersion and air quality models**. Dispersion and air quality models are used for evaluation of air quality and prediction of environmental phenomena that could finally affect people's health. These applications vary from evaluation of long-term health effects to short-term emergency response [15]. The complexity of the models depends on the computational speed and storage capacity. CFD models are widely used for urban dispersion simulation today. However, all models should include a meteorological model or parameterization scheme to examine urban phenomena such as wind slowing, turbulence increase, the vertical profile of meteorological variables in the UCL etc. Ideally, the models should also evaluate changes in meteorological conditions between different urban districts [15].

## *4.2 Spatial Scale of Analysis*

Tools for climate and microclimate analysis are usually clusterable according to the scale of application and resolution, too. In this perspective, urban climate-related phenomena were classified as meso-, local, and micro-scale [41], while [29] identified two main domains for climate tools application: macroscale and microscale models. Meso-scale represents a region or city, local scale corresponds to a neighborhood or district area, while micro-scale varies from 10 to 102 m and includes street canyons or single buildings [12].

**Meso-scale models**. Tools for climate analysis on meso-scale focus on the entire city rather than street-level phenomena [29]. The size of the model is usually a few tens of kilometers, with the grid of up to 10 or 20 km on a city scale or up to 100 or 200 km on a regional scale. The spatial resolution is usually 100 or 200 m [29]. Since 1970s, many organizations developed their own models: mentioning a few, National Center for Atmospheric Research (NCAR) and Pennsylvania State University developed their 5th Generation Meso-scale Model (MM5), Colorado State University developed the Colorado State University Meso-scale Model (CSUMM) and later the Regional Atmospheric Modelling System (RAMS). The research on meso-scale climate is mostly done by remotely sensed data and satellite images to derive Land Surface Temperature (LST), which is used for modeling UHI [29, 29], supported by meteorological data coming from urban stations [56]. Other mesoscale studies use numerical models, such as Weather Research and Forecasting model (WRF) [12], designed for "numerical weather prediction systems for both atmospheric research and operational forecasting needs to analyze impact of climate phenomena on the city" [29].

**Micro-scale models**. Research on microclimate at intra-urban level is mostly done by Urban Canopy Models (UCM) or CFD models [60]. CFD simulations for neighborhood scale models are mostly based on area range of 200 m to 2 km and they are commonly used for assessing the impacts of mitigation measures on the thermal environment of local-scale urban area, the relationship between the form and layout of buildings or blocks and the local urban thermal environment [35], the layout and planning of ventilation corridors and its impact on the thermal environment and the relationship between the thermal environment and human thermal comfort indices [5]. At this scale, "the measurements and analyses are usually the most suitable to estimate local impacts and benefits in terms of human thermal comfort at the pedestrian level and the impacts of the different planning scenarios" [29]. Mathematical modeling and simulations are mainly coupled with field measurements in order to evaluate the effects of the urban environment on the microclimate and thermal comfort [12]. UCMs are mainly used for examining the energy budget of an urban canopy layer and the airflow derives from the energy budget equations, unlike CFD models [34]. Both types can assess the impact of various parameters such as building orientation, street aspect ratio, surface materials, vegetation, pedestrian comfort and urban ventilation. However, they both have certain weaknesses. CFD models have limited domain size due to immense computational cost, while UCMs have less detailed presentation of airflow around the buildings [34].

## 5 Focus on Numerical Models: A Comparison

### *5.1 Energy Balance Models (EBMs)*

As recalled by Toparlar et al. [51] numerical models can be further clustered into EBMs and CFDs. EBMs are based on the law of energy conservation and have been used extensively in the past. They take into account energy exchanges between surfaces and ambient air in the UCL and can be used to predict the ambient temperatures and surface temperatures of buildings, pavements and streets [47]. Although they are quick to run and provide accurate results, their major drawback is the absence of air velocity [18]. Indeed, they "separate temperature and velocity fields, such that the assumptions used do not always accurately represent the interaction of velocity and temperature in reality" [47]. According to Imran et al. [18], UCMs are derived from energy balance equations "for a control volume such as two adjacent buildings". Surface and control volumes interact with each other like electric nodes, which results in the matrix of humidity and temperatures. UCMs can be the single-layer canopy model or multi-layer canopy. The difference is that the latter takes into account vertical distribution of the canopy features instead of the average building height [18], providing more detailed analysis but needing more computational resources [60]. The great limitation of the EBMs is the absence of a wind flow field, which causes incomplete representation of atmospheric phenomena. They are not able to determine the latent and sensible fluxes due to the lack of flow pattern information [18].

## 5.2 Computational Fluid Dynamics Models

Compared to EBMs, CFDs have numerous advantages. The main one is that it can assess a wide range of issues "comprising air speed and movement, air quality and pollution diffusion, wind comfort and thermal comfort as well as the effects of relative humidity and vegetation on indoor and outdoor spaces", as well as being readily available and analyzing complex environments [47]. As such, CFD is the most used numerical simulation method at microscale. CFD models include a variety of numerical models from Reynolds-averaged Navier–Stokes, through Large Eddy Simulation (LES) to Direct Numerical Simulation (DNS) [15]. They consider all principal fluid equations in urban areas simultaneously, solving the equations of temperatures, momentum and conservation of mass [18]. CFD simulations can be used to study urban microclimate, user thermal comfort, and pollutant dispersion at both meso- and micro-scale. At micro-scale CFD simulations are conducted with a resolution from less than one meter up to 100 m. Still they are able to represent more realistic information compared to the EBM [18]. However, CFD models have certain limitations. They have high computational requirements due to their complexity and the wide range of environmental parameters and indexes to be assessed (especially for mesoscale models). High resolution representation of the urban geometry is required, along with the knowledge of the boundary conditions and relevant parameters [51]. Furthermore, CFDs may require expertise in governing equations for output interpretation, while "different scales of turbulence in an urban environment require separate modeling and simplified simulation, which may result in inaccurate outcomes" [47].

## 5.3 Most Used Tools

**ENVI-met**. ENVI-met is a CFD 3D microclimate modeling software based on the fundamental laws of fluid dynamics and thermodynamics [48]. It was designed by Professor M. Bruse in 1994 and has been under constant development and scientific expansion ever since. The software uses an urban weather generator to predict the meteorological parameters based on which the most probable weather conditions are recreated [2]. It reconstructs the microclimate dynamics of the urban environment through the interaction between climate variables, vegetation, surfaces and built environment [10]. ENVI-met simulates the atmosphere processes such as air flow, air temperature, humidity, turbulence, radiation fluxes and calculates the indexes and factors of comfort in the urban area—such as Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), Universal Thermal Comfort Index (UTCI) and many others [53]. ENVI-met has been used widely in the microclimate research, urban design and thermal comfort studies due to its ability to recreate microclimatic conditions within the UCL [1, 23, 39]. The application of the software has been validated through numerous studies under different climate conditions. ENVI-met also includes plant physiology and soil science. Indeed, the software takes into account transpiration, evaporation and sensible heat flux from vegetation and air, as well as physical parameters of the plants, water and heat exchange from soil and plant water uptake [43]. The software is grid-based and has high temporal and spatial resolution, allowing accurate microclimate analysis up to a street level. The horizontal resolution typically ranges from 1 to 10 m and it is therefore suitable for intra-urban scale assessment. By the latest version, ENVI-met v5.0, Python was integrated into the system, to facilitate the management and visualization of output results via the DataStudio module. Some other new features (such as the Indexed VieW Sphere and the renovated Albero module for vegetation modeling) are meant to make simulations even more accurate on sun radiation and greenery effects. Due to holistic approach and complexity of the calculations, ENVI-met has certain limitations, mostly regarding the computation time with high space resolution and wide simulation domains, and the high temporal resolution of meteorological data needed (30-min timesteps for full forcing mode).

**SOLENE Microclimat**. SOLENE-microclimat is a simulation tool for modeling at neighborhood scale. It consists of a thermo-radiative model, a CFD model and a thermal building model [17]. SOLENE was developed in the 1990s by CRENAU, *Laboratoire de l'école d'architecture de Nantes*. It was first developed for simulating natural light both outdoors and indoors, taking into account direct solar radiation, diffused sky luminous radiation and inter-reflections [33]. New sub-modules were added as the tool continued to evolve, which allowed it to take into account radiative transfers, conduction and storage in walls and soils, airflow and convective exchanges, evapotranspiration from natural surfaces, energy balance for a building in the simulated area [38]. SOLENE-microclimat is a result of coupling two tools—Code-Saturne which is a CFD open-source code developed by EDF and SOLENE [24]. Code-Saturne allows for calculation of wind speed and airflow distribution within the model. When coupled with SOLENE, a thermo-radiative model, it is able to calculate energy and moisture transportation, based on which it can determine physical characteristics of air and its interaction with urban surfaces [17]. The tool enables parameterization and representation of vegetation, natural soil, green walls and roofs, street humidification, but it is difficult to achieve it on a high level, since it requires a very detailed input and parameters such as leaf area index, water availability and soil/building characteristics [8]. The vegetation layer included in the model takes into account energy transfer by evapotranspiration, radiation and convection [37]. SOLENE-microclimat is able to simulate solar radiation and its impacts on urban surfaces, air flow and its effect, impacts of vegetation and water bodies as well as buildings' energy demand for the whole 3D modeled urban environment [17]. As the outcome of the simulation, outdoor air temperature, humidity, wind velocity and surface temperatures are calculated along with comfort indexes (MRT, PET, UTCI). The advantages of using SOLENE-microclimat are the possibility of representing the whole urban environment [36] and its capability of detail describing, consideration of thermal behavior of buildings, taking into account energy and humidity transfers through green devices and the ability to analyze different greenery types on building energy consumption [42]. The main weaknesses of the tool are the need for coupling with a CFD model for a full assessment and the complexity in terms of program use [8]. There is no user manual, so the guidance is mostly provided by the researchers and engineers already working with it [17] or annual meeting for collective formation [8]. Some modules of SOLENE-microclimat have been validated, such as radiative module, soil, green wall and building. However, due to a wide range of parameters concerning various physical phenomena on different locations, the model has not been validated as a whole [8].

**UMEP & SOLWEIG**. UMEP (Urban Multi-scale Environmental Predictor) is an integrated tool for urban climatology and climate sensitive planning applications [25] developed in Sweden and Great Britain, written as a plug-in to QGIS which makes it easier to use in integrated urban assessments. UMEP analyses can be performed on various scales, from street canyon to city-scale. It is comprised of four main models: the SOLWEIG model (SOlar and LongWave Environmental Irradiance Geometry model), the SUEWS model (Surface Urban Energy and Water Balance Scheme), the BLUEWS model (Boundary Layer Urban Energy Water Scheme), and the LUCY model (Large scale Urban Consumption of energY model) [20]. UMEP enables users to input atmospheric and surface data from different sources, adapt measured meteorological data for the urban environment, use reanalysis or climate prediction data and compare different climate scenarios and parameters. One of the advantages of UMEP is the ability to analyze different scenarios and problems related to climate-sensitive urban design can be addressed within one tool, on various scales [20]. It is also able to integrate relevant processes and use common data across a range of applications. UMEP tools can provide export data for more complex systems and software. Data from more complex models can be imported into UMEP as well [25]. SOLWEIG is a tool for simulation of spatial variation of 3D radiation flux and Mean Radiant Temperature (MRT) in complex urban environments. The tool uses a digital elevation model of buildings and plants for construction of complex urban structures, which results in relatively high accuracy of the simulation [25]. The model requires geographical information, urban geometry, direct, diffuse and global short-wave radiation, air temperature and relative humidity [28]. The tool works best in clear weather conditions, because it does not consider the cloud amount for diffuse radiation calculation, which results in calculation error. It takes into account combined effects of ground, wall and vegetation on reflected radiation. SOLWEIG focuses on radiation scenarios and therefore calculates MRT as the main comfort indicator [8], but PET and UTCI can be calculated as well [27]. MRT is calculated by modeling shortwave and longwave radiation in six directions and angular factors. It also requires continuous maps of sky view factors to determine MRT [26]. The advantage of using SOLWEIG on a neighborhood scale is GIS representation of buildings and other important modeling elements. One of the limitations of SOLWEIG is that it requires spatial datasets that could be difficult to obtain or integrate [8]. SOLWEIG has been widely evaluated and applied at various urban locations [25]. UMEP, as well as SOLWEIG, is a plug-in to

QGIS, allowing the creation of urban climate maps. UMEP is a free tool that encourages users to participate in their development by submitting comments, reporting issues, getting updates and sharing with other users. UMEP and SOLWEIG also provide detailed manuals and training material [20].

**RAYMAN**. Rayman is a largely validated [8] micro-scale model developed by Professor A. Matzarakis at the University of Freiburg, Germany, in 2007 [28]. It is used for calculation of radiation fluxes in simple and complex environments [30, 31], with the aim of calculating various thermal indices in order to evaluate the thermal conditions of different climates and regions (Matzarakis et al. 2017). RayMan is able to simulate different thermal indices: PMV, PET, UTCI, Standard Effective Temperature (SET), Perceived Temperature (PT) and MRT [32]. The model requires certain input data regarding air temperature, humidity, wind speed, short and longwave radiation fluxes and activity and clothing data for calculating PET [20]. Aside from the thermal index simulation, the software is capable of calculating and graphically presenting the sun paths for each day of the year, as well as sunshine duration and shadows caused by the surrounding obstacles [30]. All the calculations in RayMan are performed for one point in space and are time-dependent. The software considers only the thermal effects of buildings and vegetation [8]. It takes into account both simple and complex environments with their radiation properties, albedo and emissivity. It is able to calculate radiation fluxes due to the possibility of various input parameters and forms such as topography input, environmental morphology input, free-hand drawing and fish-eye photographic input. The software also calculates the Sky View Factor (SVF) in different ways, based on fish-eye images, free drawing of the horizon limitation, topographic raster or obstacle [30]. The main advantages of RayMan are low computational requirements and clear structure allowing the non-experts in human-biometeorology to use it [31]. The software is able to simulate the microclimate in different urban environments accurately, due to the precise calculation of radiation effects of the complex surface structure [16]. The preparation of input data can be time-consuming [8], but the main limitation regards the absence of the wind model.

**Ladybug ecosystem**. Ladybug Tools is a group of four environmental plug-ins that are built on top of several simulation engines. It is written in Python, which can be plugged into any geometry engine if the geometry library is translated. It is an open-source interface which unites open source simulation engines. It is connected to the 3D modeling software, which allows the geometry creation, simulation and visualization to be performed within one interface. The tool is mainly known as a Grasshopper plug-in. However, it can be connected to other 3D modeling software, such as Dynamo or Blender. Ladybug Tools consist of: Ladybug, Honeybee, Butterfly and Dragonfly. Ladybug tools are able to assess the thermal conditions and integrate it into the design flow, which makes it a comprehensive instrument for architects and urban planners. They are used for simulating climatic conditions on various scales, from canyon to city scale [32]. Ladybug's components are modular, which makes it capable of evaluating different parameters over various stages of design. Ladybug imports EnergyPlus Weather files (*.epw) which provide weather and location data. Integration with Grasshopper's parametric tools allows for immediate simulation of environmental parameters along with the change in design. This gives designers the possibility to explore the direct relationship between environmental data and the generation of the design [45]. Honeybee performs the analysis of daylight through Radiance, energy models using OpenStudio and envelope heat flow with Therm. Ladybug and Honeybee are capable of simulating the envelope interaction with both indoor and outdoor. They calculate heating and cooling demand with EnergyPlus while evaluating outdoor MRT [13]. Butterfly creates and runs CFD simulations using OpenFOAM, which is capable of running several simulations and turbulence models. Butterfly exports geometry to OpenFOAM and runs different types of airflow design, including simulations of urban wind patterns, indoor buoyancy-driven simulations, thermal comfort, ventilation effectiveness and more. Dragonfly is able to model and estimate large-scale climate phenomena such as UHI, climate change and influence of local climate factors. It is connected to Urban Weather Generator (UWG) and CitySim as well as several datasets which contain publicly available weather data and thermal satellite image datasets. With UWG, Dragonfly is able to estimate hourly air temperature and relative humidity in the UCL [13].

## 6 Discussion

As for the links between urban climate and microclimate issues and the Agenda 2030, the majority of positive interrelations occurs with targets of SDG 11 (six interlinkages), followed by SDG 13 (four), SDG 3 (three), SDG 9 and SDG 12 (two), finally SDG 7 and SDG 15 (one) (Fig. 2). Shifting to targets and indicators, SDG 11, 3 and 9 may specifically benefit from urban climate modeling. Moreover, the indicators addressing (mostly indirectly) urban climate and microclimate issues are fifteen, coming from Agenda 2030 (ten) and the *European Handbook* (five). However, the authors argue that more robust and direct support can be provided to the indicators by the *European Handbook* (specifically to #58 on "Heat Vulnerability"), which are more urban scale tailored with respect to the ones coming from Agenda 2030 but in turn support the achievement of prioritized targets. Besides, we still argue that no indicator within the *European Handbook* supports the measure of people's exposure to Particulate Matter (PM 2.5–10), although it is considered among the main risk factors for cardiovascular, respiratory, and carcinogenic diseases. Major attention to this issue is put by Agenda 2030 (11.6.2), but the annual mean level of exposure may provide no specific insights on site-specific urban level of exposure, which may significantly vary over a city, thus not providing specific support for design.

A wide range of software for urban climate and microclimate modeling to support the achievement of Agenda 2030 exist. According to the main findings, the most used and cited within the scientific literature are presented in Fig. 4, providing a direct comparison among them. Typology, application scale, environmental parameters that can be analyzed, indices simulated, and accessibility are shown for each software. From a general overview two main aspects clearly emerge: first, all the tools analyzed allows simulations at the micro-scale while only a few of them can be used for local and meso-scale; secondly, only about the half of them (e.g., ENVI-met, RayMan, Ladybug tools, Ansys Fluent) offer a wide range of environmental parameters and thermal comfort indices that can be simulated. For instance, air pollution simulation can be carried out by ENVI-met, Ladybug, Ansys Fluent and OpenFoam. The price affordability is another key factor in choosing software. Although most software developed and provided by academia are free, the most used for advanced analysis require an annual license subscription, while free licenses may come with large constraints. Among software analyzed and for design scenario assessment for local adaptation purposes, it is worth mentioning ENVI-met and Ladybug as the two most promising software for microclimate assessment at intra-urban level, considering the wide range of environmental parameters and indexes assessable, great number of papers validating their use, accuracy of the calculation, field scalability, implementability of functions, interoperability with GIS, CAD, Rhino or SketchUp for modeling, and most user-friendly visualization tools and interfaces.

| | Type of model | | Model scale | | | Simulated variables | | | | | | Simulated thermal comfort index | | | | | | | Simulating air pollution | Native module for modelling | Free Accessibility |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EBM | CFD | Meso | Local | Micro | $T_a$ | $T_s$ | $W_s$ | $W_d$ | Q | Other | PMV | PET | UTCI | SET | PT | MRT | Other | | | |
| TEB (Town Energy Balance) | ● | | ● | ● | ● | ● | ● | ● | | ● | ● | | | ● | | | | | | | ● |
| UWG | ● | | ● | ● | ● | | ● | | | | ● | | | ● | | | | | | | ● |
| ENVI_MET | | ● | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | | ● | ● | only with very limited features |
| RayMan | ● | | | | ● | ● | ● | | | ● | | ● | ● | ● | ● | ● | ● | | | ● | ● |
| SOLWEIG | ● | | | ● | ● | | ● | | | ● | | | ● | ● | | | ● | | | | ● |
| UMEP | ● | | ● | ● | ● | | ● | | | ● | | | ● | ● | | | ● | | | | ● |
| Solene-Microclimat | | ● | | ● | ● | ● | ● | ● | ● | ● | | | ● | ● | | | ● | | | | ● |
| Ladybug Ecosystem | | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | | ● | | | | open tools for pay per use software |
| ANSYS FLUENT | | ● | | ● | ● | | ● | ● | ● | | ● | ● | ● | ● | ● | | ● | | ● | ● | |
| TownScope | ● | | | | ● | | | | | ● | | | | | | | | ● | | | |
| OpenFOAM® | | ● | ● | ● | ● | | | ● | ● | | | ● | | | | | | | ● | | ● |
| SkyHelios | ● | | | | ● | | | ● | ● | ● | | | ● | ● | | ● | ● | | | ● | ● |

**Fig. 4** A comparison among the most used numerical software. Abbreviations: EBM (Energy Balance Model), CFD (Computational Fluid Dynamics), Ta (Air Temperature), Ts (Surface Temperature), Ws (Wind speed), Wd (Wind direction), Q (long and shortwave radiation), PMV (Predicted Mean Vote), PET (Physiological Equivalent Temperature), UTCI (Universal Thermal Climate Index), SET (Standard Effective Temperature), PT (Perceived Temperature), MRT (Mean Radiant Temperature)

## 7 Conclusions

The development of a full awareness by architects, urban planners, designers and policy makers on Industry 4.0 potential to drive cities in transition towards carbon neutrality is central in supporting environmentally sound policies. Parallelly, the paradigm of enabling technologies may allow for greater quality of life, in a context—the urban one—within which people's health is threatened by several structural stress conditions, to finally "leave no one behind". This chapter highlighted the specific role of urban climate and microclimate modeling tools with respect to open space redesign, as a means to accomplish climate adaptation and mitigation of the UHI effects within cities, the main "theater" of sustainability-related challenges. As mentioned, climate modeling can be a practical tool for measuring and achieving several indicators of the Agenda 2030 SDGs, especially 11, 13 and 3 when on-field measurable data is scarce or not available. To successfully implement the SDGs, interlinkages and trade-offs evaluation should be central. Climate models for simulating and minimizing the effect of projects on the urban thermal comfort and resource consumption may help to achieve multiple targets, but other targets may benefit from the usage of these tools.

Although still mostly requiring a high degree of specialization, numerical modeling in the field of micro-urban climatology is crucial when it comes to *ex-ante* assessment of several design options, affecting the user comfort, the UHI mitigation and, thus, the climate adaptation scenarios. Indeed, the authors highly recommend the use of such tools for enhancing the role of architecture and urban planning in supporting climate-proof urban landscapes design, as well as to consider possible trade-offs when implementing a project by embracing the SDG framework. Besides, further recommendations may regard the production and use of more and more site-specific and temporal fine-grain input meteorological boundary conditions to rely on accurate climate and pollutant distribution simulation [53]. Finally, enhancing the interoperability of these tools with GIS may constitute a tremendous opportunity to perform complex multivariate analysis, by which to turn climatic data into georeferenced climate maps to be coupled with other type of information (e.g., population density, pattern of land use and coverage, epidemiological data etc.). Indeed, boosting an evidence-based approach in the technological environmental design at urban and micro-urban scale needs updated and robust datasets, accessible to the stakeholders. Turning data on microclimate into georeferenced information may definitely constitute the next field of research for intra-urban scale modeling and simulation. Indeed, the role of open data on urban climate and microclimate, as proper GIS databases derived by advanced simulations, may support a system of shared information policy makers and domain experts may rely on, towards performance-based design as a praxis. In this perspective, performing climate simulations based on projection of temperature rise could contribute to the assessment of climate change impacts in the near future too, strengthening the role of performative design as a sound means to face current and future environmental emergencies and achieve the SDGs.

**Acknowledgements** This chapter is part of the work developed by the Research Unit of Politecnico di Torino as partner of the National Research Project PRIN TECH-START (*key enabling TECHnologies and Smart environmenT in the Age of gReen economy, convergent innovations in the open space/building system for climaTe mitigation*). This chapter is the result of a joint research by the Authors, who are equally responsible for it.

Author contributions: Conceptualization, M.T. (Matteo Trane), R.P. (Riccardo Pollo); investigation coordination: M.T., M.G. (Matteo Giovanardi), R.P.; methodology: M.T., A.P. (Anja Pejovic); literature selection and review process, M.T., A.P. (Anja Pejovic); writing—original draft, M.T., A.P.; writing—review and editing, M.T., M.G., R.P. All authors have read and agreed to the published version of the manuscript.

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# Industry 4.0 and Bioregional Development. Opportunities for the Production of a Sustainable Built Environment

**Luciana Mastrolonardo and Matteo Clementi**

**Abstract** The paper answers the question about how the technologies characteristic of industry 4.0 can support the bioregional development paradigm, focusing on local building production chains to support the energy retrofit of existing buildings. In particular it investigates design choices capable of activating supply chains that can intercept real and already existing spending flows and activate a workforce capable of evolving the anthropic system in the same direction characteristic of the natural systems. The paper focuses on the description of the features that industry 4.0 could assume in the field of building production to support energy requalification, reorienting urban metabolism of neighborhoods or small settlements towards local territories. It describes the characteristics of technologies adopted in the Industry 4.0 paradigm, in the context of open data, open-source software alongside low-cost microcomputers and sensors, and illustrates their potential in the possible activation of generative local microeconomies. Acceleration, digitization and automation of the construction sector are showing the relevance of having open real-time information to support decision-making processes. In particular the text focuses, on the one hand, on the applicability of such technologies and devices to areas characterized by very limited resources (such as for example the internal and more fragile areas in Italy); on the other hand, on how they enable community of prosumers and local cooperatives to complex productive activities characteristic of the energy communities.

**Keywords** Circular architecture · Data-driven design strategies · Real environmental performance-based design · Time digital representation and visualization · Enabling community

**United Nations' Sustainable Development Goals** 7. Ensure access to affordable, reliable, sustainable and modern energy for all · 8. Promote sustained, inclusive

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_16

and sustainable economic growth, full and productive employment and decent work for all · 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 12. Ensure sustainable consumption and production patterns · 13. Take urgent action to combat climate change and its impacts

## 1 Industry 4.0 for the Bioregional Development

Industry 4.0 has been focusing on the use of integrated technologies for improved efficiency and flexibility in the production. Its role in Europe recently emerged and evolved in Industry 5.0 on the social, societal and environmental concept of:

(1) Human-Centric Approach: involving human need in the production process adopting technology usage and the production process to the workers' needs;
(2) Sustainability: technology should be used to optimize resource efficiency, minimize waste, reduce energy consumption and greenhouse emissions and use local renewable sources and develop circular processes.
(3) Resiliency: industrial production should be adaptable in the times of crises, such as geopolitical shifts and natural calamities with resilient strategic value chains, adaptable production and flexible processes [1].

Industry 4.0 and the democratization of machines open up new possibilities and support the construction industry to implement Circular Economy standards and achievement of the S.D.G.s, promoting resource efficiency from project inception to end-of-life. By incorporating circular design requirements and innovation into the technologies, such as design for disassembly, deconstruction, and recycling, properly manage the waste stream, and close the materials loop and by increasing the efficiency in material use and reducing the use of non-renewable natural resources, promoting the use of renewable resources. The terms circular and renewable find an effective synthesis in bioregional development as man-made systems in which energy and matter demand and supply tend to meet on the same territory, increasing the efficiency of use of resources, using mainly locally available renewable ones. The same model finds support in the theories relating to a generative economy [2].

The need for sustainable communities (UN-SDG11) sees the model of bioregional development as the most eco efficient one, since it most closely reflects the characteristic dynamics of evolving living systems. That is, in accordance with the maximum empower principle, towards the maximum use efficiency of solar energy incidents on the local territory [3]. It constitutes a promising reference model that combines environmental sustainability and circular economic development [4–6].

The construction industry is facing the opportunity to benefit from the open availability of digital data and online digital access, to really interconnect physical and digital information. This evolution transforms the business models, enabling transitioning the current reactive to a predictive practice and reducing waste.

The link between Industry 4.0 and construction was primarily based on the potential of digitization and identified four key areas: digital data, automation, connectivity and digital access [7]. They are represented by a confluence of three main trends: industrial production and construction, cyber-physical systems and digital technologies. The increasing importance of concepts such as sustainability, human centric, resiliency and therefore bioregional development imposes tighter constraints based on the intensification and optimization of relations between the built environment and the territory. Open availability of digital data and online digital access can provide the communities inhabiting the territories with tools capable of creating new economies based on the optimal use of territorial metabolism starting from a theoretical basis already consolidated over time.

## 2 Bioregional System, Built Environment and Upcycling

Industry 4.0 is particularly interesting in its relationship with bioregions, defined through physical and environmental features, including watershed boundaries and soil and terrain characteristics and emphasizes local populations, knowledge, and solutions. Bioregion's environmental components (geography, climate, plant life, animal life, etc.) directly influence ways for human communities to act and interact with each other which are, in turn, optimal for those communities to thrive in their environment. As such, those ways to thrive in their totality—be they economic, cultural, spiritual, or political—will be distinctive in some capacity as being a product of their bioregional environment [8].

In a path towards local self-sustainability, the construction of informed and connected flows of energy and material, through technologies, defines the possibility of a low-tech sector at the service of its territory, perfectly integrated with agricultural resources (through sensors, constant evaluation of performance and robotization of production phases), to disused urban stocks and urban mining, and variables of local energy demand that can be defined through real-time evaluations of energy and sun light flows, as climatic conditions [4].

The Industry 4.0 model insists on system innovation related to robotization as an indispensable instrumental method for renewal of production processes. The integration of machine-to-machine communication and the internet of things (IoT) help to increase automation and improve communication and self-monitoring. Industry 4.0, when combined with the circular economy, represents an industrial paradigm enabling new strategies of natural resource use [7, 9]. In turn, the circular economy is driving more attention in support of innovative life cycle management, communication, and the development of smarter systems reconceptualizing waste as intrinsically valuable. This industrial revolution relies on digital technologies such as wireless connectivity and sensors that connect everything to everyone to gather data to analyze, visualize the entire production system, and provide applicable information to the business system [10].

Built environment is part of city metabolism as a palimpsest of urban stock, a record of human history partly erased and rewritten. The urban structure grows during time, through a succession of reactions and processes that develop from previous stages, a territorial morphology expresses a continuity of development, and a vital and unifying exchange with the environment. Thus, time appears as the great 'master builder' [11] to which human settlements owe their most durable, fittest configuration within a given environment: time becomes a key factor in this evolving system of resources, describing a variable configuration model, related on season, resilient capacity and region based. In Olgyay's work, the term "region" relates to the solar altitude angle, and the regional characters of buildings are defined in terms of heat conservation, thermal demand, orientation, natural lighting and ventilation. Olgyay explained how basic building forms, in traditional architecture, answer to the needs of comfort and protection against the local environmental difficulties; yet there is no prosaic determinism in this approach.

Upcycle principles encourage designers—and anyone interested in this new approach –to see everything on Earth as having potential to be something else. Realize that there is not a garbage can, forget the concept of "trash" and consider that everything has to go somewhere and become useful [12]. The challenges we face are multifarious—population pressure, climate change, energy security, environmental degradation, water and food availability—to name a few. To address them we will have to change our business and production processes, become significantly more energy and resource efficient, and minimize waste. Advanced technologies will accelerate this process of transformation and will play a pivotal role in addressing the immediate need of resource conservation and climate change concerns. Technology supports in utilizing renewable energy resources, developing smart grid systems, making efficient public infrastructure producing environmentally friendly materials and products will be crucial to achieve the overall goal of sustainability.

## 3 A Method from Big Data to Territorial Metabolism GeoData

### *3.1 The Informed Open Source Material/Energy Databases*

The text presents a method and specific tools aimed at creating open source databases to support the development of integrated material/energy systems for the production of building material and energy from locally available resources. The proposed methodology was developed starting from the open data available on Italian territory, with the intention of allowing local communities to implement this information with self-detected data. The objective is enabling the local community to trigger processes aimed at bioregional development, activating local economies and transferring existing good practices, through an information platform. This objective is achieving through:

1. The preparation of a georeferenced information system starting from open data currently available to all minor municipalities throughout the country.
2. The implementation of geodatabase with data made available to the local community through self-detection activities using low-cost sensors.

The final result would constitute a Territorial Metabolism Geodatabase (TMG) to support the development and application of design strategies. In order to meet the emerging role of Industry 4.0 on Human-Centric Approach, Sustainability and Resiliency, the method aims to map specific information on the same IT medium.

With regard to the Human Centric Approach, the methodology arises from the awareness that in order to trigger new circular and local economies in small settlements, it is necessary to intercept the local expenditure flows starting from the expenditure flows manageable by the public initiative. The provision of this information allows to identify and quantify the money leaving an area and therefore formulate a solution for a sustainable local development processes. Housing, food and transport make up the main spending streams of the settled population [5] (Fig. 1).

The pursuit of environmental sustainability, together with the need to activate circular economies at the local scale, imply matching local demand for energy and material and available resources, in compliance with the regenerative cycles of ecosystems. For example in the sustainable retrofit of existing buildings [13, 14], in order to redesign integrated supply chains of energy and building materials that intercept the largest share of expenditure flows, it is essential to supplement the data relating to the local demand for energy and materials, with the outflows from the system and the renewable resources available and not used (Fig. 2).

The increase in Resiliency is instead closely linked to the possibilities offered by the method in managing the temporal variability of the data. In fact, the information associated with the demand for energy and matter allows us to understand its variability over time and that the same happens for the mapping of flows leaving the system in the form of waste and other renewable resources available locally. For example, this type of data availability allows the easy passage from one supply

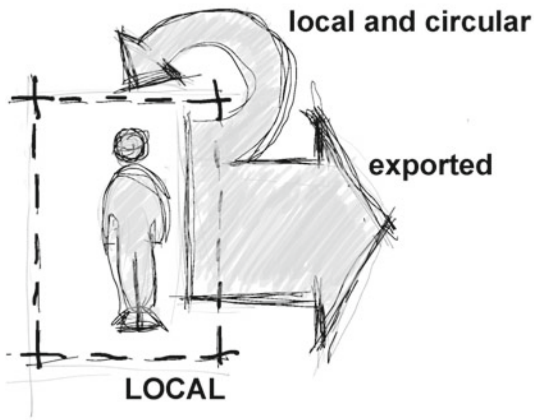


**Fig. 1** Human centric approach for circular economies associated with spending flows

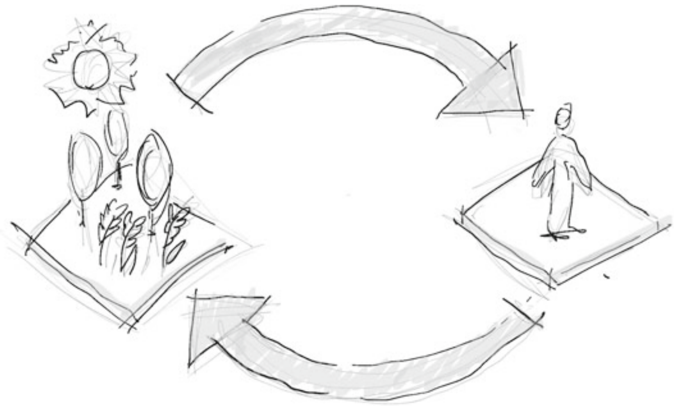

**Fig. 2** Sustainability for circular economies

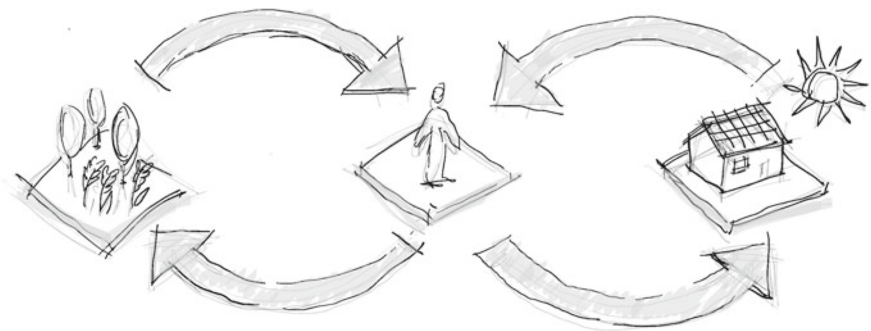

**Fig. 3** Resiliency and temporal variability for circular economies

source to another simultaneously available, increasing the resilience level of the supply system. In order to have useful data available to understand the variability of the territorial metabolism in different periods of the year and over several years, it is essential to define appropriate time intervals to describe the complexity of the territorial system and at the same time predict the possible effectiveness of improvement practices. The time intervals considered refer to the monthly, annual and five-year average. The monthly average figure is a useful compromise in order to make such complexity manageable (Fig. 3).

## *3.2 The Local Territorial Metabolism Data Analytics*

The elaboration of thematic maps and the publication on a shared portal make it possible to relate the estimated data to each other [15], and to integrate such assessment with the data actually collected. By integrating new methods of data collection and analysis, stakeholders would be able to take evidence-based decisions on resources allocation and product use and query their processes to meet the local energy necessity. Open source tools, low sensors and microcomputers give the possibility to map the punctual availability of underutilized resources, such as the amount of solar energy on the ground and on buildings envelope, of biomass or other resources such as hydro and wind power (including in the same dataset agricultural wastes, municipal solid waste, and waste heat in the sewage system). In summary, the scope of Big Data Analytics would turn into Local Territorial Metabolism Data Analytics [4, 9] and is closely linked to the local community's ability to produce and self-manage open information oriented towards the generative use of local resources.

The proposed methodology and application tools are divided into the following phases (Fig. 4):

1. LDEM—Mapping the local demand for energy and matter, and therefore the availability of expenditure of the settled community.
2. LR—Mapping local renewable energy potential.
3. EF—(Exported flows) Mapping material flows out of buildings/open spaces.
4. AW—Mapping the potential workforce and skills available locally.
5. DB—Sharing a database of local closing cycles practices.
6. Defining parameters to verify the transferability of best practices; starting from the information mapped and collected in a single open source Geographic Information System.

### *3.3 Open Tools and Open Data*

The current development of the open source software allows operations of big complexity and it gives the possibility of using complex data even to actors who cannot purchase proprietary software such as local administrations, especially minor ones, and designers who are not directly involved in urban planning. These tools represent an important opportunity to process and communicate information to support decisions aimed at designers, planners, and local communities. The open source feature of these tools meant possible to merged some tools into specific platforms and the creation of specific institutions and related websites that report news relating to the current level of development of such tools, such as the Open Geospatial Foundation. Among the open source GIS tools made available, the elaborations of this work used Quantum GIS (QGIS) and GRASS-GIS.

The method starts from the information normally made available to citizens to create support tools for decisions that can be managed from below. Therefore, to ensure the replicability of the procedure to a wide audience the research relies exclusively on open data provided by government and institutions. The open-access data used for the development of the present case study are described in Table 1. In order to be able to create a common geo-referenced database and correlate the information, the data on the geometry of the buildings available or other data relating to smaller areas, have been aggregated by the census block.

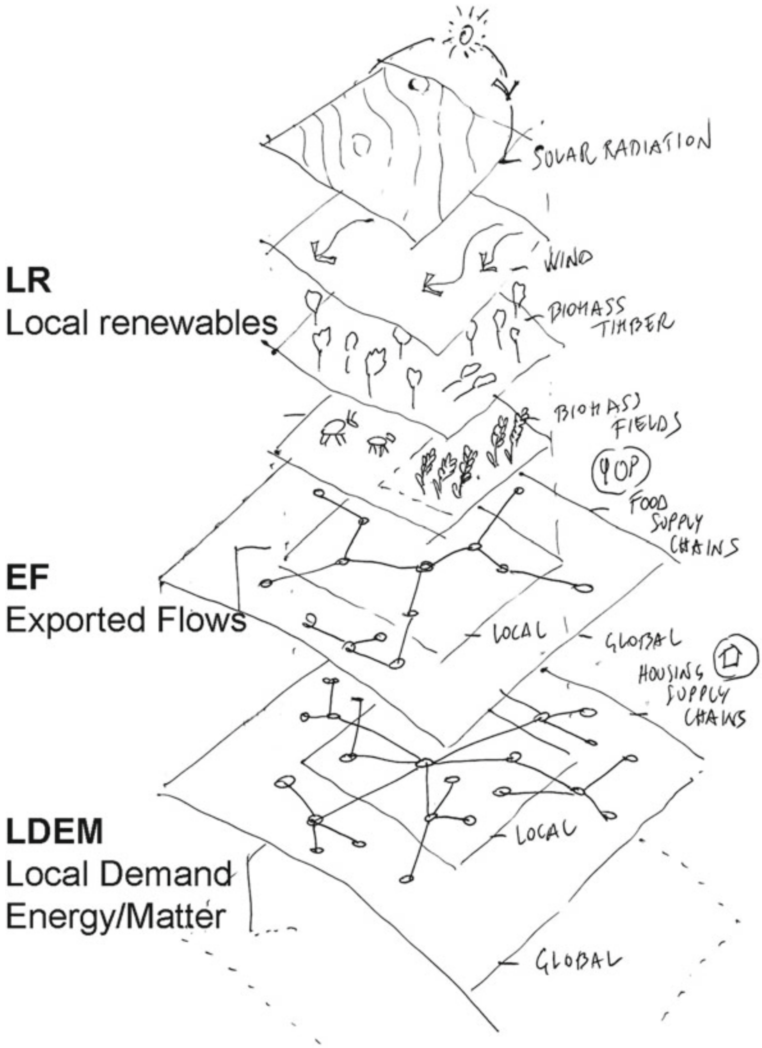


**Fig. 4** Phases of methodology and application tools

# 4 The Case Study

## *4.1 Local Territory*

To test the effectiveness of the methodology, an internal area of the Abruzzo region representative of the Italian minor municipalities was chosen as a case study: San Valentino in Abruzzo Citeriore (Pe). The smaller municipalities of inland areas are

**Table 1** Source data table

| Data | Data type | Source |
|---|---|---|
| Populations, households, industry, services | These datasets include information on the height of the buildings, the number of dwellings, the construction system and period together with population age group and number of inhabitants | Italian National Institute of Statistics [16] |
| Regional data consumption | Data on household consumption in the Abruzzo region | CRESA [17] |
| Urban waste flows | Data from the regional urban waste observatory | Regional observatory [18] |
| Energy | Preliminary assessment of possible energy consumption, divided by different consumption categories in the municipality of San Valentino | SEAP San Valentino [19] |
| Land use | Productive land available, using the Copernicus georeferenced database which publishes the different land use destinations and the related geometric configuration for the entire European territory | CLC [20] |

**Table 2** Comparison with average national data

| | Total productive land (sqm/inhab) | Agricultural (sqm/inhab) | Woodland (sqm/inhab) | Pasture (sqm/inhab) |
|---|---|---|---|---|
| Italy | 4.362 | 2.540 | 1.519 | 303 |
| Abruzzo | 7.682 | 3.675 | 2.322 | 1.685 |

characterized by a large availability of resources per capita and allow for experimental alternative models of local development. The availability of natural capital per capita is in fact higher than the Italian average. The data in the Table 2 constitute comforting information on the vocation to sustainability of the minor municipalities of the Abruzzo area and make it a candidate for possible experiments oriented towards bioregional development (Fig. 5).

## *4.2 LDEM Mapping of the Main Spending Flows of the Local Community*

The results associated with the progress of the geodatabase are developed in the municipal area of San Valentino with the mapping of the main expenditure flows. With 1922 inhabitants, the energy needs in 2008 was estimated at 31,053.21 MWh/y and probably a small negligible part comes from biomass (in particular wood). Otherwise the municipality depends on petroleum products, natural gas and electricity. Petroleum with 18,735.38 MWh/y is the most substantial part (60%) of the total

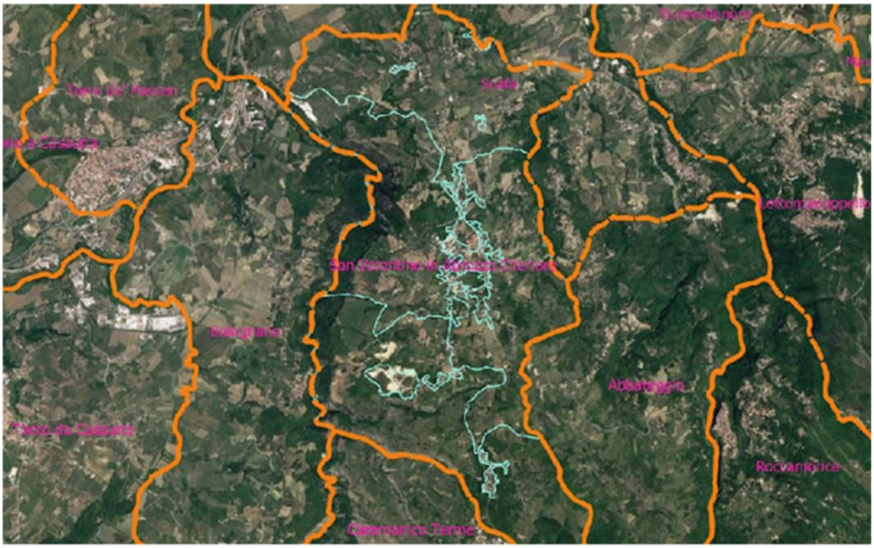


**Fig. 5** Profiles of the municipality of San Valentino and neighboring ones (in orange) superimposed on the profiles of the census blocks of the municipality (in light blue)

energy of which diesel—among the by-products—reaches the primacy of the overall supply with 12,458.59 MWh/y (40%) followed by natural gas with 8,504.65 MWh/y (28%), gasoline with 6,267.64 (20%) and electricity with 3,715.54 MWh/a (12%). The LPG does not represent an important part at the percentage level. The data below can be integrated with information relating to food costs, which together with housing and transport costs represent the main consumption categories of a community (Table 3).

By associating the unit costs of fuels with the main energy consumptions reported in the SEAP [19], it was possible to quantify the costs related to household utilities and transport and compare them with food costs. In particular, the graph in Fig. 6 compares the consumption categories that are most suitable for an experimental use of local resources and for the activation of possible synergies for housing. The interceptable dynamics that require the least investments are related to the supply chain of cereal products, vegetables and legumes and the supply of fuel for winter heating. However, this assumption is not sufficient and it is necessary on the one hand to map information useful for verifying the effectiveness of these strategies, and on the other hand to understand the local weight of public initiative in promoting strategies oriented towards integrated supply chain planning.

**Table 3** Energy use by sectors in San Valentino

| Sector | Transport | Residential | Tertiary | Agriculture | Public |
|---|---|---|---|---|---|
| Energy use | 54% | 29% | 5% | 4% | 3% |

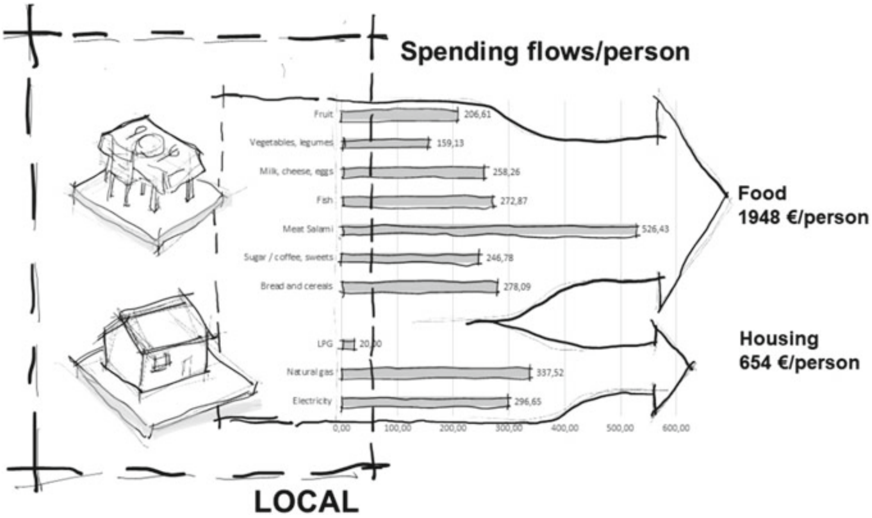


**Fig. 6** Main spending flows associated with a San Valentino inhabitant and relating to the categories of consumption, food and home

Once the data on the resident population and on the physical configuration of the urban space have been collected, the geolocation of the information associated with the expenses of the local community can be carried out in two specific ways. A first preliminary assessment associates the data on household expenses with the individual census blocks information, as the number of inhabitants. A second method associated some items of consumption refined with a specific assessment of the energy consumption of buildings, with the different building shapes and technological features. At the current state of research, the assessment of the expenditure flows of the settled community was conducted using the first method. Among the energy costs associated with housing, the main one is related to winter heating followed by electricity consumption: it gives indications on the possible willingness to pay for alternative solutions, or the willingness to face an investment beyond the public incentive systems.

Future developments intend to refine the current development status of the TMG with specific data used for further processing. Data mapped by census block and based on estimates of needs and statistical regional data have to be implemented with the direct contribution of the inhabitants with a participating monitoring. In particular, the data made available to the SEAP [17] are associable to the consumption in a specific year (2008) to each polygon relating to publicly owned buildings. The continuous updating of these spending flows in the TMG itself would be extremely useful.

### *4.3 LR: Mapping Unused Renewable Energy and Material Potential*

According to the various land use destinations that characterize the local area of reference, this phase of the methodology aims to assess and map the type and amount of renewable energy available. Whereas it is not a very densely inhabited area, the research project maps the solar renewable energy potential together with the possible production of energy and materials from renewable sources obtainable from types of territory such as arable land, pasture and wood. In San Valentino the municipal area amounts to 16.39 km$^2$, the availability of land per person is 8531.56 m$^2$. The productive area per person is equal to 8.332 m$^2$ (of which 7.129 for agricultural use and 1.203 forest) [20] (Fig. 7).

The availability of productive land present in the municipal boundaries divided by the number of inhabitants. The potentially usable area for the installation of solar collection devices is a percentage of the built up area, and gives indications on the amount of land made biologically unproductive usable for the collection and use of solar energy. The topographic database (RTDB) allows to enrich the TMG with information on the geometry of buildings. It associates the eaves height to the building's polygons. That information, together with the street level contour lines, allows for generating high-resolution digital elevation models (DEM-1 pixel/50 cm) useful for mapping solar radiation incidents on open spaces and roofs, thanks to tools such as the one proposed by Hofierka [1]. If accompanied by isopleths, these maps can be consulted using common web services such as Google Earth (Fig. 8). The quantities relating to solar radiation, thus included in the TMG, would indicate the precise conditions of solar radiation representative of the monthly average associated with diffuse and direct solar radiation, and to distinguish the portion that affects the roofs from the one related to the open spaces (Figs. 9 and 10). These themes, superimposed on the mapping of publicly owned buildings, are able to identify those census blocks in which the availability of incident solar radiation on roofs or open spaces of public management is greater [21].


**Fig. 7** Surface of production area available per person in the municipal area of San Valentino

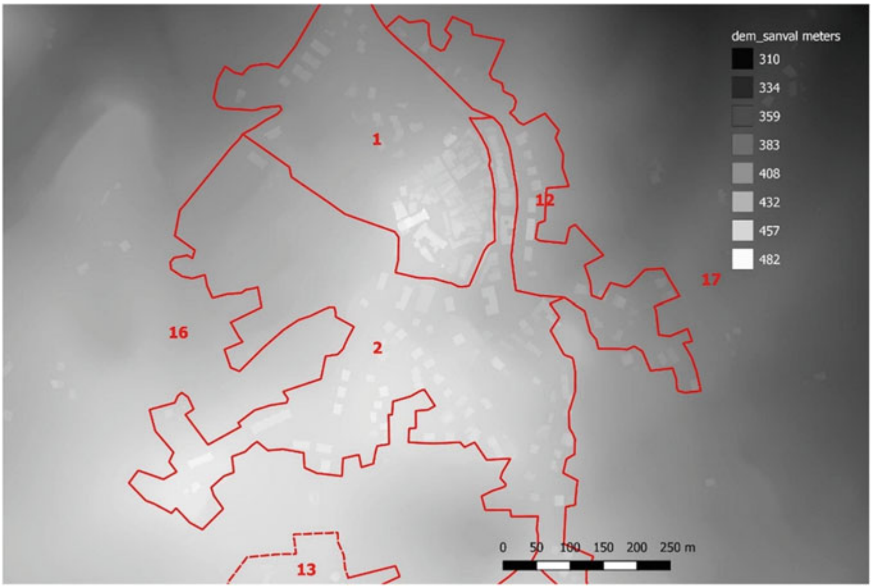


**Fig. 8** Digital elevation model of a portion of the urban area of San Valentino (resolution 1 pixel side: 0.5 m) with in red the profiles of the census blocks

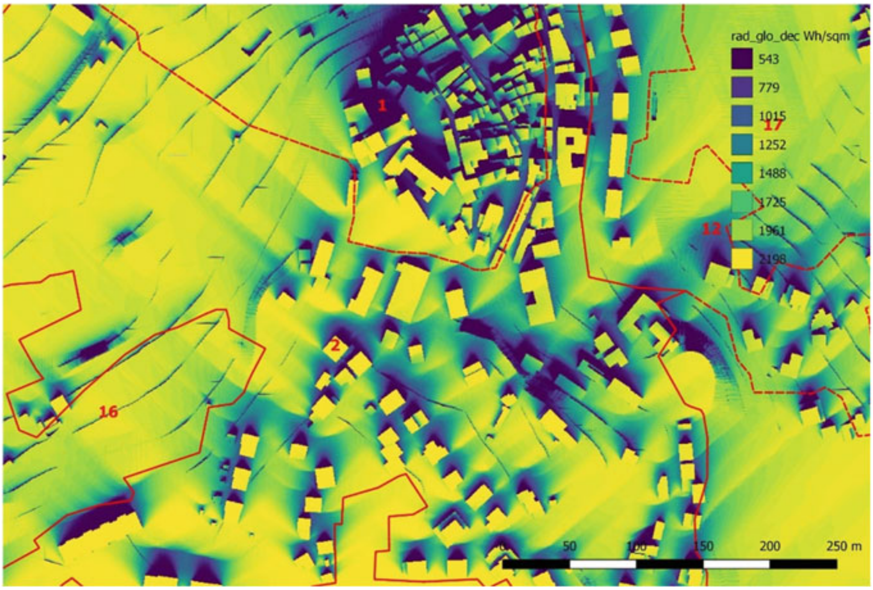


**Fig. 9** Map of direct solar radiation representative of clear sky day of December (unit of measurement Wh/sqm * day), in the red profile of the census blocks

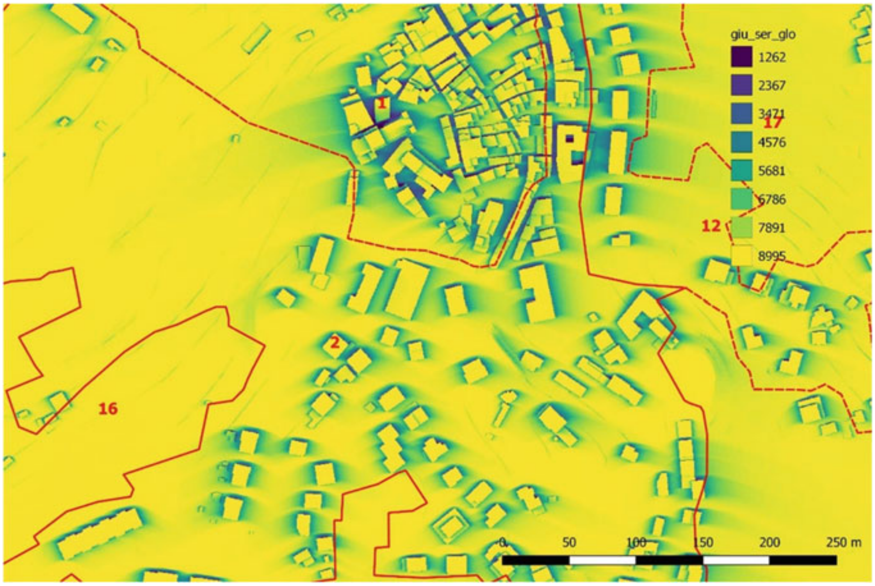


**Fig. 10** Map of direct solar radiation representative of clear sky day of June (unit of measurement Wh/sqm * day), in the red profile of the census blocks

## 4.4 EF—(Exported Flows) Mapping Material Flows Out of Buildings/Open Spaces

The mapping of outgoing material flows as solid urban waste was carried out by associating the per capita yearly flows and associate outgoing household waste material flows for the area. By multiplying the quantities of waste generated with the number of residents, the total amount of MSW generated within the area can be obtained.

The current level of resolution of the TMG allows to visualize:

– information on the geometry of the surfaces occupied by different land use destinations;
– maps of the relative solar irradiation representative of the monthly average that take into account the geometry of the buildings;
– the flows of waste emissions by census block.

The use of low-cost sensors and facilitated forms of database self-compilation would make it possible to refine the database by inserting information on future crop planning in advance. In the case of solar irradiation maps, sensors positioned on some roofs allow to compare the data relating to the monthly statistical average with the real irradiation data. Finally, as regards the emission flows of TMG waste, it could include the flows actually conferred by individual users, through the weighing of the tubs (Figs. 11 and 12).

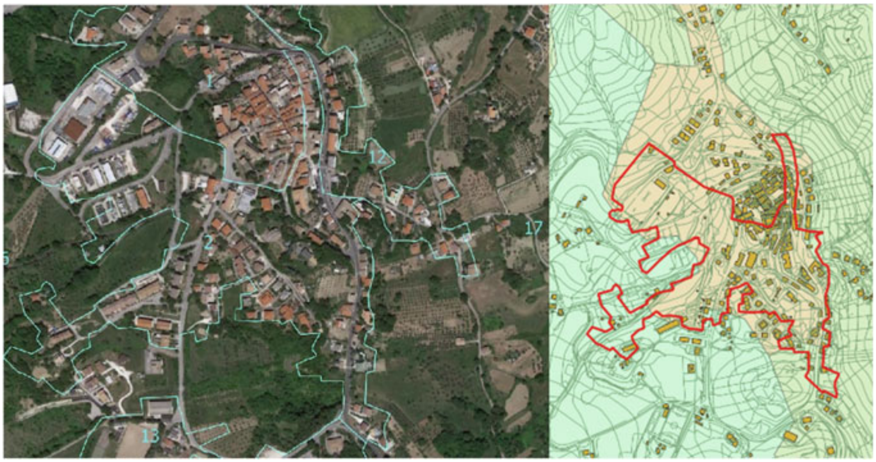

**Fig. 11** Geometric configuration of some of the census blocks of the more urbanized area of San Valentino; CB2, in the center, records the presence of publicly owned high-level solar roofs

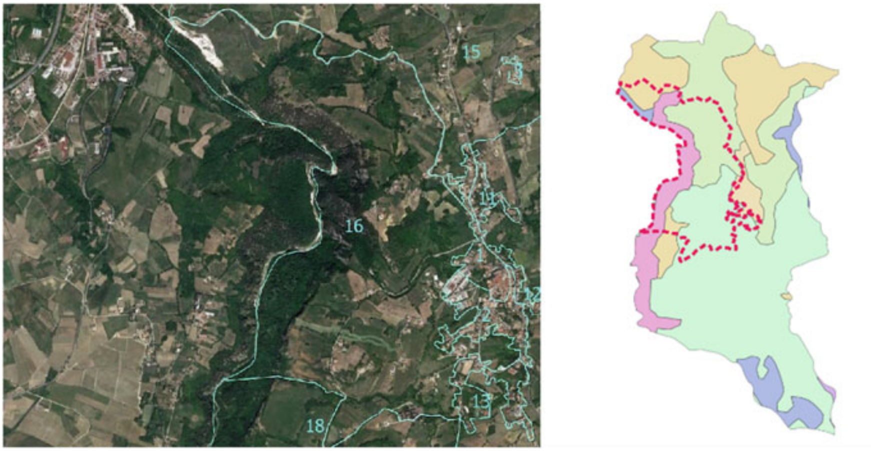


**Fig. 12** Geometric configuration of some of the census blocks of the San Valentino area most suited to plant production. The west boundary of block 16 is covered by publicly owned woodland

### 4.4.1 AW: Mapping the Potential Workforce and Skills Available Locally

Among the unused local resources, person-hours are a fundamental component. The real possibility of triggering local prosuming processes depends on local availability of human resources. Useful information on the available person-hours are obtainable by crossing age-groups with employment status within the census data (Fig. 13).

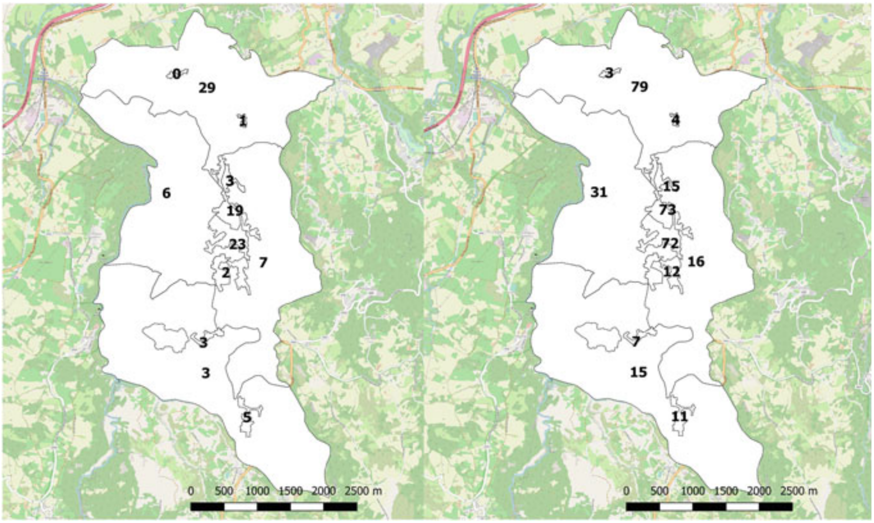


**Fig. 13** The map on the left illustrates the number of unemployed by census block, the map on the right illustrates the number of unemployed and housewives by census block

For the present case-study the following categories were selected:

– Total resident population more than 15, unemployed seeking new employment
– Total resident population aged 15 and over, non-labor force
– Total resident population aged 15 and over, house husbands and housewives
– Total resident population aged 15 and over students.

Due to the restrictions associated with the current pandemic emergency, the data relating to the presence of unemployed are changing considerably. It is therefore of fundamental importance to integrate the data already mapped with what will be detected by the current census activity at the end of 2021 [22].

## 5 Closing Local Loops: Abacus of Best Practices

### *5.1 Defining Scenarios*

The data stored in the TMG constitute an information base aimed at becoming a collaborative platform, updated in real time through sensors, and associated with further quantitative community data. The update is in real time through algorithms shared with the community that intervenes on some categories of data:

**Table 4** Good reference practices

| Group | Product | Uses | Level of tech | Case study |
|---|---|---|---|---|
| *Energy* | | | | |
| Timber | Pellet or wood chips | Heat, electricity generation | Medium | Trentino forest management |
| Photovoltaic | Electric energy | Public building or private facilities | Low | Energetic communities |
| Local energy | Biogas | Heat or electric generation | Low | Local farm |
| *Material* | | | | |
| Cellulose | Recycled cellulose | Insulation, cardboard, construction | Medium to hight | Applied CleanTech |
| Hemp | Shives (woody bark) | Building materials (blocks, insulation panel) | Low to medium | Edilcanapa in Abruzzo |
| *Data* | Public dataset | Collaborative platform | Theoretical | – |

– through sensors associated with cultivation, buildings, production activities
– through manual data implementation methods.

Starting from existing good practices, different scenarios are simulated aimed at bringing together local expenditure flows with the potential local production. The identified expenditure flows are related to the resources available locally and respond to local needs by making materials and energy available, focusing on the seasonality of local resources. The table shows some good reference practices which refer to the possible circularity of resources and highlight connections that intercept the potential for local triggering of entrepreneurship or the availability of public goods capable of hosting production at km.0 (Table 4).

## 5.2 Example Scenarios

This paragraph briefly presents two examples that illustrate the potential use of the data stored in the TMG to verify the transferability of some good practices by developing simplified scenarios. In particular, scenario 1 works on the possible transfer of the good practices comparing them with strategies aimed at local food production (Fig. 14):

– BP1—use of woody biomass from forest maintenance to cover the thermal needs for winter heating of buildings;
– BP2—use of photovoltaic roof systems, connected to the conventional grid, to produce electricity from solar sources.

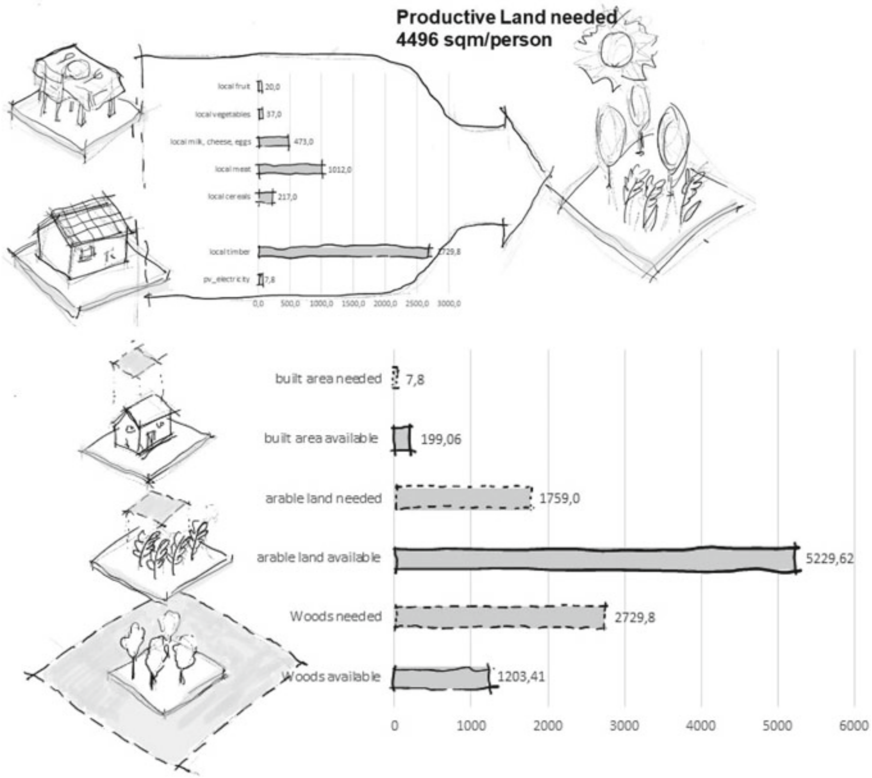


**Fig. 14** Productive land necessary to locally cover energy and material needs and data relating to the production area available per person and the area necessary to cover energy and material needs (Scenario 1)

From the comparison between the TMG data and relating to the extension of production area needed and actually available, it emerges that the energy needs relating to winter consumption for heating homes exceeds the actual local availability of woody biomass (considering with the local regenerative cycles). The activation of possible local micro-economies aimed at intercepting the flows of expenditure associated with the energy needs for heating homes will therefore have to develop integrated supply chain projects. They will be oriented on the one hand to cover local energy needs with locally available resources, on the other hand to activate useful strategies to increase the energy efficiency of the homes. The local production of insulating material such as hemp, thanks to the availability of arable land has high potential for success.

Scenario 2 provides for the possibility of growing hemp to be used as an insulating material, in particular the graph in the Fig. 15 shows how a reduction in the thermal transmittance of the building envelope equal to 0.17 W/sqm*K, would correspond to a reduction in consumption energy equal to 2/3 of the initial value. The implementation of activities aimed at the integrated development of the energy supply chain and the insulating material would involve a remodeling of the surfaces of the necessary production area. Optimistically hypothesizing to produce the insulating material in an annual cultivation cycle, the production land balance would see an increase in the arable land component equal to 800 sqm/person, to the advantage of a reduction in the extension of woods useful for producing energy of about 1700 m$^2$ (Fig. 15).

The comparison between available productive land and necessary land in Scenario 2 shows that the needed surfaces do not exceed the amount of available areas (Table 5).

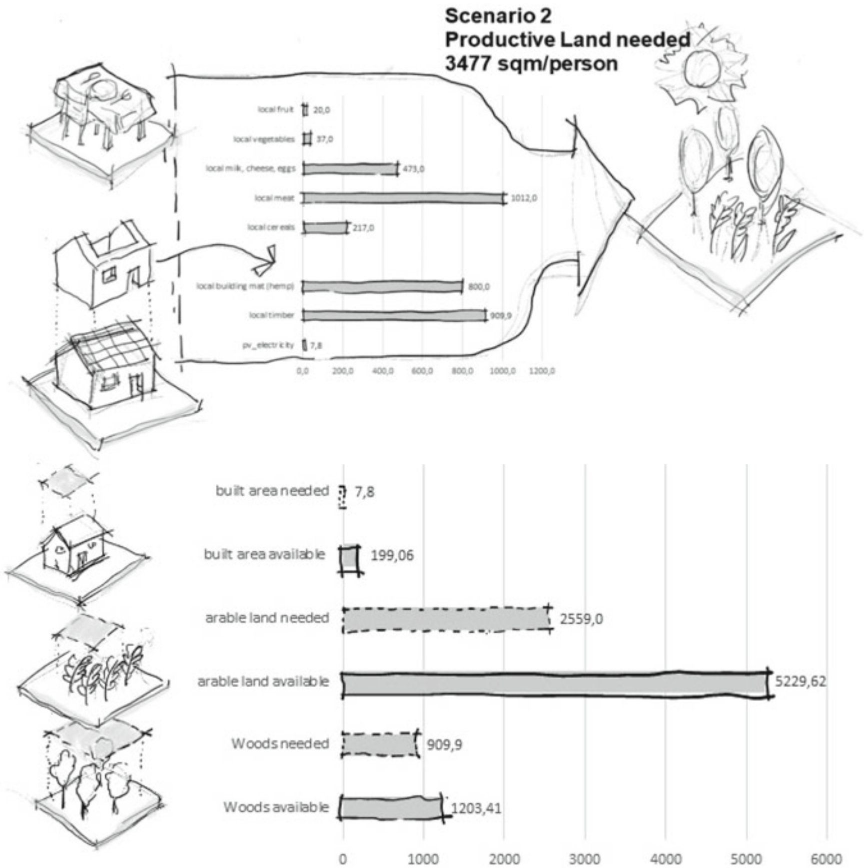


**Fig. 15** Scenario 2: Above, surface of the production area necessary using hemp to improve the energy performance of the existing buildings. Below: data relating to the production area available per person and the area necessary to cover the energy and material

**Table 5** Available productive land and necessary land in Scenario 2

| Practice | Energy/Material | Unit | Productive land | Area ($m^2$) | Source |
|---|---|---|---|---|---|
| BP1 woody biomass | Thermal energy | sqm/kWh*y | Woods | 0.763 | [1] |
| BP2 rooftop pv | Electricity | sqm/kWh*y | Rooftop area | 0.00714 | [16] |
| BP3 hemp mat | Insulating material | sqm/kg | Arable land | 1.33 | [18] |

## 6 Conclusions

New emergent technologies and methodologies generate new enabling possibilities for local self-sustainability. Technologies 4.0 is not only an evolution of the sector, but also pleads for its radical transformation based on three concepts: re-industrialization, digitization and sustainability. Three concepts directly bomb a sector that is recognized as a non-industrialized sector (only the production and manufacturing of its materials and products can be considered as factory-made, so under the usual lean management philosophy), and then, industrialized construction is strictly part of the new paradigm [10]. The simplified assessments proposed in the scenarios give a rough idea of how to use the data mapped in the TMG for an informed platform, and exchange information with sensors for giving time response energy and material solution. The coexistence in the same georeferenced database of information on land features and on the population allows to relate data to the expenditure flows of a community with data that can be associated with the production capacities of a territory in compliance with the regenerative cycles of local ecosystems. The georeferencing of this information allows the data to be expressed in general terms or per capita terms, providing clear information on the possible strategies that can be pursued. The TMG itself gives the possibility to include information on the metabolism associated with public properties, i.e. both data related to the demand for energy and matter and information associated with the potential renewable supply. This data availability is fundamental for planning triggering activities of local microeconomies, it will in fact be in the census blocks where public ownership is most present that the start of the first experimental activities will be expected.

In this local systemic design the governance of local production with computerized systems, digital manufacturing, collaborative platforms, self-assembly, robotization of production, Communities 4.0, can provide answers to the economic circularity of the construction sector oriented towards the systemic sustainability of the territories, focusing on humans and social sustainability and enabling local communities in data management to increase their production capacities.

**Acknowledgements** The contribution has been tackled jointly by the authors and the introduction and the conclusion are to both authors. The 2, 3, 4.1, 4.2 parts are attributed to L. Mastrolonardo, the 4.3, 4.4, 4.5, 5 are attributed to M. Clementi.

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# Towards Construction 4.0: Computational Circular Design and Additive Manufacturing for Architecture Through Robotic Fabrication with Sustainable Materials and Open-Source Tools

**Philipp Eversmann and Andrea Rossi**

**Abstract** There is a constant increase in demand for new construction worldwide, which is one of the main contributors of worldwide $CO_2$ emissions. Over the last decades, such increase led to scarcity of raw materials. Although design methods have been developed to increase material efficiency, this has not yet led to a widespread reduction in material consumption. This is due to a variety of factors, mainly related to the inability of conventional fabrication methods to produce the complex shapes that result from such computational methods. Industrial robots, while offering the potential to produce such optimised shapes, often rely on inflexible interfaces and highly complex industry standards and hardware components. In response to this dual sustainability and technology challenge, this article describes a series of research projects for the design and manufacture of architectural components using renewable materials and robotics. These projects are based on novel additive robotic building processes specifically designed for renewable and bio-based building materials, ranging in scale from solid wood elements to continuous wood fibres. We propose methods to optimise the distribution of such materials at their respective scales, as well as manufacturing methods for their production. In this context, the use of novel and automatable joining methods based on form-fit joints, biological welding and bio-based binders paves the way for a sustainable and circular architectural approach. Our research aims to develop intuitive open-source software and hardware approaches for computational design and robotic fabrication, in order to expand the scope of such technologies to a wider audience of designers, construction companies and other stakeholders in architectural design and fabrication.

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_17

**Keywords** Additive manufacturing · Sustainable materials · Circular architecture · Open-source software · Material efficiency · Flexible prototyping · Robotic fabrication · Computational design

**United Nations' Sustainable Development Goals** 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns · 13. Take urgent action to combat climate change and its impacts

# 1 Introduction

## *1.1 Construction Technologies and Sustainability*

There is a constant and growing increase in demand for new construction worldwide, which is one of the fundamental drivers of increase of atmospheric $CO_2$, and hence one of the leading causes of climate change [1, 2]. Over the last decades, such increase and logistic limitations led to scarcity of building materials [3]. This is also partly because massive construction techniques remain the most popular choice of construction [4, 5]. Instead, circular construction techniques, material-saving design methods, and manufacturing processes based on renewable, carbon -storing resources [6] are required.

## *1.2 Renewable Materials*

Since afforestation is not infinitely scalable, additional fast-growing renewable resources are needed. Novel construction techniques with bamboo can be mentioned [7, 8], but unfortunately the material mainly grows well in Asia and south America, leading to a large impact of transportation in a Life-Cycle Assessment for other countries [9]. An alternative, which can be grown in Europe, are willow rods, which can be processed into filaments for additive manufacturing and textile architecture [10]. Natural fibres have good structural properties but are energy intensive to produce, resulting in a positive carbon footprint [11]. The fibre/resin ratio of 30–40% [12] is significantly lower than the material/adhesive ratio in engineered timber products (85–98%) [13]. Recently, construction techniques with mycelium, the root network of fungi, have been developed, i.e. as insulating material, plaster base [14], and mycelium bricks [15, 16]. Even intelligent behavior of mycelium in architecture and buildings is investigated [17, 18]. First companies are developing mycelium-based products, as acoustic elements, and floor panels [21].

## 1.3 Towards Construction 4.0

**Definitions**. The term “Industry 4.0” was coined in 2011 as part of a high-tech strategy project of the German government that promoted the computerisation of manufacturing [22]. In this perspective, information and communication technologies such as the Industrial Internet of Things (IIoT) will enable automated, responsive manufacturing in high volumes and with a high diversity of variants. Although there is no single definition of “Construction 4.0” (C4.0), it seems to revolve, similar as Industry 4.0, around a decentralised connection between physical and cyberspace through ubiquitous connectivity. However, C4.0 is not limited to these technologies but draws on a broader spectrum, the most important being Building Information Modeling (BIM), Additive Manufacturing (AM) and Cyber-Physical Production Systems (CPPS) [23]. The great promise of C4.0 lies in the almost complete automation of the entire project life cycle, not only through highly efficient design, fabrication and material use, but also enabling circular construction through digitally traceable reusability of components, material flows and recycling processes [24].

**Current state**. Digitization in planning has already advanced compared to construction, due to its complexity with many sub-systems, materials and details. Automation of existing processes is often still very difficult and inefficient, being originally designed to be carried out manually. Although little has yet reached construction sites, significant progress has been made in researching novel robotic construction techniques [25, 26]. Due to a strong acceptance and long history of digitization, timber construction is nowadays the most automated building sector [27], with a seamless integration of existing processes as well as new technologies [28, 29]. Automation in concrete construction is generally much lower. Examples are precast building parts and semi-finished components, such as partially precast slabs [30]. The most substantial digital advancements can be found in entirely new construction processes, as 3D printing through extrusion. Besides a series of attempts in the last decades [31, 32], automation in masonry construction is still hardly used, with the exception of prefabricated walls parts [33]. In steel construction, formatting is mostly automated, while assembly and welding are still performed mostly manually. Research is being done on form-fit steel connections [34] and additive manufacturing with steel, and automated assembly and welding for large structures [35, 36].

**Key technologies: BIM and Computational Design**. Building Information Modeling (BIM) is a concept of associating all kinds of data to 3D Models of buildings [37]. Within C4.0, the major challenges are the successful integration and management of data over the whole conception, planning and life cycle, including the tracing of materials and components in accessible databases to enable digital circular design flows, the integration and merging of Computational Design (CD) with BIM, and the integration of design to fabrication workflows. The term CD is commonly used for design methods associated with scripting, parametric modeling and all kinds of digital form finding methods [38]. Towards a “Computational BIM”, two approaches are currently pursued: one is the integration of parametric modeling and simulation in one large software package [39], the other one is creating software bridges, allowing to freely combine multiple smaller packages for their respective strengths [40].

**Key technologies: Additive Manufacturing**. Subtractive machining processes describe an approximation to the final contours of a workpiece by material removal. Formative manufacturing processes are a volume-constant change in the workpiece geometry [41]. Additive manufacturing processes, on the other hand, describe the successive construction of a workpiece by adding individual elements or layers [42]. In the construction industry, additive manufacturing techniques are currently most advanced in concrete construction with already available solutions on the market [43–46]. In steel construction, first prototypical projects exist, showing the potential for larger-scale applications [47, 48]. For timber construction, research is done on extruding timber particles with different binders [49, 51, 52]. For small-scale applications for design and prototyping polymer-based filaments exist and applications for replicating the textures of wood are available [53, 54]. In the literature, the term "additive manufacturing" or "additive construction" has been broadened to include also assembly processes as in robotic timber construction, referring to the additive nature of the process in contrast to subtractive processes as CNC milling [55–57].

**Key technologies: Cyber Physical Production Systems (CPPS)**. CPPS link real (physical) objects and processes with information-processing (virtual) objects and processes through ubiquitous information networks [58], such as production systems with sensors and feed-back processes, capable to adapt to collected data or provide human interactivity. An example of this is an assembly system we developed for irregular wooden shingles for façades, where geometry scans are sent to a connected computer, which calculates a desired position and sends the data back to the robot for execution [59]. Unlike repetitive processes of past industrialization [60], C4.0 requires highly adaptable workflows. This requires highly accelerated time intervals in which automation systems must be adapted and changed. CPPS promise to achieve these formerly extremely difficult tasks through new sensor technology, kinematic simulation, coding technology, a wide range of industrial components and the ability to create industrial networks with customisable functionality. In the following sections, a distinction is made between the kinetic simulation needed for the conception of CPPS, and the additional control mechanisms of the various components for robotic tools and processes.

*Kinetic Simulation.* In CPPS, automation needs to be flexible to accommodate for highly variable components. Therefore, kinematic simulation techniques are necessary to plan the robot motions, check for reachability and prevent collisions. Most manufacturers provide their own kinematic simulation software, as ABB RobotStudio [61], KUKA.sim [62], Fanuc Robotguide [63] and Universal Robots URSim [64]. Also, manufacturer independent commercial solutions exist, as Visual Components [65], Gazebo [66], CoppeliaSim [67], HAL Robotics [68] and RoboDK [69]. There are also a range of software solutions developed by research institutes, often based on Rhinos Grasshopper interface, as Robot Components by University of Kassel [70], Compas FAB by ETH Zurich [71], KukaPrc by RobArch [72] and robots by the Bartlett [73]. Research for the development of new robot systems is mainly done using the Robot Operating System (ROS) for programming, path planning and direct robot control [74]. Here, it is also possible to use automated path planning algorithm packages such as Moveit [75].

*End-effector design and control.* C4.0 requires fast adaption of processes and new robotic tool development. Current industrial automation engineering approaches are very time-consuming and expensive, and few plug-and-play products exist. Therefore, fast, adaptable, configurable prototype-able and cost-effective approaches are needed. This concerns both the communication with the different end-effector components as sensors, moving parts, etc., and the fabrication of the tool. Depending on the task, these components can be differently combined, as i.e., an intelligent industrial camera to detect an object position, and a pneumatic gripper to pick it and place it to its final position. Most components can be controlled by a simple on/off mechanism through digital IOs (Input/Output) [76], as pneumatic valves, simple sensors, or actuation of an electric device. For more complex control, as i.e., controlling the speed, timing etc. of a stepper motor, open-source electronics platforms such as Arduino can be used [77]. These allow for preprogrammed behaviors, which can be further integrated with signals from the robot control system. Also, analog IOs [78], and older protocols, such as serial messaging, can be used for transmitting the actual values of sensor data [79]. Most robot controllers provide I/O boards, to which the tools and sensors can be hardwired. Newer BUS systems as IO-LINK using industrial networks can be digitally configured and require less hard-wiring [80], even via wireless industrial networks [81]. Some systems require more direct tool control and data transmission, which can be achieved through direct connection to the axis computer for real-time adaption, which can be necessary i.e., for force-sensing and adaption [82].

## 2 Aim/Motivation

The aim of this article is to describe methods to combine these recent advancements in computational design, digital fabrication and robotics with the requirements to reduce material usage, rely on biological and renewable processes, and develop circular design systems. This is achieved by directly linking digital fabrication processes with computational methods for material optimization, as well as adapt them to the unique characteristics of fabrication with renewable, bio-based and living materials. Furthermore, circular strategies for reuse, and for recycling and compositing at end-of-life, are achieved by developing reversible and/or bio-joining systems between elements of a construction system. This is supported and enabled by the development of an adaptive and intuitive robotic programming and actuation framework, relying on open-source software and hardware tools.

The article is organized as follows. In Sect. 3, we present computational design methods for circular and material-efficient components and corresponding robotic fabrication technologies. In Sect. 4, we present a series of case-studies, ranging from discontinuous material placement, as robotic assembly and joining techniques for timber components, to continuous assembly, as veneer winding, additive manufacturing with timber filament, biofabrication with timber reinforced mycelium and compressed bio-bound wood particles. These case-studies are ordered through the scale and resolution of used materials. In Sect. 5, we conclude by highlighting the potentials of the described approach, as well as identifying the further steps to enable a more direct connection between sustainability goals and digital fabrication strategies.

# 3 Methods

## *3.1 Computational Design Methods*

We apply computational design logics at three different levels: firstly, through a comprehensive circular design approach at the component level and in material selection; secondly, through optimization methods for material distribution within the components; and thirdly, by organizing the information of our design models directly for robot manufacturing.

**Circular Design Approach**. We define a circular design approach through a holistic integration of the following topics: a computational modular design approach for building components, and a structured choice and characterization of material systems in relationship with their digital processing, assembly and joining technologies, grading and up/recyclability. Instead of highly specific, single purpose building components, modular design systems are developed to allow for elements which could be potentially reused multiple times in different circumstances. While modular same-sized elements often result in uniform designs, computational combinatory logics enable high level of variation in the final assemblies, using only minimal number of component types (see Fig. 1).

Furthermore, often current approaches to modularity rely on a small number of identical components applied in a variety of different conditions within the assembly, often resulting in over-dimensioned elements, and hence high levels of material waste. A more material-efficient approach to modularity, as we propose it, is to assume the outer geometric form and interface areas of components as fixed, but to then develop methods to customize its internal structure to the unique needs of each component, given its specific structural and environmental requirements in its location within a larger assembly. However, when aiming for higher customization within a circular material system, particular attention must be placed on the material assembly and joining techniques, to ensure both reversibility of assembly and recyclability and/or composability of the components within their life cycle. For this reason, we understand design of components as the combinatorial integration between material, binding/joining techniques, fabrication technologies and specific performance requirements (Fig. 2).

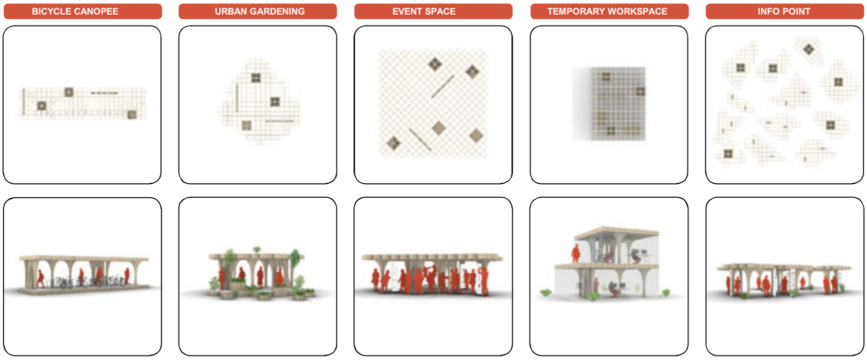


**Fig. 1** A modular design approach combined with combinatorial logics enable a range of different geometries and possible user scenarios as demonstrated in the 3DWoodWind research prototype project (see Sect. 4.2)

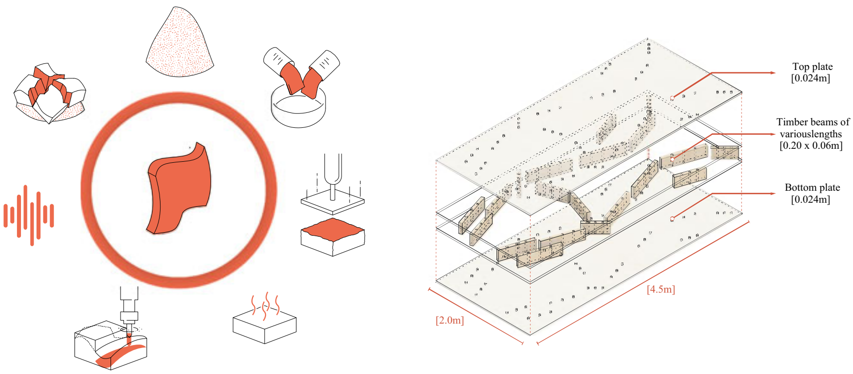


**Fig. 2** Left: Circular material process: construction methods using compressed waste-wood particles in combination with bio binders. The material can be shredded and reused multiple times in the same process. Right: Robotic assembly and adhesive-free joining of beams and plates for material-efficient building components, that can be easily recycled

**Material Distribution**. Current approaches to the use of sustainable materials in construction are often based on solid building components, such as clay, bio-bricks or cross-laminated timber constructions. If the goal is to increase the scope and quantity of renewable resources, it is therefore necessary to develop methods for more efficient use. Computational design tools and digital fabrication technologies offer an alternative, enabling the development of processes for efficient material distribution under different load and support conditions. Furthermore, they also enable to account for the combination of materials of different grades, embedding the unique characteristics of each material as parameters. We propose various computational methods and adapt them to the specific requirements of design with sustainable materials and reversible joining techniques. This includes (see also Fig. 3):

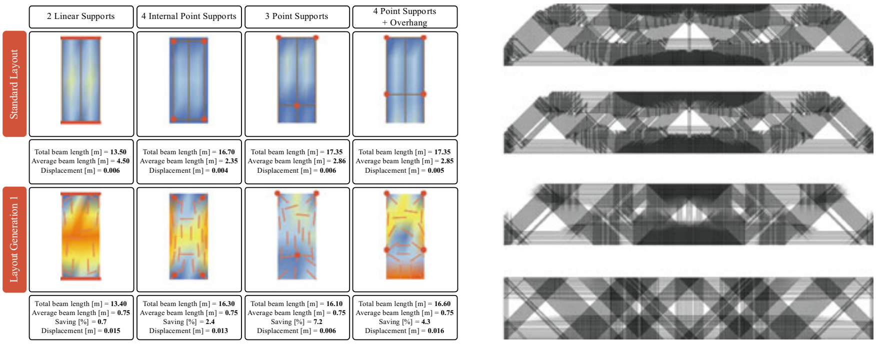


**Fig. 3** Left: Distribution of timber beams in a robotically assembled hollow slab component based on stress-lines tracing (see Sect. 4.1). Right: Distribution of willow filaments in a beam manufactured through robotic additive manufacturing based on topology optimisation (see Sect. 4.3)

– Tracing principal stress lines on slab components with the aim of locating and orienting support beams in the areas where higher stresses occur.
– Topology optimization [85, 86], for which we developed a variety of discretization processes of the continuous material distribution obtained through a TO method [87]. Various applications of such method include the placement of beams in slab components, as well as the placement and orientation of timber fibers in our custom AM process.
– Shape optimization, through physical simulation and real-time stress material stress analysis, as we showed in a study on cold bending of glass [88].

These methods offer a flexible matrix of strategies to define an efficient material distribution. To this regard, one of the goals of our research is also to redefine the concept of material efficiency itself, going beyond the exclusive usage of material amount as the dominant metric, and rather attempt to also include material dimensions and grading, as well as the possibilities of reusing existing stocks of waste material from other sources rather than primary ones. Redefining material efficiency in this way allows for a more open and flexible design workflow, able to account for the unique characteristics of architectural construction (see Fig. 4).

**Design for Robotic Fabrication**. Using the above-mentioned computational methods for material distribution often results in very complex and irregular geometries, making conventional production processes highly inefficient for manufacturing. For this reason, we propose the use of robotic arms as flexible fabrication platforms, able to perform a variety of tasks within a single process. However, this requires designers to account for the unique characteristics and limitations of industrial robot arms already in the design phase, to ensure the buildability of the generated structures. Our approach relies on the definition of any fabrication process as first step in the development of a new design and production workflow. Using computational design tools, it then becomes possible to embed the limitations of the developed fabrication

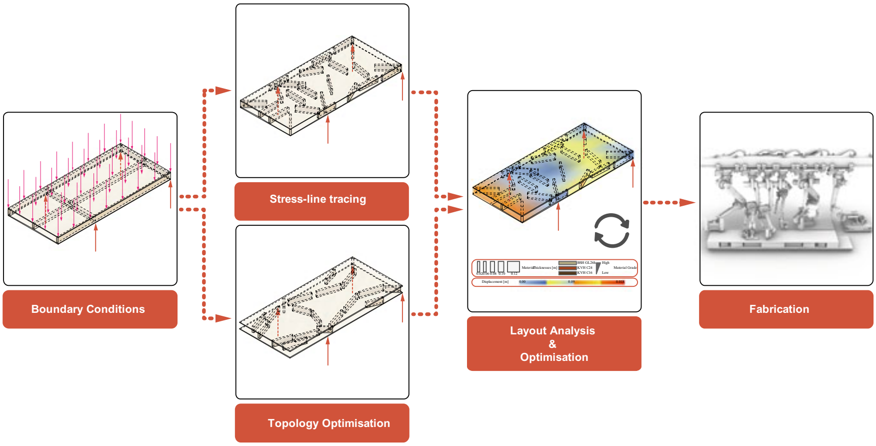


**Fig. 4** Overall diagram of a continuous workflow of a hollow-core beam and plate system with form-fit, adhesive-free joining, linking together material layout generation, layout analysis & optimization, material sizing, grading and robotic assembly

process already within the design tools, hence enabling fabricability while generating the design itself. Moreover, having already determined the requirements for fabrication also means that design models can embed all information required for fabrication, which can be regenerated for each design iteration parametrically. One of the limitations to be addressed is the scale of fabrication and transportation equipment. Such limitations come to define the main manufacturing constraints, which in turn determine the maximum allowable size of a building component. Thinking in systems rather than in monolithic structures, these dimensions form the base for the development of individual elements, which can be further combined in modular building components fitting within an overall construction system.

## *3.2 Robotic Fabrication Methods*

The use of robots for additive processes can be largely categorized in:

– Discontinuous Assembly: Pick-and Place processes
– Continuous Assembly: Additive Manufacturing.

For a successful implementation of these methods, an adaptive robotic setup, modular open-source tools, and automated material joining methods are required.

**Adaptive robotic setup**. In the framework of a DFG major research instrumentation grant, we developed a research facility for Robotic Architectural Production (RAP-Lab), which enables a wide range of architectural, building construction and materials

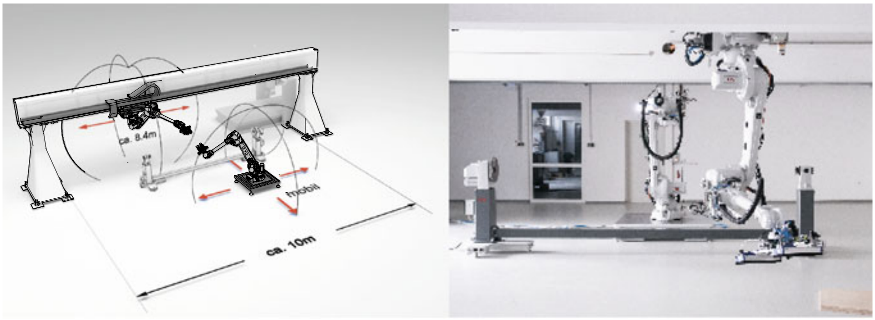


**Fig. 5** Robotic Architecture production lab, experimental and digital construction, University of Kassel

science research projects. A suspended ABB IRC 4600 industrial robot on a TMO-2 Güdel gantry was combined with an ABB IRBPL rotational axis, and a mobile, same-sized robot that can be moved and used in cooperative workflows. The system is designed for maximum flexibility through the possibility to run the robots and axis in multiple combinations separately or as a real-time synchronized, 14-axis multi-move system. For tool control, Baluff Profinet IO-Link hubs and digitally configurable pneumatic valves from Festo are integrated on each of the robots, so that only a small amount of additional wiring is required and changes in the control structure can be made via software. The tools themselves are seen as modular functional entities within different control layers. This means that i.e., a tool or tool-system is not integrated in the main controller, but has all the functionality and data collection integrated, so it can be actuated by different robots with simple means. Since the lab is mainly used for research purposes, the entire robot hall was defined as a safety zone. Four mobile three-level enabling safe-switches allow several people to operate the robots in collaborative processes. Even though the facility is unique in its design, adaptability, security and control methods, we used only standard equipment, therefore enabling simple transmission and adaption by industry (Fig. 5).

**Modular open-source tool ecosystem**. Integrating our various manufacturing processes requires a flexible approach to both robot programming and end effector control. Previously described existing approaches rely either on a centralized approach, where a single tool attempts to address all issues, often resulting in low flexibility, or on the custom combination of separate tools, which needs to be redeveloped for each project, resulting in low transferability of the results. Borrowing the metaphor of the "cathedral vs. bazaar" of Raymond [89], we propose an approach which combines software and hardware elements of a robotic fabrication process through a series of shared interfaces, without imposing a fixed workflow [83]. This is achieved through an approach combining tool components fabrication using low-cost FDM 3d printing and readily available electronic components, with a software interface able to integrate and control such elements in a coherent workflow, and to allow their communication with the robot control code.

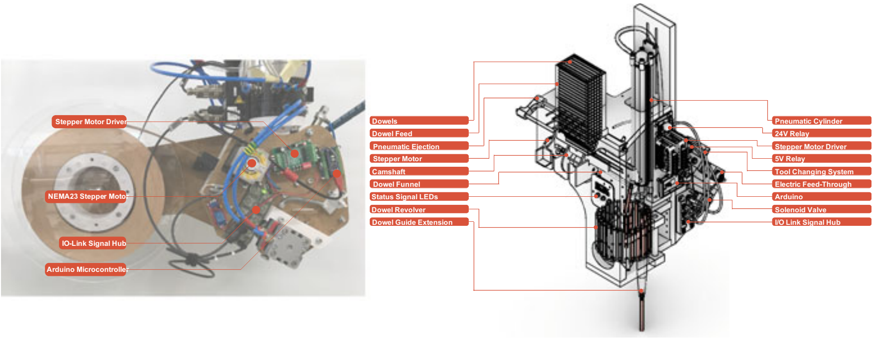


**Fig. 6** Modular robotic endeffector examples. Left: Winding tool integrating a stepper driver and its motor, an Arduino microcontroller, and an IO-Link hub interfacing the signals with the robots ProfiNET network. Right: Doweling tool with various components for dowels loading, alignment and press-fitting through a pneumatic piston. A series of motors guide the dowels from the magazine to the insertion position, and sensors track the process

To achieve such goal, we developed two separate open-source tools:

– Robot Components [90], an intuitive robot programming and simulation framework for the Grasshopper visual programming environment, which enables to easily transform CAD geometry in robot instructions for ABB robots.
– Funken [91], a serial communication interface for the Arduino framework, which allows the programming and actuation of electronic components from various computational design and creative coding tools, such as Grasshopper, Python, Processing and NodeJS.

Together, these two tools, combined with our modular and open approach to tool design and manufacturing (see Fig. 6), enable the level of flexibility and adaptability necessary to the unique needs of research in architectural fabrication.

**Automated Material Joining**. Both for discontinuous and continuous fabrication processes, methods for joining materials are required. The joining technologies and materials also have a large impact on sustainability, since they determine the reusability and recyclability of the components. It is necessary to investigate the specific sustainability requirements according to the base material choice, and to evaluate the performance requirements (structural, building physics, acoustic), to determine the feasibility of natural binding methods. Wherever these requirements allow for it, natural binding methods should be used with bio-based adhesives or even adhesive-free methods as form-fit connections or bio-welding (see Fig. 7). Form-fit connections are created through shaping the material in ways that it can be interlocked in direction of the applied forces. This can be achieved through CNC milling [84], laser-cutting [34] or 3d printing [92]. Also, higher-grade material can be used only for the joining part, as for dowels [93] and other forms of interlocking joining [94]. It is also possible to design the whole component in a way that it topologically interlocks with the neighboring ones [95]. Bio-based adhesives can be based on starch, lignin,

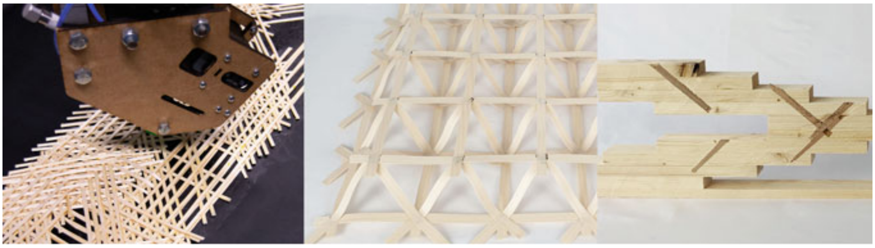

**Fig. 7** Left: Robotic willow filament placement process. The use of bio-based binders is possible for non-structural applications. Middle: 3D lattice of maple veneer for integration with mycelium as a bio composite. The joints are realized adhesive-free, through ultra-sonic welding. Right: Robotic press-fitting of beech wood dowels, section cut

tannin, proteins and chitin, among others [96]. We experimented with protein and glutin-based adhesives in additive manufacturing with solid willow filaments (see Sect. 4.3). We have also been investigating starch and protein for binding wood particles (see Sect. 4.5) [97], as well as chitin-based foils to laminate timber filaments. It must be noted that they have not yet been reaching similar performance levels as synthetic ones, particularly concerning structural capacity, humidity and temperature resistance. Material inherent binding agents can also be activated, as lignin in wood, as research on friction welding of timber shows [98]. We recently started investigating ultra-sonic welding of thin veneer filaments with promising results (see Sect. 4.4) [100]. For high-performance components as for structural use, chemical binders might still be necessary. Here, a strategy can be to apply these adhesives, in analogy to 3d printing, only where there are actually necessary in digitally controlled precise amounts (see Sect. 4.2).

## 4 Case-Studies

Five case studies exemplify the previously described methods at different scales, ranging from the robotic assembly of entire structural slab components to additive manufacturing with wood filaments to investigations on new materials based on wood fibres and biogrowth. The studies are described through the employed materials, computational design approaches, robotic fabrication processes and tooling.

### *4.1 Assembly and Joining Methods for Modular Timber Components*

This project researches computational design and integrated structural joining methods for robotic assembly in timber construction. The focus was on planar surface

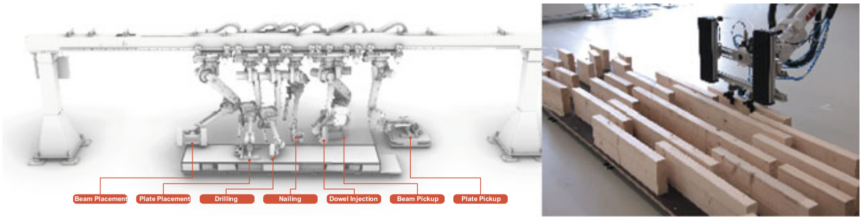


**Fig. 8** Left: Diagrammatic perspective view of the robotic fabrication setup showing the individual steps of the assembly process: Pick and place procedure of the beams, laying the top plate without any fixation, nailing the plates for fixation, drilling, injecting dowels. Right: Image of pick and place procedure of the beams

elements, the most common typology of building component used in architecture, as floor and wall elements, often requiring adapting to variable supports and loads. We investigated a novel connection system with robotically placed wood nails and dowels, adapted to force direction. As materials, we used standard solid wood beams of variable dimensions, OSB Wood strand plates, beech wood dowels and nails. We investigated computational optimization approaches (tracing principal stress lines, topology optimization and sizing) in combination with multi material optimization (different timber grades and materials (softwood, beech) (Fig. 3), to optimize for goals as the reduction of the total material volume, reduction of the total costs of the structure, by using lower grade timber where possible and reduction of the global warming potential (GWP) of the used materials [99].

Robotic fabrication was structured as a "pick and place" process (see Fig. 8). Since the joining is effectuated through wood nailing and dowelling, no additional chemical adhesives are required. In terms of automation, we integrated pneumatic two-finger grippers for beam assembly and surface vacuum grippers for handling plate elements. For assembly fixation, we used a manual wood nail-gun, which we automated through pneumatic control. For automated dowel insertion, we developed a custom tool with 3d printed components for material stock, loading through stepper motors and a pneumatic piston for automated dowel insertion (Fig. 6). The dowels were pre-dried for simpler insertion.

By using a layered system of wood plates and short beams, the system is continuously extendable, and it was possible to break away from the reliance on non-reversible gluing processes, as well as to potentially allow the reuse of material from construction demolition, the use of offcuts from production or even to differentiate material grades depending on specific project requirements.

### 4.2 Robotic Winding of Hollow-Core Timber Elements

Winding technologies are commonly used for the manufacturing of highly resistant lightweight synthetic fiber composites. Our research investigated new potentials for lightweight, material-efficient construction with timber through robotic winding of thin continuous timber strips, providing intact, continuous, and tensile natural fibers. Linear and freeform components with varying cross-sections can be created, as architectural and structural components in construction: furniture and industrial design objects, columns, beams, floor slabs or façade components. The material system is composed of locally sourced hard- and softwood-based veneers strips of only 0.5 mm thickness and certified moisture-curing polyurethane adhesives for structural applications.

We developed both NURBS and mesh-based winding-line generation methods which minimize buckling or twisting of the filaments using locally-geodesic curves [101]. Through computational control of the winding layout, surface geometry and winding sequence, the material can be optimally distributed and customization possibilities as variable patterns with open and closed surfaces and braiding effects can be achieved. The structural filament layout optimization is currently investigated through FE-modeling.

Different robotic setups were used during the development of the project. Initially, the winding process was prototyped on a small robotic arm with a custom-developed rotational axis, controlled via Arduino. For further development, we used a 4 m long horizontal winding axis, which was integrated with the robot controller for precise synchronous movements. The winding tool integrates pneumatic devices for filament cutting, stepper motors for extrusion and an automated adhesive application system (Fig. 6). The proposed robotic framework enabled to switch between the different setups with minimal changes to the design and programming setup, allowing to adapt the production process to the different fabrication equipment available in different stages (Fig. 9).

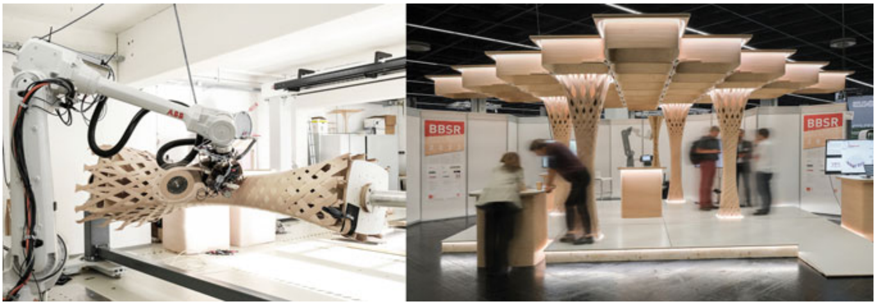


**Fig. 9** The 3DWoodWind project uses strips of thin veneers to and industrial robots to wind structural components as columns and modular ceiling components for full-scale architectural structures. Right: The BBSR Research Prototype was presented at the Digitalbau 2022 in Cologne

### 4.3 Additive Manufacturing with Solid Timber Filament

In timber construction, currently few large-scale 3D-printing methods exist. Present processes use wood in pulverized form, losing material-inherent structural and mechanical properties. This research proposes a new material, which maintains a complete wood structure with continuous and strong fibers, and which can be fabricated from fast-growing locally harvested plants [102]. We investigated binding and robotic additive manufacturing methods for flat, curved, lamination and hollow layering geometric typologies, and characterized the resulting willow filament and composite material for structural capacity and fabrication constraints [103]. As materials, we used willow filament, developed within the project FLIGNUM at Uni Kassel [10].

To be able to design while keeping material and manufacturing constraints in mind, as the maximum overhang angle, heights, and minimal radii, we created computational design methods that integrate and control resulting geometries for fabricability directly [104]. We also investigated a high-resolution material distribution through topology optimization (Fig. 3) constrained to the dimensions and linearity of the willow filament [23].

The robotic fabrication is characterized as a continuous process of material application, apart from cutting the wood filament when other direction lines are applied. For joining we investigated a range of chemical adhesives, as contact adhesives, uv curing adhesives, and PU hotmelt adhesives. We also investigated natural adhesives as Glutinglue, Kasein, and Chitosan. Automation of the process is performed by stepper motors for extrusion, pneumatic devices for cutting the filament, adhesive application through extrusion, and an automated UV curing LED system (Fig. 10).

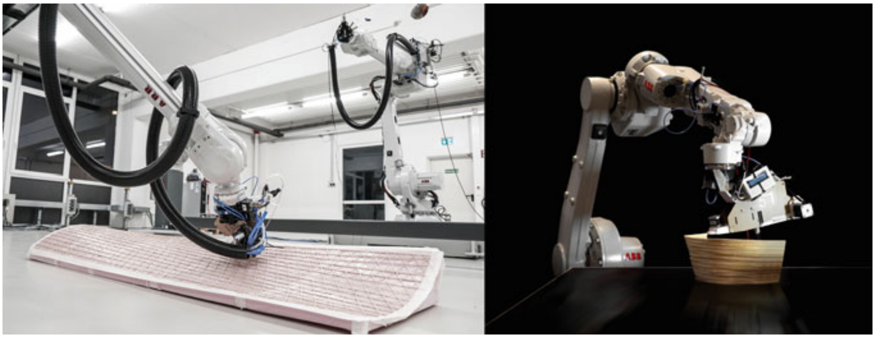

**Fig. 10** Additive Manufacturing with a new material: a solid, endless filament made of split willows, an extremely fast-growing plant that can be harvested in Europe. Bio-based adhesives were investigated

### 4.4 Biofabrication with Timber Reinforced Mycelium

In this research project, a wood-mycelium composite construction method for $CO_2$-neutral, circular interior systems was investigated. Since mycelium has a low load-bearing capacity, reinforcement and 3D lattices were developed via additive manufacturing techniques from local wood species, which serve as a matrix for biogrowth. This allows to increase the scale of mycelium-based components from the available acoustic panels [21] to a wood-reinforced interior building system, while keeping the 100% bio-based, compostable material qualities. We used Ganoderma lucidum and hemp hurds for mycelial growth and maple veneer for reinforcement. [105].

Design rules for 2d and 3d wood lattice structures were developed both for structural efficiency and fabrication constraints. Initial tests were performed using 2-dimensional flat grids of veneer placed on the outer surfaces of the mycelium components. While this slightly increased bending resistance, it resulted in shear failures within the material. Hence, a novel 3-dimensional grid was developed, where the two flat grids on the outer surface are connected with veneer stripes through the material cross-section, providing the required shear resistance to the final panel [105].

A continuous robotic fabrication process was employed for laying the veneer strips, using extruders, pneumatic cutting devices and robot motion for the placement. For adhesive-free-joining of the veneer layers, we developed an ultrasonic welding method (Fig. 6). Thereby, the wood inherent lignin is performing the material joining [100]. The bio-growth process must be precisely controlled and has to go through the following steps: Substrate inoculation (collection, sterilization of hemp hurds, inoculation with G. lucidium grain spawn, 2 weeks in incubation room with temperature and humidity control); Molding (3D lattice of maple veneer is filled with mycelium substrate, 3–6 days in incubation room), demolding (Fig. 11).

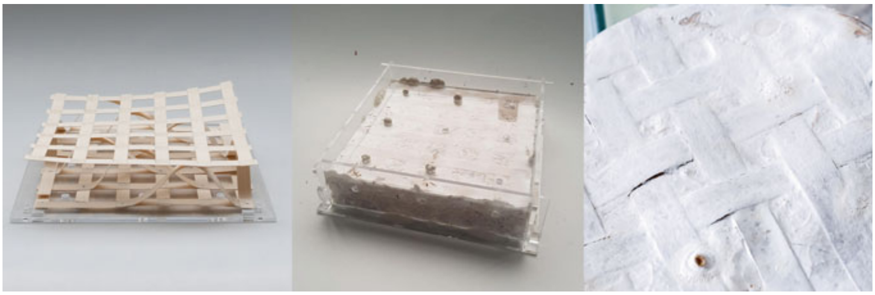

**Fig. 11** The HOME project investigated the combination of additively manufactured timber 3d lattices in combination with bio-growth of mycelium, producing a novel reinforced biomaterial, that is fully compostable

**Fig. 12** Left: Compacted and milled acoustic elements from used wood particles and starch. Right: Investigations in a 3D-printable, 100% bio-based wood paste

### *4.5 AM—Compression and Reuse with Wood Particles*

The aim of this current research project is to reuse waste wood in a zero-waste process to produce components with a high degree of curvature, for use as lightweight, fireproof and precisely manufactured insulation and acoustic elements, enabling a complete circular material cycle (see Fig. 2). Applications for interior, model and furniture construction as well as concrete formwork are also conceivable. The waste wood is completely recycled and reshaped in the form of wood chips with the addition of sustainable biogenic types of binding agents and with the help of digital manufacturing processes and transferred to new circular construction applications with a requirement for complex geometries. For this we investigated the use of starch, animal and plant-based proteins, and chitosan binders, which are biogenic and result from industrial waste flows.

At the end of the life cycle, the particle-based components and the wood chips from the shaping process can be recycled and reused, creating a closed material cycle. Also, additive manufacturing processes are investigated through the development of an extrudable wood paste (see Fig. 12). The material has a promising compressive strength, enabling a possible substitution for concrete printing in the future. For preliminary investigations, we automated a manual clay extruding device, and added 3d printing parts for material storage and actuation.

Computational design methods are being developed for the surface pattern and acoustic design in conjunction with digital fabrication constraints.

## 5 Conclusion

This article addresses developments needed in the construction industry to reduce $CO_2$ emissions and enable strategies to achieve the goal of “more with less” through circular design approaches and lightweight, material-efficient structures using sustainable materials. We provide an assessment and review of current research, automation technologies and practice, to place our research in the context of industry 4.0. Integrative design and manufacturing approaches are needed that simultaneously provide holistic, circular design approaches and fully exploit the advanced geometric capabilities of robotic manufacturing for material efficient components. Digital design methods not only provide the data for their constraints, but also enable a direct and seamless workflow between design and manufacturing. Towards these goals, our research provides computational methods, material development, and robotic automation technologies.

We proposed combinatorial logics in conjunction with modular components that can be functionally expressive and highly optimised to enable component reuse for different application scenarios. Through computational tools, we are able to combine optimisation technologies for material efficiency with the constraints of robotic manufacturing.

This is demonstrated through five case studies in different scales, ranging from the robotic assembly of entire structural slab components to additive manufacturing with wood filaments to investigations on new materials based on wood fibres and biogrowth. The studies were distinguished through the used materials, computational design approaches, robotic fabrication processes and tooling. The difference in size of the employed materials thereby determines the possible resolution of assembling and has an impact on the application scenarios of these technologies. The additive nature of the described systems allows for continuous extensions in multiple directions, allowing for a maximum of design freedom and functional use through geometric variability. These studies show that not only the materials, but also the joining methods have an impact on the sustainable potentials.

We showed that timber beams and plates can be connected through form-fit wood-wood joint methods in automated processes. Therefore, after their service life, no material separation is necessary, making the components easily recyclable. We presented methods for material-efficient, hollow, lightweight components through 3d winding of timber in combination with adhesives. Since certified bio-based adhesives for structural applications are not yet available, we developed a highly precise digital application system, which minimizing adhesive use. An alternative to timber is fast-growing willow plants, that we used to produce an endless solid filament. We investigated novel robotic additive manufacturing processes with bio-based joining, that can be used for semi-structural applications and interior fittings and furniture. Our research on mycelium-wood composites shows that biomaterials that are reusable and fully compostable after their end of life could be used in large-scale applications in architecture. The rethinking wood project starts already a step further in a circular process in taking as base material timber particles from waste wood. The bio-binding process allows also to repeat the process several times from waste of components derived from this method.

Furthermore, tackling the challenge of lowering the access threshold to the adoption of such technologies in construction, our research demonstrates the development and application of open-source tools for the programming of industrial robots, as well as for the actuation and orchestration of the various hardware and software components involved in the production. By providing the tools as open-source packages, as well as developing more accessible and intuitive software and hardware approaches to robotic fabrication, we aim to extend the range of applicability of such technologies to a broader audience of designers, construction firms and other stakeholders in the domains of architectural design and fabrication.

Combined, these proposed approaches aim at providing a model for integrated design and fabrication of sustainable and efficient building components for architecture, providing an effective alternative to conventional design and production processes.

**Acknowledgements** Research presented in this article was funded by the following grants: Flignum (FNR, #22026418), 3DWoodWind (BBSR, 10.08.18.7-20.24 and 10.08.17.7-21.10), Robotic Timber Assembly (DFG, 436451184), RAP-Lab (DFG, #416914951), Rethinking Wood (BBSR, #10.08.18.7-21.22), Home (BBSR, 10.08.18.7-21.48).

Research was developed in collaboration with Prof. Dr.-Ing. Stefan Böhm (Flignum), Prof. Dr.-Ing. Julian Lienhard (3DWoodWind Research Prototype), Prof. Heike Klussmann (Flignum), Prof. Dr.-Ing. Werner Seim (Robotic Timber Assembly), Prof. Dr.-Ing. Jan Wurm and Prof. Dirk Hebel (Home).

Scientific development and creative contributions to the different projects were done by our chairs team members Anne Liebringshausen, Andreas Göbert, Julian Ochs, Julia Hannu, Eda Özdemir, Nadja Nolte, Kristina Schramm, Hannah Hagedorn, Guido Brinkmann and former team members Zuardin Akbar, Mohammed Dawod, Arjen Deetman, Carl Eppinger, Christoph Schlopschnat and Benedikt Wannemacher.

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# RFId for Construction Sector. Technological Innovation in Circular Economy Perspective

**Matteo Giovanardi**

**Abstract** The transition towards the Circular Economy (CE) sets new challenges in the construction sector. In addition to reduction of resource consumption and "closing the loop" concept, CE requires the dematerialization of services and products. Building processes and products need to be rethought to ensure sustainable and circular management of the asset. In this context, the progress in the field of Industry 4.0 technologies, such as Internet of Things (IoT) and Radio Frequency Identification (RFId), promises interesting scenarios in fostering circular transition. Indeed, information technologies can assume a critical role in achieve the Sustainable Development Goals 9 and 12. For about fifteen years, RFIds are used by several industries to automate process, optimize cost, and manage asset information through data-driven approach. This paper aims to investigate the feature of RFId technologies and its application in construction sector. In the perspective of promoting CE principles, such technologies can play an enabling role. Thorough the analysis of scientific literature review and experiences in the market, 20 of the most innovative case studies are presented. A clustering analysis of the case studied presented clarifies the most investigated fields and those where research should focus in the future.

**Keywords** RFId · IoT · Industry 4.0 · Construction industry · Circular economy

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 12. Ensure sustainable consumption and production patterns

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_18

## 1 Introduction

The environmental and economic limits of the current linear development model highlight the need for a rapid ecological and circular transition. As required by the European Union [1], moving towards Circular Economy (CE) means renewing products and processes by overcoming models that are no longer sufficient and crystallized in a habitual vision of the present [2]. In this perspective, the progress in the field of Information and Communication Technologies (ICT) can be identified as a driving force for change, as an exogenous phenomenon that points the way for economic and social transformation [3]. Indeed, digitalization and dematerialization of products and processes are considered key factors to support CE and one of the "Six Transformations to Achieve the Sustainable Development Goals" (SDGs) [4]. More precisely, such approach, identified in the pervasive use of Industry 4.0 technology such as Internet of Things (IoT), Big Data, cloud computing, is now essential in fostering fair, responsible, and sustainable innovation (SDG 9: target 9.4, 9.b) to raise resource-use efficiency (SDG 12: target 12.2, 12.5) [5]. The strategic role of data in the ecological and circular transition is confirmed by several scholars [6, 7] and verified by many sectors (e.g. automotive, aerospace, retail, etc.).

Such approach opens extremely interesting scenarios in the construction sector. Still considered among the main sector exerting the strongest pressure on the environment [8] and accounting for almost 9% of European GDP [9], the construction sector plays a crucial role in circular transition, and it has high scope for digitization. In this perspective, the Industry 4.0 technologies represent, on the one hand, the most recent phase of industrial activities digitization, and on the other, a constantly evolving paradigm [10] that stimulates building product innovation through new dematerialized value. Integrated, connected, and collaborative cyber-physical systems, identified on the IoT, can thus facilitate circular transition and restructuring of industries' capital profitability.

An emblematic case concerns Radio Frequency Identification (RFId) technologies. Greater transparency and efficiency in asset management has pushed RFId technology into various sectors such as manufacturing, retails, and logistics. The ability to create, share, and transform data into information along value chains is the key to creating a circular approach using resources in a more efficient way [11]. With a view to stimulating the introduction of circular approaches, this paper aims to clarify the application potential of RFId technologies in the construction sector. A collection of 20 case studies in the last 15 years are presented to map the state-of-the-art. The clustering analysis of such experiences shows the most investigated fields and those where research should focus in the future.

# 2 Radio Frequency Identification

## 2.1 RFId Technology

RFId sensors are considered the new paradigm of the IoT [12]. Although the first applications of the technology date back to World War II for “friend or foe” recognition of anti-aircraft [11], recent progress in chip miniaturization and industrial process production have allowed a drastic reduction in price making the technology extremely versatile for many applications [13]. In the last twenty years, interest in this technology has been discontinuous. After a period of great interest between 2004 and 2007, the trend grew again after 2016 driven by an increased focus on IoT technologies. This trend is confirmed by Google Trend, too. Although to be considered from a qualitative point of view, the Fig. 1 showing the interest in Google searches for the terms ‘RFId’ or ‘Radio Frequency Identification’ in the last 18 years, compared to ‘IoT’ [14].

Used in logistics, automatic payment, access control or the identification of components or animals, RFId systems are already mature technologies that have found widespread application in many market sectors. Basically, it is a technology that allows the remote recognition of an object by using radio communication. The system architecture consists of two main elements: a reader with a data processing module and an antenna to generate the electromagnetic field, and a tag, a device placed on the object to be identified, consisting of an antenna, an integrated circuit (IC), and a substrate. Once entered in the radio signal range, the reader queries the tag, reads data, and organizes it in databases and/or shares it over the network. Several types of RFId technologies exists and different classifications can be made according to.

The presence/absence of a battery in the tag. RFId systems can be divided into passive, active, and semi-passive/semi-active. Passive tags are the most popular type, they do not have a battery and receive their power from the RFId reader. Active tags have an on-tag power supply such as a battery, which emits a constant signal containing identification information [15].

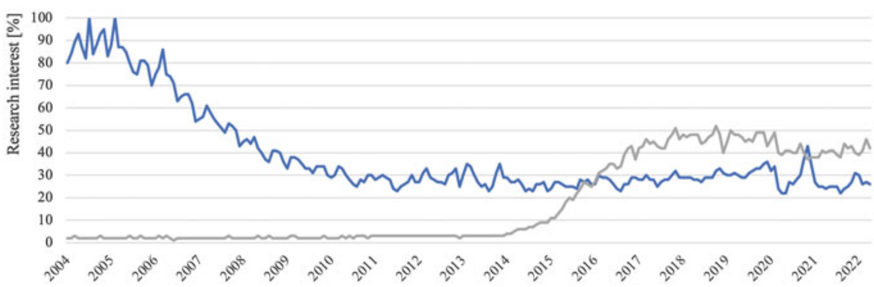


**Fig. 1** Search trend on Google [19]: “RFId” (blue) and “IoT” (grey)

**Table 1** RFId technology classification

| Type | Frequency | Range | Active/Passive | Cost | Main applications |
|---|---|---|---|---|---|
| LF | 125–134 kHz | 1–10 cm | Passive | Very low | Access control, car anti-theft systems, etc. |
| HF | 13.56 MHz | 10 cm–1 m | Passive | Low | Labels for retail, safety, etc. |
| UHF | 433 MHz<br>866–868 MHz (EU)<br>902–928 MHz (USA) | 1–100 m<br>1–12 m | Active<br>Passive | High | Identification of moving objects, etc. |
| Mw | 2.45–5.8 GHz<br>3.1–10 GHz (USA) | 1–2 m<br>Up to 200 m | Active | High | Alarms, speed gauges, automatic openings, etc. |

The frequency of the signal. Low Frequency (LF), High Frequency (HF), Ultra High Frequency (UHF), and Microwave (Mw) are the main types. Generally, LF systems operate in the 125 kHz to 134 kHz range and have a read range of up to 10 cm. HFs operate in the 13.56 MHz range and provide reading distances of 10 cm to 1 m. UHF systems have a frequency range between 433 and 938 MHz depending on the context, offer read ranges up to 2 m, and have faster data transfer rates. Microwave frequency are less common for RFId technologies [15].

The material tag. The chip and antenna are mounted on a substrate, which can be paper, polyethylene terephthalate (PET) or some other type of plastic. The choice of material depends mainly on the type of transponders and the types of actions to which the asset is subjected. Price and durability of the tag depend strongly on the material used [16].

The memory capacity. In current tags, identified as Gen2 RFId tags, the IC contains four types of memory: Reserved Memory, EP Memory, TID Memory, User Memory. The capacity can vary from 8 bits in the case of passive technologies up to 8kbits. Tags with memory can be of the "read only" or "read/write" type when the data can be modified dynamically [17].

The main features can be summarized in Table 1.

## *2.2 Lesson Learnt by Other Sectors*

In recent years, the widespread application of RFId technologies in many product sectors have shown environmental and economic benefits. There are three main experiences that can be stimulating for the construction sector: the auto-identification of assets, geolocation and spatial monitoring of assets, and environmental parameters monitoring. Lessons learnt from other industries can facilitate faster deployment in the construction industry.

**Auto-identification**. It is one of the main advantages of using RFId systems. Such technology can rapidly raise data collection in supply chains by automatically identifying the assets' features creating new business values by data. The most striking example emerges from the aerospace field [18]. For around 15 years, RFId technologies have been used in the production of airplanes to rationalize production and maintenance time and costs. The Boeing 787 DreamLiner, for example, consists of around 6 million components, provided by around 40 different suppliers. The production cost and maintenance phases require constant monitoring of the status of its components. To improve the control of supply chains, contain costs, and reduce time for inventory, 1.750 RFId tags are used to track aircraft components. Moreover, the digitalization of the inventory process drastically reduces human errors ensuring a greater quality [11]. The civil sector is also moving in this direction, too. Consolis, a world leader in the production of prefabricated tunnel segments and rail sleepers, uses tags embedded in each tunnel segment to identify assets during construction phase, manage information during assets life-cycle, and ensuring greater control and process transparency over the supply chain [19].

**Geolocalization monitoring**. Real-time geospatial sensing of assets is one of the main scope for RFId technology. Monitoring position of assets in a space could result in greater efficiency in controlling supply chains and governing the timing of a process more accurately. Delivery data, shipment tracking and material stock management are extremely useful actions for logistics and efficient management of complex processes. In many productive companies, doors such as readers monitor the entry and exit of goods and/or people to control matter flows, occupancy, and increase safety in the workplace [20]. In addition to this, position sensors, GPS, accelerometers, and vibration, sensors can be used with RFId systems for performance monitoring of an asset. For some years, structural monitoring is an extreme topic in the academia research, several researchers over the years have tested RFId based solutions. RFId systems have been studied for the structural monitoring of bridges, viaducts, roads and infrastructure works [21]. The ability to track statical position and fluctuations allows operators providing operation and maintenance to intervene in advance, thus reducing the cost of corrective maintenance and the risk of failure. Vizinex, a leading RFId systems company, has developed a passive UHF sensor for automatic maintenance schedule management [22]. In Missouri, the Center for Transportation Infrastructure and Safety has carried out a research project on the implementation of RFId sensors for bridge monitoring [23]. To monitor the corrosion status of a physical element and evaluate its load stress history, a passive RFId sensor was developed.

**Environmental parameters monitoring**. A further field of application is the use of RFID systems to monitor environmental parameters. Joint use with wireless sensor (WSN) network provides to RFId systems a greater versatility. The typical hardware platform of a WSN node consists of a sensor, a microcontroller, a radio frequency transceiver and a power source. Each node is equipped with a sensor to detect parameters such as temperature, humidity, light, sound, pressure or other physical parameters. Power consumption, chip size and computing power, as well as on-chip memory are very important features to define in an integrated RFId system. A crucial feature of a sensor node is the power source and battery management, especially in WSNs, where the battery can't be replaced [15]. In this context, significant experiences come from pharmaceutical and food chain fields. The cold chain control ensures that products, drugs or food can reach the final consumer in the best condition. Changing in temperature during production and distribution process could lead to alteration of the chemical features of the good with possible damage to the health of the user. In 2016, European MC Donald's and other leaders in the food industry funded the testing of an RFId temperature loggers that could track the food product temperature throughout the supply chain [24]. This ensures high quality in the product sold to the consumer and offers new tools to regulate the relationship with suppliers. A similar example is provided by PostNL's (Belgium). The delivery company has developed together with SenseAnywhere a device for detecting internal conditions in vehicles used for the delivery of pharmaceutical materials [25].

## 3 Materials and Method

Defining the maturity level and the state-of-the-art of a technology that is difficult to place in a specific context is a tricky issue. Indeed, depending on the application field the maturity level of RFId technology can be drastically change. In recent years, technology development has been taking place more within companies than in academia. This sometimes leads to real difficulties in finding technology-specific information. As confirmed by Costa et al. [15] it emerges that by 2015 the number of patents registered using RFId technology was far higher than the number of scientific papers. This justifies a degree of maturity of the technology that can be widely used in the market. In Europe, more than 16,000 patents have been filed using RFId technology [15]. For these reasons, the collection of case studies used a hybrid approach integrating scientific literature review with experiences from the market.

From the literature review on SCOPUS and ResearchGate databases, of the total 43.000 articles that can be traced through the keywords "RFId" or "Radio Frequency Identification", about 1.283 (about 3%) also integrate the term "construction". An initial analysis of the metadata obtained shows how the distribution of scientific research between 1995 and 2022 (April) follows the trend of Google research show in Fig. 2. The shift of the peak in 2013 is probably due to the research and publication time. Since 2015, the number of papers per year has been constant with around 70 papers per year. Computer Sciences, Automation in Construction and Applied Mechanics and Materials are the three journal papers that include the largest number of articles.

Screening the most innovative cases led to the selection of 20 case studies. Applied research and market application from 2006 to 2022 are presented. The case studies analysis and clustering according to the purpose of the technology provides an overview of the RFId system and highlight new emerging trends for future research.

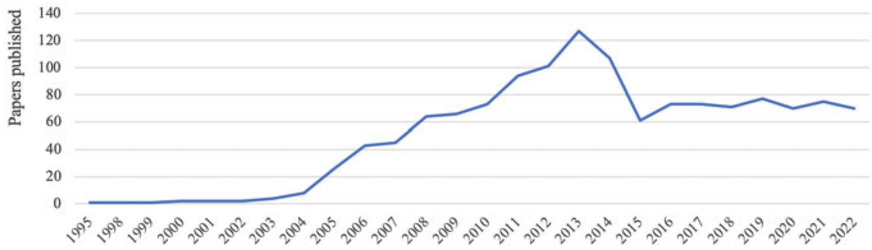


**Fig. 2** Number of papers published per year containing "RFId" or "Radio Frequency Identification" AND "Construction" in title, abstract or keywords

## 4 RFId in Construction Industry

Table 2 shows the case studies with a brief description of the purpose of the technology. Information regarding the year, location, and companies involved helps to clarify the evolutionary process. The case studies are listed in chronological order.

## 5 Discussion

Form the case studies presented emerges a very wide context. The RFId experiences, as shown in Fig. 3, show a still heterogeneous degree of maturity, proving that it can be considered a recent technology in the construction sector. The market pervasiveness of the cited technology are strongly dependent on national regulatory barriers, the economic value of data provided by technology, and technical issues related to digital and physical integration. Access control for site management or restricted zone in the building represents the most mature and popular in the market. In this case, a lower integration level of tags facilitates the use of cards and keys RFId-based. An emerging and interesting application field is production and supply chain management. Although still used to optimize and control material and component flows within the same company or between a few stakeholders, the creation of a digitized supply chain opens up interesting scenarios for construction sector. A current barrier is the functional and technological unity of the building component, where to install the tag. The promotion of prefabricated systems and dry construction, which facilitates the idea of a building organized by parts that can be replaced over time, may allow a greater application of such tracking systems. The issue becomes more complicated, and the degree of technological maturity and market application declines, when the typical challenges of facility management and computerized asset management arise. Although the advantages from a rational use of resources point of view are obvious, the time dimension, the physical integration, the number and role of stakeholders becomes an obstacle. On the one hand, the technological obsolescence of RFId technology does not (yet) allow its use for components with a long

**Table 2** RFId in construction sector case studies

| Name, main info | Goal and technology description |
|---|---|
| RFID-Based Facilities Maintenance. 2006, Frankfurt Airport (DE) | All fire shutters are equipped with RFId tags that store maintenance related information. The technicians identify themselves by scanning their badge and the tag attached to the fire shutter. After performing the checking or the maintenance, the tag is scanned a second time to record updated information. The transponders are designed to be attached to metal. The reading range is only 3 cm and frequency is 13.56 MHz [26] |
| Intelligent Concrete. 2006, Tilst (DK). Dalton, Aarhus Innovation Lab | An integrated microchips for controlling production and supply chain and optimizing facilities activities for concrete panels. Concrete panel data are shared via internet and organized in specific database. By means of a personal digital assistant with a special reader mounted on the back, the men at the construction site can find all information about the panel immediately (e.g. measurements, weight, serial number, production history, exact mounting instruction and maintenance instructions) [27] |
| New Meadowlands Stadium. 2010. New jersey (USA). Skanska USA | In 2010, Skanska USA used RFId tag to track over 3.200 pre-cast concrete panels and visualizes it on BIM model for the New Meadowlands Stadium project. Each concrete panel, which weighed around 20 tons, was fitted with a RFId tag to allow it to monitor supply chain information in real-time. The RFId technology allowed to identify and solve problem early in the process, reducing in this way the construction period by 10 days and saving US$ 1 million [28] |
| Service-Oriented Integrated Information Framework. 2011, Seoul (KR). Sungkyunkwan Univ., Doalltech Co | This research aims to develop a seamlessly integrated information management framework that can share logistics information to project stakeholders. To provide "just in time" delivery for construction sector, the research group have developed an integrated framework to digitalize component and building material flows. The pilot test showed that it can improve time efficiency by about 32% compared to the traditional supply chain management. The result of this research is expected to be utilized effectively as a basic framework to manage information in RFId/WSN based construction supply chain management environments [29] |
| Door Control System (DCS). 2012, Bielefeld (DE). Schüco | The DCS control system provides access control using RFId technology. A passive RFId card tag for operators is the digital key to access a specific room. Integrated into the door, a RFId reader recognizes the operators and enables them to pass through. Such application is interesting for security and access control to private areas such as hospital, bank, offices etc. [30] |

(continued)

**Table 2** (continued)

| Name, main info | Goal and technology description |
|---|---|
| Precast Concrete. 2014, North Carolina (USA). Cherry Precast and Concrete Pipe & Precast. HUF RFId | To aid the state North Carolina Department of Transportation's inspections, some American companies' suppliers have integrated an RFId tag embedded in each precast concrete panel to keep track of manufacture data. The RFId led to a fast evolution of the control process. An online database (HiCAMS), accessible to all suppliers by password, allows them to view project data, orders, and delivered products [31] |
| HardTrack. 2014, San Francisco (USA). Shimmick Construction Co., Wake, Inc. HUF RFId | HardTrack technology consists in active RFId (UHF) tags with integrated sensors to monitor the temperature and humidity of the concrete. In San Francisco, it was used by Shimmick Construction for the concrete foundation of building project. 16 concrete slabs integrated RFId tag and sensors. Each slab must be fully cured before the next one can be poured, to prevent it from cracking due to any stresses from the next slab. HardTrack provides real-time data on the concrete temperature and a software determines the curing date of the poured concrete. This approach has proven direct benefits on construction site timing [32] |
| Redpoint. 2015, Boston (USA). Redpoint Positioning Corp., Skanska USA | The Redpoint technology helps the company to know when staff members go into an area of a construction site. The system also provides historical data so that management can identify workers who repeatedly enter an unauthorized area and provide them with additional training to prevent such mistakes from happening again. The development of such devices can find rapid application in buildings with restricted access areas [33] |
| Cluster based RFId. 2015, Montreal (CA). Concordia University | In this research, a localization method based on RFId systems which does not need infrastructure is proposed. The developed of an active RFID technology for the localization of movable objects is proposed. Building components, and equipment with an integrated RFId tag using handheld readers. By extending a Cluster-based Movable Tag Localization technique, a k-Nearest Neighbor algorithm is used [34] |
| Smart Construction Object. 2016, Hong Kong (CN). The University of Hong Kong | An integrated smart building component was tested and demonstrated in a real-life case in a prefabricated construction in Hong Kong. In this case, an RFId-enabled BIM system was required to track the status of prefabricated façades from off-shore manufacturing, cross-border logistics, through to on-site assembly. The tags for supply chain control included data regarding prefabrication factory, transportation routes, and a construction site [35] |

(continued)

**Table 2** (continued)

| Name, main info | Goal and technology description |
|---|---|
| IFC-RFId. 2016, Montreal (CA). Concordia University | The mechanical room of the Genomics Centre at Concordia University is chosen for the case study. The building is modeled in BIM and the mechanical elements are added to the model. RFId tags are attached to a selected set of elements to host their related BIM information. Active and passive RFId tags are modeled in Revit under the electrical equipment category and added to the BIM model of the building [36] |
| The Spot-r worker safety system. 2017, East Harlem, New York (USA). Lettire Construction, Triax tech | The system developed aims to ensure the safety of workers on the construction site. When workers arrive on site, building project manager can use the real-time data to view the total number of workers per floor and zone and organize the work. Furthermore, such solution allows managers to verify if potential incident occurs. For example, the RFId system can detect sudden falls. The software's algorithms can also determine if the data is indicative of a fall or if the worker may simply have dropped the device [37] |
| Elbphilarmonie façade. 2017, Hamburg (DE). Permasteelisa Group | Permasteelisa, world leader in building façade technology, used an RFId tag to optimize production and construction phase in complex project. To manage a large number of different façade elements, each façade panel was tagged with an RFId that, thanks to a specific ID number, could remotly identify each individual element. In Elbphilarmonie project, such system facilitated and sped up the panel delivery to construction site that was particularly challenging, given its unique urban location and space constraints. This data will also be used for maintenance purpose [38] |
| MULTIfid project. 2018–2021, Università degli Studi dell'Aquila. (DICEAA), 2bite S.r.l, Pack System S.r.l | The main objective of the MULTIFId project is to create an innovative product consisting of an intelligent, low-cost, and low-emission panel, made from waste from the industrial processing of paper and cardboard. An RFId system is integrated into the panel to monitor the position of workers in risk areas, thermal performance, and monitoring humidity conditions. The academia project tested and verified RFId signal transmission through different campaign monitoring [39] |
| RFIBricks. 2018, National Taiwan University, Taipei. HUF RFId | RFIBricks is an academia project carried out in Taiwan University. Hsieh et al. [40] present an interactive brick system based on ultra-high frequency RFID sensing. The researchers present a system that enables geometry resolution and geolocation of the asset in a space. Although the state of research is in prototype form, the development of a dynamic user interface opens up interesting scenarios in the field of tracking and tracing components in a space |

(continued)

**Table 2** (continued)

| Name, main info | Goal and technology description |
|---|---|
| Checked OK. 2018, Cork (IE). Anderco Liftging, CoreRFId. HF RFId | Anderco Lifting, one of Ireland's largest lift companies, is employing an HF RFId solution to improve the efficiency of inspections of the lift equipment that its customers use at construction sites. The system was developed in 2018, and the data collected is being accessed by utilities and several other customers to which Anderco provides six-month cycle inspections [41] |
| Flexible thermal monitoring. 2018, Turin, (IT). Polytechnic of Turin, DAUIN Department | Giusto et al. [42] investigate RFId technology for indoor climate control. Benefits of a dense deployment of pervasive temperature sensors are presented. The analysis takes into account many features, such as technology simplicity and time of development, flexibility, wired/wireless range, battery life, reliability and cost. A case study with field test shows that the RFId network is nowadays suitable for thermal monitoring |
| The SensX Extreme. 2019, Cupertino (USA). Smartrac and SensThys. HUF RFId | The SensX Extreme is primarily focused on the smart building and construction market. The aim is to develop technology for leak detection and concrete curing. RFId tags, which can be embedded in the roof section, can detect the presence of water, and the drying phase of concrete during paving, thus enabling higher quality and speed on site. The tags can be used in common building materials, such as gypsum board, insulation, roofing, flooring, and concrete [43] |
| IFC-RFID system. 2020, Theran (IR). Islamic Azad Univ., Shahid Beheshti Univ., East Carolina University | This research presents a computerized system that integrates the BIM objects in IFC and radio-frequency identification to improve building maintenance performance. The computerized system is successfully applied to the building of a soccer stadium in Theran via the proposed research methodology using a qualitative and practical approach. The research indicates how a slight effort on the implementation of the proposed system could allow a significant improvement of overall maintenance performance [44] |
| WoodSense. 2021, Gävle (SE). Woodsense, ByggDialog Dalarna | WoodSense provides moisture measurement using passive sensors in the form of tags that can be attached to the wood building façade, wood slab panel, and or others building components. These sensors measure the moisture on the surface and have to be scanned on site with an RFId reader. The application of such solutions is particularly effective in facilities for wooden building that require more attention to environmental phenomena [45] |

service life such as building components. The service life of a tag can be as long as 15–20 year but is still shorter than that of building components. On the other hand, technological integration and the need for a battery may represent a limitation for large-scale application. Furthermore, it is evident that one of the main gap is the time limited responsibility of stakeholders in the management of an asset during its useful life. Transferring responsibility for an asset to the user once it has been sold (or the

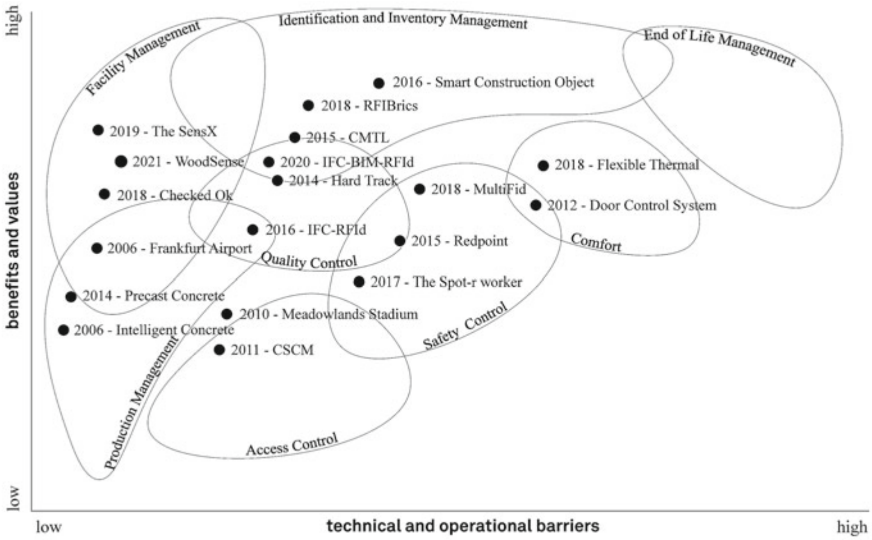


**Fig. 3** Thematic areas and case studies for RFId technology in construction sector

warranty has expired) severely limits the interest of manufacturers in such technologies. However, the transition to circular approaches aimed at enhancing the value of the material and extending services (e.g. leasing, Product As a Service, Pay per Use, etc.) over time could change the current paradigm. In that case, circular solutions for inventory, management and end-of-life of an asset could require a much larger amount of information. A separate issue is the use of technology for comfort and thermo-hygrometric regulation of indoor environments. The increased attention to this topic could thus favor the application of RFId solutions for the built environment and offer new services and advantages to the user. The graph below clusters the experiences reported according to macro-topics emerged. A qualitatively identifying areas that have already been widely tested (e.g. access control) and potential areas (e.g. deconstruction) for future development in RFId is proposed. The deconstruction phase and end of life management could represent an emerging areas for RFId application. Although the technical and operational barriers makes the issue more complex, benefits and values in CE perspective could be relevant.

## 6 Conclusion and Future Development

More than 15 years later the first experiences of RFId in construction sector some considerations can be made. Advantages in a more rational use of resources, automation of processes, and the introduction of new dematerialized services promise new scenarios for construction sector. Industry 4.0 offers new technological tools and approaches to redesign production processes and create new opportunities for economic and environmental value generation. The digitization of the construction sector requires therefore a radical upgrade of the industrial infrastructure boosting product and process innovation (SDG 9). This objective is necessary to the achievement of SDG 12, which aims to promote more resource-efficient models. However, the impact that such technologies and the creation of big data from an environmental point of view must be considered. The most recent estimates indicate that the amount of digital data will grow from 33 zettabytes in 2018 to 175 by 2025. In this perspective, RFId and IoT technologies will contribute considerably to data creation generating an impact on the environment. Future developments in technology and data processing should thus aim to reduce their environmental impact in terms of materials consumed (e.g. to build tags and sensors) and climate-changing gas emissions (e.g. big data management). Although the challenge is complex and extremely interdisciplinary, the circular transition in the construction sector can be strongly enabled by new Industry 4.0 technologies.

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# Digital Tools for Building with Challenging Resources

**Christopher Robeller**

**Abstract** We present an assembly- and fabrication aware reciprocal frame construction system that exploits new possibilities of the latest generation of automatic joinery machines. Sweet chestnut wood (Castanea sativa), is a species that is currently not used for building construction in Germany. The wood of castanea sativa is highly durable and ideal for exterior conditions, but it will corrode metal connectors unless they are stainless steel. Therefore, our system uses only digitally fabricated wood-wood dovetail joints. It was inspired by Friedrich Zollingers "Zollbauweise", in its geometry as well as its philosophy—while adding a second curvature to increase stability and considering assembly constraints of the dovetail joints.

**Keywords** Digital timber construction · Building with less used timber species · Digital fabrication

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

## 1 Introduction

Following the UN Environment Global Status Report 2017, the global need for buildings will drastically increase in the next few decades. According to the report the "global floor area" of currently approximately 2.5 trillion square feet will double to 5 trillion square feet until the year 2055 [14]. Facing such an enormous need for new buildings raises the question for new building methods with less carbon dioxide emissions, renewable resources and generally less material consumption. In

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_19

this context, wood is a highly promising building material. While it has been used for buildings since ancient times, applications such as its use in larger, multi-story structures have seen considerable progress in recent years. These advances have been greatly supported by two developments. For once, building with sustainable materials has been incentivized by many countries, for example through funding or timber construction quotas, as well as companies and individuals choosing sustainable materials for their buildings taking personal responsibility. Also, energy prices have greatly increased and the processing of wood requires less energy than other building materials such as steel or concrete. At the same time, in many regions such as the European Union, the building industry is facing shortages of skilled workers, since fewer young people decide for physically demanding and dangerous work on building construction sites. Therefore, prefabrication of buildings in factories has increased in popularity, allowing for a more automated, safe and precise way of building compared to on-site construction. In this context, wood is particularly valuable due to its outstanding weight-to-strength ratio. Combined with its low-energy processing, this makes it an ideal material for prefabrication and transportation. "Integral attachment", the joining of components through features in their form plays a particularly import role for such prefabricated structures, since it allows not only for the transfer of stresses between parts, but also for "embedding" alignment features in the components, which greatly improve the ease, precision and safety of the final on-site assembly [13].

A major disadvantage of wood however is, that homogenous, isotropic materials such as concrete and steel can be calculated more easily than materials such as timber, which is anisotropic and hygroscopic. Depending on the type of tree species, wood may also have many defects, which make calculations even more difficult. Similarly, European forestry is focused on growing spruce trees, as straight and as free of knots as possible. However, many of the monocultures that were created this way are currently challenged by climate change. This raises the general question, can we build efficiently with less optimal, more challenging materials? In the early twentieth century, Friedrich Zollinger, city building director of the German town of Merseburg was challenged with a similar question. After World War I, resources such as high-grade materials, construction equipment and skilled workers were scarce. His approach to this problem was engineering a smart building system, using only short wood components and generally saving 40% of the material compared to a standard roof construction. The system was even designed in a way that would allow the participation of citizens in the construction process safely. In our history, technological advances have often lead to an increased demand for energy and resources, however scarcity can also be a driver for innovation.

## 2 Castanea Sativa

According to climate change prognoses, the forests in the warmer regions of Europe, such as the German state of Rhineland-Palatinate, will be facing great changes and challenges in the next decades. For example, the 2021 report of the department of forestry in Rhineland-Palatinate shows that only 20% of the trees in the entire state are healthy without any damage. In the year 1980, this was the case for 60% of the trees being completely healthy. Especially the spruce, currently the most important wood for building construction is greatly affected by climate change, with a prognosis of complete disappearance in this state within the century. While many of the spruce trees in this region were planted rather than growing there naturally, the most common tree species in the European forests and especially in Rhineland-Palatinate, the Beech (Fagus Sylvatica), also shows a worrying rate of damage with only 10% of the trees being fully healthy, compared to 55% in the year 1980. Therefore, it has been the subject of recent research to determine tree species which can fill the gaps and stabilize the forests during the observed and predicted climate changes during the next decades [10, 12].

The sweet chestnut (Castanea Sativa) (Fig. 2) is native and well known in the Mediterranean countries in Europe, such as Spain, France and Italy. Compared to the other European leafed trees, such as the Oak (Quercus Petraea) and the beech (Fagus sylvatica), the sweet chestnut is considerably more resistant to dry and warm climate. Due to the climate change in recent years, the occurrence of Castanea Sativa has therefore increased in many regions, including regions north of the alps where it was very rare previously [11] (Fig. 1).

## 3 Construction System

The construction system for our research demonstrator utilizes the *reciprocal frame method* to allow for building large floor or wall components using relatively small wooden elements. Reciprocal frames have been known for a long time, including bridges in ancient China, medieval ceiling constructions, famous sketches in Leonardo da Vinci's Atlantic Code, and the "Zollbauweise" construction methods developed by Friedrich Zollinger. However, only relatively few structures have been built using this method, most likely due to the widely available of relatively inexpensive alternatives such as steel or concrete structures, or glue-laminated wood products, which all allow for the relatively simple construction of large span structures. Many of the previously listed historical reciprocal frame structure were built due to a lack of alternatives (e.g. medieval ceilings) or scarce resources, such as the Zollbauweise, which was developed after the first world war. Facing our future challenges and modern technological possibilities, such material-saving, lightweight construction methods should be reconsidered, especially since robotic fabrication technology is very well capable of producing complex building components. Recent

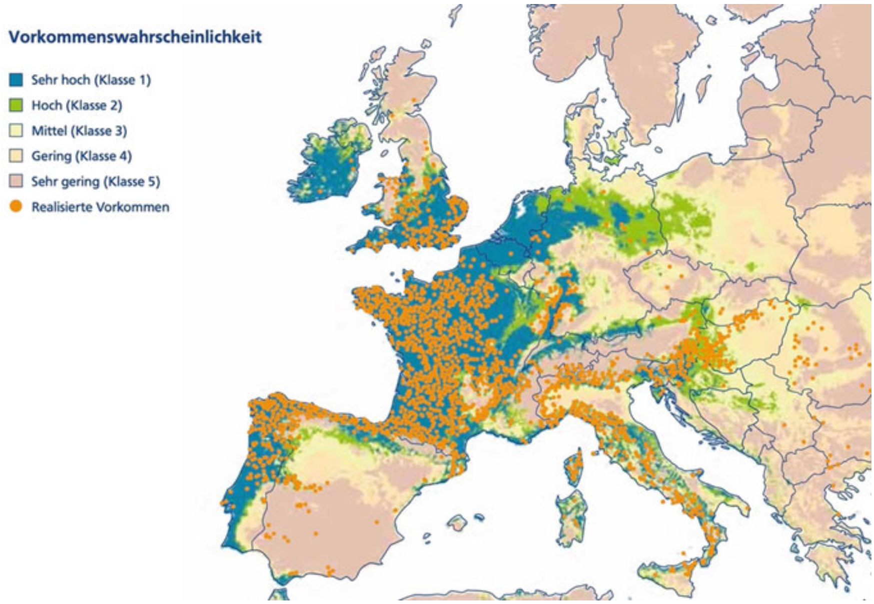



**Fig. 1** European species distribution model of the sweet chestnut, illustrated using Worldclim 2.0 data. The orange dots represent the occurrence data included in the occurrence model based on the national inventory data of the respective countries. *Source* Thurm et al. [10] (use with friendly permission)

**Fig. 2** Sweet chestnut hardwood, locally sourced near Annweiler, Germany

research has presented new interpretations of reciprocal frames using computational methods such as dynamic relaxation [1, 2, 5], and computer-aided structural analysis [3, 6]. Prototypes were presented using softwood and butt joints [3].

## 4 Assembly Constraints

Due to the high acidity of sweet chestnut wood, typical steel connectors will corrode. As an alternative, stainless steel connectors can be used, however those are considerably more costly. Reciprocal frames require a large number of connectors. Generally, achieving wood constructions using fewer chemical adhesives, more regional resources and less transportation to centralized facilities, will require a considerably number of other types of joints, such as form fitting connectors. Integral "wood-wood" connectors are a sustainable joining solution for timber structures, especially due to their previously mentioned other benefits such as a precise, simple, fast and precise on-site assembly of digitally prefabricated components. An important concept of integral "form-fitting" joints is to constrain relative motions between parts through the form of the connectors. Wood-wood connections such as mortise-and-tenon joints and dovetail tenons are so-called single-degree-of-freedom connectors (1DOF joint), where the form of the joint constrains the relative motions between the joints to only one translation vector, which allows for the assembly of the parts (Fig. 3).

In the case of dovetail tenons, the insertion of the dovetail tenon will always be from above, following the direction of gravity. Therefore, the majority of the stresses between parts is transferred through the wood-wood joint and only a minor additional joint, such as a single metal screw is needed to secure the joint in the opposite direction of its insertion. Another important feature of such integral joints

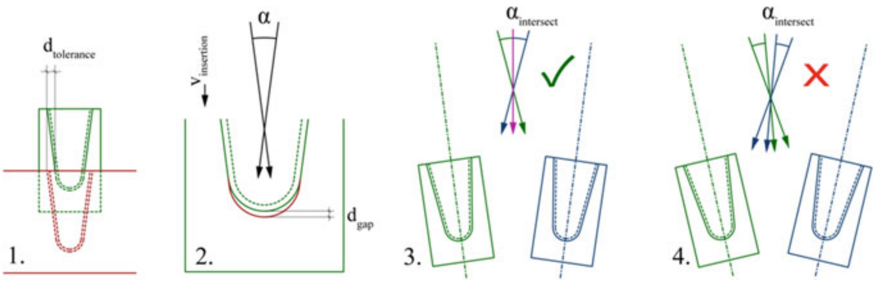



**Fig. 3** **a** 1. Dovetail joint in front view, during assembly. Due to the V-shape of the tenon, there is a tolerance for the initial alignment. 2. Shows the fully engaged joint, where gap at the bottom allows for the complete insertion, even if the tenon is slightly too small. 3. Shows how two joints are assembled simultaneously. Due to the cone angle α., parts can be slightly rotated up to a max angle of α. 4. If parts are rotated beyond their joints cone angle α, they cannot be joined. **b** Reciprocal frame construction system, drawing shows main parameters alpha (dovetail joint cone angle) as well as beta (angle between neighboring components)—on target surfaces which are not flat, the dovetail joint angle must be equal or larger than the angle between neighboring components

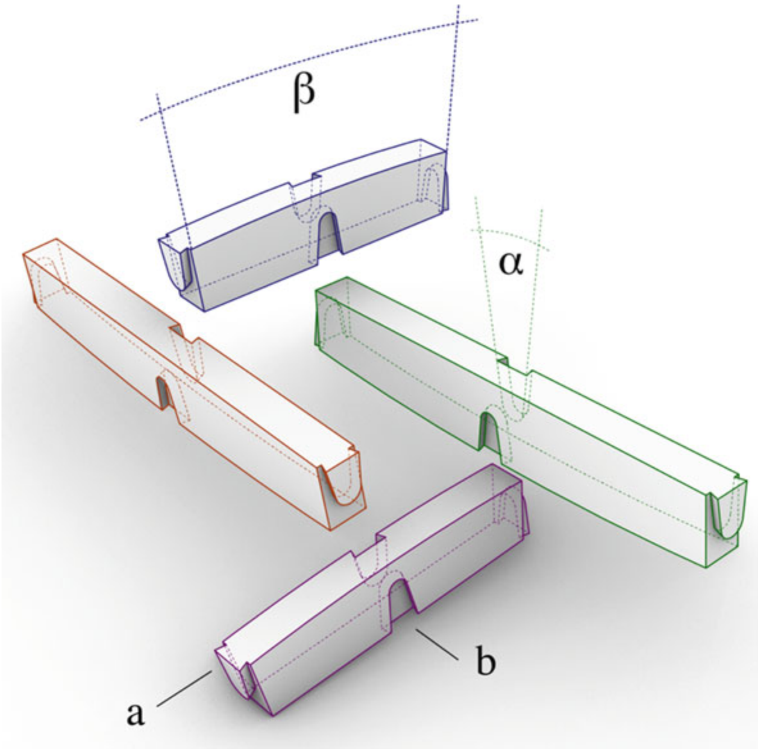



**Fig. 3** (continued)

is to allow for a simple assembly. Therefore, the joint should ideally allow for some imprecision during the joining procedure, which is also called mating. Due to its V-shape, the dovetail connector perfectly combines these features, at the top of the V-shape, it allows for a simple, initial positioning of the elements because the dovetail mortise is wider than the dovetail tenon. This difference in width is gradually reduced during the mating of the parts, until a perfect fit is achieved. If a gap is left at the bottom of the V-mortise intentionally, it can be assured that even in the case of imprecise fabrication, a perfect fit of the V-joint is always achieved. A particular challenge with 1DOF joints, which have only one possible assembly direction, is to consider the overall assembly sequence of the construction. This challenge can be split into joint geometry constraints and component assembly sequence constraints.

## 5 Joint Geometry Constraints

Very often, parts will simultaneously connect to two or more neighboring parts. If these connections are 1DOF joints, their assembly vectors must be parallel. In the case of V-shaped dovetail tenons, the 1DOF connection is only established once the joint is fully engaged. Due to so called cone angle $\alpha$, the joint can be inserted not only along one insertion vector, but along any vector within the cone angle. This means that parts can be slightly rotated and still connected with dovetail tenons, if the rotation between parts $\beta$ does not exceed the cone angle $\alpha$. This possibility was exploited for our research demonstrator "Castanea Sativa Pavilion", which uses a doubly-curved overall shape to increase the stability of the lightweight reciprocal frame gridshell. In this structure, the individual angles $\beta$ of each component result from the target surface curvature and the length of the components. A higher target surface curvature will increase the component angles $\beta$, while a shorter length of the components will decrease $\beta$. The cone angle $\alpha$ of dovetail tenon joints is typically 15°. In our demonstrator, we have slightly increased this angle $\alpha$ to 18°, since the maximum curvature of the target surface and the maximum length of the individual components result from this angle.

## 6 Assembly Sequence Constraints

When multiple joints on a part can be joined simultaneously, they might still be blocked by other components in the assembly. Such mutual blocking of components in an assembly can be described through so called blocking graphs. A sequence must be found, so that every part in the assembly can be inserted. In the case of our demonstrator, due to the curvature of the gridshell, parts can only be inserted from the convex side of the shell. There is a start component in the bottom left front corner of the structure, from where all other components are inserted in a predetermined sequence.

## 7 CAD Plugin/Generator App

Knowing the geometrical constraints of the system, we developed a "generator app" to further explore the possibilities of this reciprocal frame gridshell system. This app was developed using the RhinoCommon Software Development Kit for the CAD Software Rhino3D. As inputs, the app requires 1. A target surface described by two sets of curves for the gridshell. This surface may be flat, singly-curved or double-curved. Also, the curvature or radii do not have to be constant, as in the original Zollinger Bauweise. We consider this an improvement, since structurally feasible shapes have a catenary cross section, with changes in curvature. The target surface

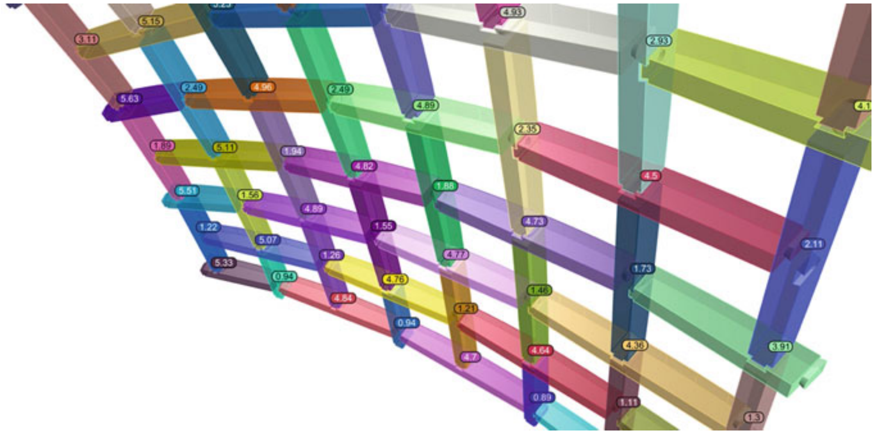


**Fig. 4** Detailed 3D geometry file with joints, processed by the generator app in Rhino 3D

may also have positive or negative curvature, or both within the same surface 2. Two integer values for the gridshell subdivision of the surface in both directions. 3. The width of the beam components. 4. A minimum height of the beam components (the actual height will depend on the curvature of the target surface). 5. A selection what type of model should be generated, the geometry of the components, a detailed model including 3D joints, or an industry standard fabrication data file. All of the models can be generated simultaneously, however this will require slightly more time to process. The fabrication data file will automatically consider "raw part" sizes, which are rationalized to only a few different raw beam heights in 20 mm increments. This simplifies the processing in the factory (Fig. 4).

## 8 Fabrication-Aware Design

The construction system and the generator app were developed specifically for the industry standard wood joinery machines for linear wood elements, such as the most common Hundegger K2i. Other than normal, generic CNC machines for various materials and purposes, these wood joinery machines are highly specialized for linear timber beams. In particular, they have an automatic loading system with two independent gripper arms, feeding the raw parts through various stations such as sawing, milling, or drilling, each with individual motors and tools. In comparison to a typical CNC machine with only one motor, the wood machines offer much higher efficiency, while still offering very complex machining options. A very specific limitation however is presented by the gripper arms, shown in red color in Fig. 6. In order to safely hold the components during high-speed sawing, milling and drilling, the grippers need a relatively large surface area to clamp the workpieces. However, our chestnut-wood based construction system is utilizing short pieces of solid wood, following the materials naturally provided by the chestnut trees which do not grow very straight. Therefore, we had to find a compromise between the required gripper area and the locations for the 4 joints on every piece, 2 dovetail tenons and 2 dovetail mortises (Fig. 5).

Furthermore, since our generator app allows for the design of structures based on “freeform” surfaces, the individual components and their joints will all have individual shapes, lengths, components angles β and cone angles α. In a typical CNC fabrication process, this would be very challenging because only geometry is transferred from CAD to the Computer-Aided Manufacturing Software (CAM). The machining parameters are then set manually or semi-automatic, which is fine for the typical mass-production, mould- or prototype making processes. However, in the building industry each building is unique and CNC programs are created and run only for a single building component. Therefore, complete automation is critical. Our generator App was designed to directly export final production data, where no further CAM programming is needed. The files for our demonstrator, consisting of

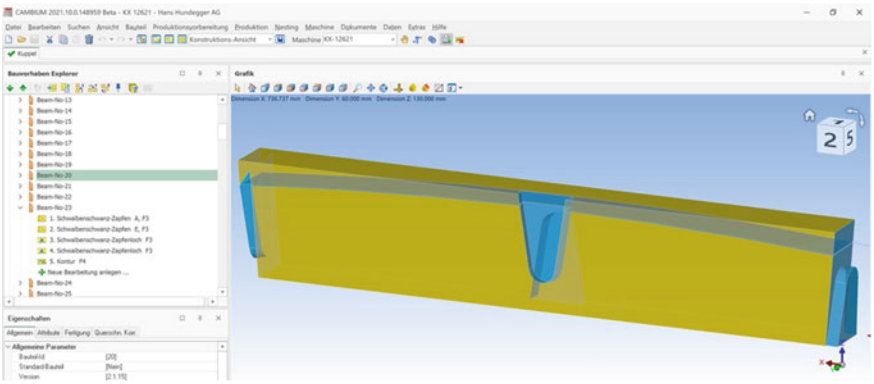


**Fig. 5** Fabrication data file, processed by the generator app in Rhino 3D

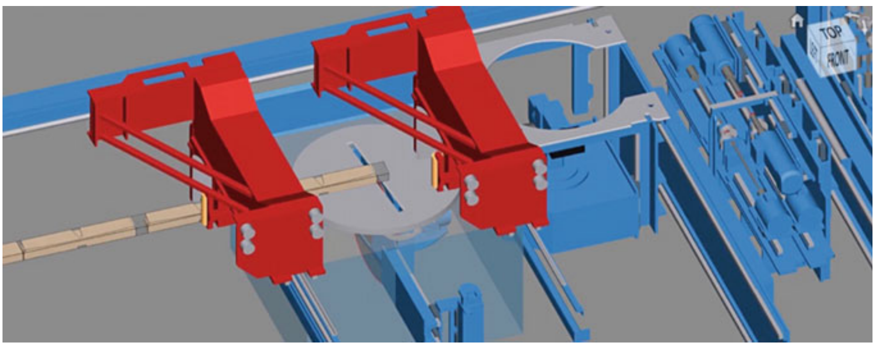


**Fig. 6** Machine operation Simulation with a Hundegger K2 industry machine

147 individually shaped chestnut wood components were directly loaded into the software on a K2 industry machine.

## 9 Demonstrator Realization

After a series of fabrication and assembly tests, our goal was to test the production and construction of a small building structure. Due to our close collaboration with the state and regional forestry departments, we were offered the possibility to replace an old, existing forest hut along the "Chestnut hiking trail" near the town of Annweiler. The exact location is called "Wegspinne am Zollstock", which was a historical customs station, at the crossing of two old trails. This location allowed us to design a permanent structure, which was not demolished after our tests, but will serve the public for decades to come. The chestnut wood was left completely untreated, it is ideal for such exposed applications, without needing any harmful chemicals for the wood protection against decay and fungi. This strategy of combining the demonstrator with a permanent building project fit the overall sustainability spirit of the research project. First, the old forest hut was removed, since it was already in a bad condition. The foundation however, 1 3.5 m × 2.5 m concrete slab was left and re-used as a foundation for our demonstrator project. The ground surface of our demonstrator was slightly larger with 4.1 m × 2.8 m. The target surface was a doubly-curved surface forming an arch, where the cross-section was a catenary with a radius of 20 m at the bottom and 0.9 m at the top. In the other cross-section, along the surface the radius was 2.8 m up to 3.8 m, rising from an interior height of 2.7 m at the back to 3.4 m at the front. This surface was then divided into a gridshell with 6 segments in the short and 20 segments in the long direction. This resulted in 147 individually shaped beam components, with a total mass of 0.91 $m^3$ of wood, and a maximum component length of 0.92 m. the beam width was 60 mm with a minimum beam height of 100 mm and resulting raw part heights of 120, 140, 160, and 180 mm (Fig. 7).

The demonstrator was produced on a 2019 model Hundegger K2 industry machine with the Cambium Software system. The parts were produced in two days, the assembly was also carried out quickly and simply within the factory, since the structure was small enough to transport it to the site in one piece (Fig. 8, left). However, the system would also allow for the prefabrication and pre-assembly of multiple larger segments, which could then be combined on site, for example with a small amount of stainless-steel fasteners. In our demonstrator structure, each dovetail tenon joint was secured in place using a single self-tapping wood screw. These screws simplified the assembly, but the carry no loads in the structure and therefore costly stainless steel load bearing connectors were not necessary. Also note that other than typical Zollinger structures, our demonstrator does not have additional cross-bracing elements. Due to the double-curvature of the gridshell, the rigidity of the joints and the small size of the structure this was not necessary, however in a larger structure it would have to be added in the form of diagonal slats, just like the original Zollinger

**Fig. 7** Dovetail joined parts, produced using a Hundegger K2i industry machine

System. Finally, on site, a shingled floor (Fig. 8, right) and a wooden roof were added to our demonstrator, where all of the wood was sweet Chestnut (Castanea Sativa) without any exemptions. The structure was inaugurated and opened to the public on the 30th of October 2021 (Figs. 9 and 10).

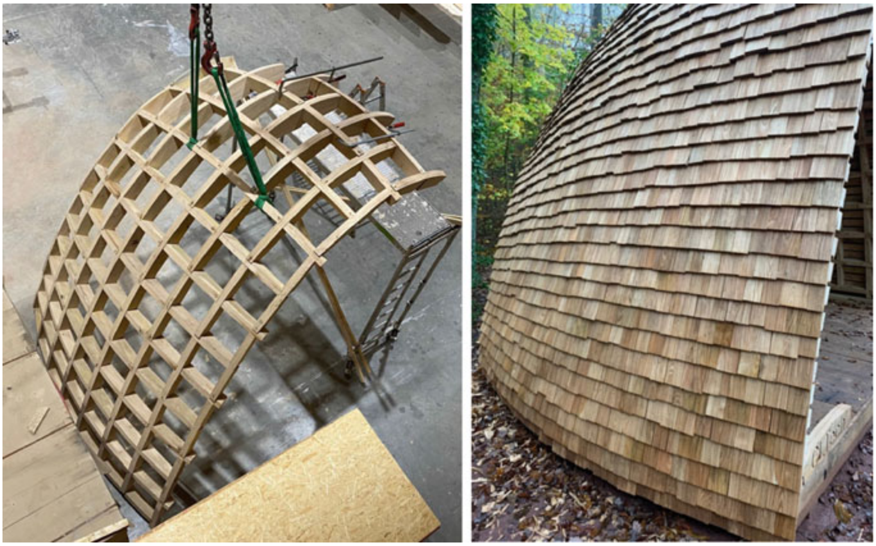
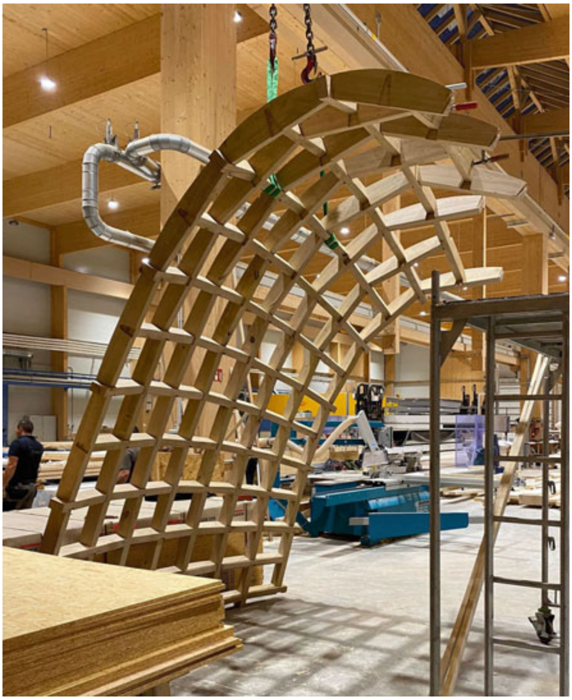


**Fig. 8** Left: Assembly of the parts, Right: Sweet chestnut shingles roof cover installation

**Fig. 9** Completed structure with sweet chestnut flooring and roof cover

**Fig. 10** Pre-assembly of the structure in the factory



## 10 Conclusion

Facing the future challenges of architecture in times of climate change, a high demand for buildings structures and a lack of skilled workers in many countries, this research project wants to combine material saving lightweight constructions with renewable local materials and high-tech automated production technology. Our construction system is based on an assembly-aware algorithm, which considers the dovetail joint geometry and overall assembly sequence constraints. It is the first reciprocal frame structure made from Castanea Sativa wood and the first sweet chestnut wood structure produced on an automatic joinery machine. The vast majority of new buildings using renewable materials is currently made from softwood such as spruce. As described in this article, many areas where we currently source these softwood trees have been hit hard by the warm and dry summers of the last decade in particular [12]. Following the prognosis, we will not be able to grow these trees any more in many of these areas within the next 100 years. While many of these trees where not naturally growing in these areas, the natural trees such as beech and oak are also greatly affected by climate change, therefore research suggests to stabilize these forests with tree species like Castanea Sativa, which is highly resistant to heat and drought. The local region of our demonstrator has the largest amount of Castanea Sativa trees in Germany; however, our demonstrator was the first permanent structure using sweet chestnut wood as a structural material. We believe that further research in the architectural potential of lesser used and future proof wood species in close collaboration with the forestry experts is urgently needed.

**Acknowledgements** We would like to thank our generous project partners CLTech GmbH Kaiserslautern, Landesforsten Rheinland-Pfalz, Forstamt Annweiler, Haus der Nachhaltigkeit Johanniskreuz, Holzbaucluster Rheinland-Pfalz and Hundegger AG. The demonstrator project was funded by the Ministry of the Environment Rheinland-Pfalz (MUEEF). A special thanks to Jürgen Gottschall, Hannsjörg Pohlmeyer, Gregor Seitz and Michael Leschnig.

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# Digital Deconstruction and Data-Driven Design from Post-Demolition Sites to Increase the Reliability of Reclaimed Materials

**Matthew Gordon and Roberto Vargas Calvo**

**Abstract** The research develops tools and strategies for urban mining and digital deconstruction to diminish the building sector's dependency on new natural resources. It facilitates the data capture, analysis, and characterization of secondary raw materials and defines a database system for recovered post-demolition components, promoting high-quality upcycled materials for new construction projects. A "form follows availability" digital design strategy is explored from a sparse quantity of reclaimed material. It develops a relational database from a semi-automated post-demolition item assessment, and the consequent extracted material (wood battens) is cataloged and stored before being matched and used for a new demonstrator using robotic fabrication. Each recovered element is imaged, scanned, and weighed to create a unique material health indicator. This information is presented in a user interface to help the designer filter for relevant materials. The final step of the system matches designed components with relevant stored materials by their generative design requirements. The system's flexibility is demonstrated using a construction system realizing curved surfaces from linear elements. By extracting multi-dimensional data on each wood batten and presenting their relevant indicators in a user-friendly interface, it is possible to create a dialogue between the designer and irregular shapes, augmenting the widespread use of reclaimed materials in structurally predictable assemblies. 85% of design components were well matched with the presented methods' database materials. The predictability of the system after fabrication is verified by a 10 mm maximum deviation between the as-designed and the as-built structure.

**Keywords** Reclaimed materials · Computer vision · Robotic fabrication · Circular economy · Relational database

**United Nations' Sustainable Development Goals** 9. Industry, innovation, and infrastructure · 11. Sustainable cities and communities · 12. Responsible consumption and production

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_20

## 1 Introduction

In order to transition to a high level of circularity in the construction industry, it is imperative to understand the number of resources we are consuming against the amount of waste we are producing. The sector is the number one consumer of global raw materials [1] while generating an alarming 25–30% of waste [2]. Resource efficiency can be increased by implementing technical innovations at multiple stages that keep our built environment circulating and contributing to local economies. For example, in the United States, 50% of all solid waste [1] created every year by construction processes could be accounted for in new buildings if we change the perspective on recyclable, reusable materials.

One solution to start using our resources smarter is to keep track of and connect the lifespans of our buildings. By better matching the supply and demand of building stocks, the more sources of high-value assets and materials the city can take for new projects, giving those resources useful second lives and market availability. Shifting the material flow back into urban areas will reduce the overall construction and demolition waste while simultaneously increasing the material recovery rate by one-third worldwide [3].

Current analysis of a demolition site is often carried out by visual inspection, along with judgments about recovery and reuse viability. The variability and clutter of work-sites make it challenging to digitize this process efficiently, while post-demolition digitization suffers from increased disorder among the relevant materials themselves. Lastly, further information about material location, storage, and transport is necessary for approaching these processes cost-effectively. Creating a sufficient scope and depth of database is critical to connecting each material with a consumer while ensuring these connections are highly local and efficiently found.

Within this field, the research aims to increase the reliability of reclaimed materials by automating post demolition capture and assessment of material-specific information on a building and component level, thereby contributing to the capabilities and scale of material reuse effectiveness by reducing the data collection effort. Using a system of reality capture and analysis methods to digitize and qualify critical materials from post deconstruction sites makes it possible to better inform and plan future uses of discarded construction material off-site.

## 2 Methodology

The implemented methodology inverts the standard design strategy by starting the creative process from the available resources. A set of available parts informs and generates a dynamic communication between the intended design and material type, properties, place, and user. The irregularity and sparsity of the database are a catapult to unexpected architectural form and complexity.

The research explored other similar methodologies for reusing standardless and reclaimed materials. Projects like "Form Follows Availability" [4] and "Minimal-waste design of timber layouts from non-standard reclaimed Elements" [5] use the length and size data of linear elements to match the available database with the intended structure within certain design parameter flexibility. "Cyclopean Cannibalism" [6] explores the re-adaptation of material debris and creates a precedent for using a digital inventory of reclaimed material obtained through point cloud representations of each item. It also pairs the dataset with performance goals like waste reduction and fitting optimization.

"Digital fabrication of standardless materials" [7] deals with the inherent properties of standardless materials; being the natural variation, uncertainty, and unexpected geometrical and dimensional properties found in bamboo. The project advances towards utilizing non-standard components that work structurally as predicted by a parametric model. As with the other examples, digital tools help optimize and automate laborious manual evaluation and consider deeper material properties.

Based on the learnings from the previously mentioned research, the process started with selecting post-demolition material; in this case, reclaimed wood battens that were retrieved from a previous pavilion in the Institute for Advanced Architecture of Catalonia. The selection for this material was based on proximity, availability, and variability found on the site. 140 out of 2263 pieces were selected by visual judgment and stored without initial sorting. From the selection, 94 elements were fully scanned by a robotic procedure and tagged for future traceability.

The obtained point clouds and textural imagery underwent low-cost physical testing and digital evaluation to pre-select elements more appropriate to structural vs aesthetic uses. After a robotic procedure has scanned the material, the research proposes a qualitative score on each element. The synthesized qualitative data becomes a "Material Health" indicator and is communicated via web-based and design-software-integrated viewers.

A parametric design strategy was chosen considering the amount of material available. Based on a form of doubly-curved surfaces, the system exposed the scale, width, height, and local curvature parameters for adjustment. A SQL database with the information gathered in the previous step served as a digital inventory representing the physical objects and their reuse potential within the design. A multi-objective optimization algorithm ran several iterations until the chosen criteria were met.

Due to design flexibility and a division of geometric complexity, the most energy-intensive robot fabrication techniques were only necessary for producing the smaller connective components in the structure. After producing a buildable digital model, the construction began by retrieving the indicated items from the storage location and marking them by projecting rationalized information into each piece. Finally, with all the battens marked, the assembly took place in situ with the help of the digital twin.

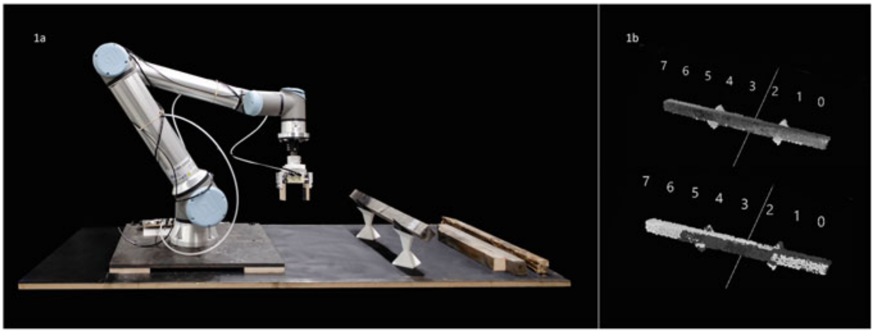


**Fig. 1** **a** The UR10 in combination with the gripper-scanner tool and the scanning holder. **b** For the scanning process, each side requires seven camera captures to be registered afterward

# 3 Post-Demolition Item Assessment

## *3.1 Robotic Data Capture*

The setup consisted of one UR10 robot, operating a customized pneumatic gripper mounted with a D435i Intel RGBD camera (Fig. 1a). The workspace featured a scanning stand, printed with TPU and mounted to the table magnetically, to balance between creating a steady platform and preventing damage in case of dropped materials or materials with unexpected dimensions. Intended explicitly for components with a rectangular cross-section, the stand holds components at 45° to expose multiple sides and allow for scanning in only two passes. The end tool's depth camera was mounted at an offset and at a 35° angle to prevent vision occlusion from the gripper.

Drawing from a known safe zone behind the scanning area, the robot picked up individual components for transfer to the scanning holder. While multiple angles of inclination were tested, it was found that further analysis worked sufficiently from a single row of scan captures along each half of the object. Finally, the robotically controlled camera position allowed for automatically registering captured clouds producing the final geometry (Fig. 1b).

## *3.2 Photogrammetry Procedure for Data Capture*

While a viable automation procedure, due to the relatively low capture resolution from the Realsense camera, it was impossible to perform surface quality analysis on the reconstructed mesh or accurate point cloud measurements. In order to capture high-quality point clouds and create a reliable dataset, a photogrammetry method was also employed (Fig. 2a). An automatic subject masking was performed to increase the speed of each point cloud creation and ensure a quicker way to create a sparse cloud.

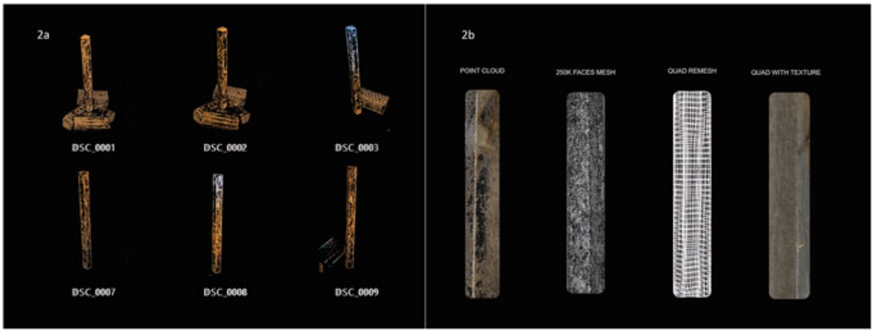


**Fig. 2** **a** Tie points between each picture with subject segmentation. **b** Process for a usable mesh. Geometry decimation and optimization for mesh topology of each item

Each of the point clouds was produced from 25 to 35 high-resolution photographs. The resulting geometry was automatically scaled and normalized to the world axis to align the items. Each cloud was then converted into a high-resolution mesh, further decimated, and finally remeshed with a high-quality texture but low polygon count for faster processing (Fig. 2b).

### 3.3 Analysis

**Surface curvature**. Curvature analysis was based on the finalized mesh rather than the raw point data; while this resulted in a somewhat lower resolution, it led to viable efficiency within the Grasshopper environment. Consequently, an absolute curvature was extracted on every batten; the values were then averaged into a score later combined with the other analyses for a "Material Health" final score (Fig. 3a).

**Curvature evaluation of mesh skeleton**. The curvature evaluation of the mesh skeleton analyzed the possible wood warping in the longitudinal axis of each wood batten. The system averaged the centerline of the point cloud on which curvature analysis was performed; it could then approximate and relate them with wood warping problems depending on its location and frequency of values (Fig. 3b).

**Mass comparison**. Given that all methods thus described operated on surface details, an analysis of the components' mass was carried out to judge the quality of the element's interior. Given the known or estimated species of wood used (based on location, building trends, etc.), the expected mass was calculated using the measured dimensions and species average density. Simultaneously, the actual mass was measured manually or via torque sensors in the automation system. The ratio of the actual-to-predicted mass indicated how much decay may have occurred over


**Fig. 3** **a** Surface curvature analysis. **b** Two examples of mesh curvature visualization. **c** Example mass ratios for structurally usable vs a highly decayed wooden element. **d** Example output when localizing texture defects using Mask RCNN

time. For example, the worst decayed test pieces had only 55% of the expected mass (Fig. 3c).

**Textural defect detection**. As not all issues were detectable via geometry, analysis was also performed on the image textures extracted in previous steps. The primary defects considered were knot holes and nail/metal connector holes, appearing visually similar and representing similar possible structural issues. Localization was performed using the Mask R-CNN algorithm [8]. This allowed each defect to be stored by its face and local position, available for deeper future structural analysis (Fig. 3d).

**Element Tagging, Lifespan Tracking, and Interface**. Each recovered piece received a data frame of extracted geometric, structural, and textural information applicable to its future lifetime. For aesthetics and data stability, it was decided to store the bulk of this information in an external database. This was built as a relational SQL database, with a primary table storing each element's rough dimensions and origin site, with additional associated tables storing data from each analysis method. Each table was associated by the element's UUID (universally unique identifier), thus allowing each element only to be marked by a representation of the id's 128-bit number. QR codes were chosen to store this id, given their built-in redundancy, low-cost application, and ubiquity of software to read them.

A mobile app was developed for on-site data lookup to test ways this tracking system would be accessed on-site. The app scanned the QR codes of chosen elements and retrieved a portion of the information from the MySQL database.

## 3.4 Database Interface

A user interface was developed to visualize the information gathered and verify the relevance of the database categories (Fig. 4a). This digital inventory viewer served as a retrieval tool and displayed indicators like mass ratio, usage, warping percentage, number of nails found, surface curvature, and in combination, a weighted synthesized score comprehending the previous indicators called "Material Health". Lastly, profile shape and dimensions are also shown (Fig. 4b).

A web-based interface (Fig. 5a) served as an approach to test the applicability of the database for a broader range of users. In this case, the information gathered could be accessed by a secondary resources supplier or remanufacturer (Fig. 5b); simultaneously, it functions as a retrieval system for designers, with filter options like minimal quality, distance, and defects to retrieve the material needed for each task. After the material has been selected, the relevant database entries can be downloaded into a design environment like grasshopper through a SQL plug-in.

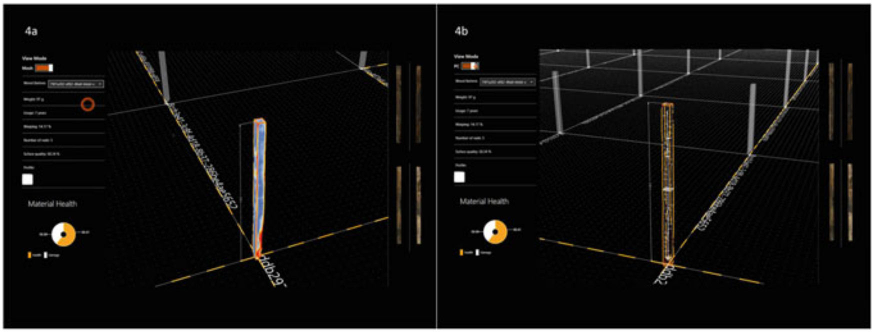


**Fig. 4** **a** Database interface image on mesh view. **b** Database interface image on point cloud view

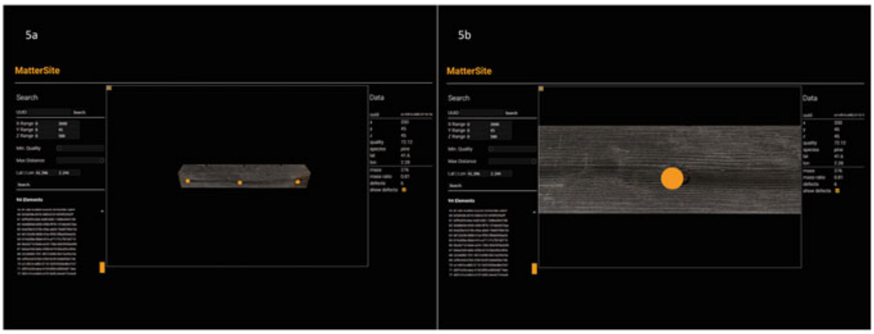


**Fig. 5** **a** UI Image. The prototype viewing interface for recovered elements running on Firefox. **b** UI Image. Possible defect locations are highlighted

## 4 Design Strategy for Uncertain Materials

The design of the demonstrator highlighted the goals of design and material adaptability that digitization brings to the process in the form of a small-scale shelter pavilion. The design was based on approximating arbitrary input surfaces using two layers of opposingly oriented pieces. The development of this system took initial inspiration from the overlapping geometry of reciprocal structures, although this orientation does not utilize the same structural ideas. This strategy allowed for maximum flexibility to adapt to the available inventory as individual lengths can vary significantly and still fit the overall dimensions and design requirements (Fig. 6b).

Given a starting surface, it was first converted into a mesh consisting of diamond strips. These edges were then turned into initial solid 'reciprocal'-layout forms using the Grasshopper NGon plugin. These pieces were divided into two layers based on their orientation in the original surface's UV space. Each piece was then scaled to overlap with its neighbors, and offset from the surface by a calibrated amount. Thus, the two layers are connected by a series of specifically cut connector pieces (Fig. 6a).

Each connector (Fig. 6c) decomposes the vector between each main face into two simple rotations at the end faces of the connector. This simplified the digital fabrication of the connectors and allowed them to be more clearly aligned with the main pieces they attached to.

The structure considered the dimensional data to reduce the design space variants and the labor and energy required to cut the item. As with the linear elements of the structure, the connectors needed to be consequent with the usage optimization from available resources, reduce waste production, and use as much as possible the length of the item from which the connectors were going to be extracted.

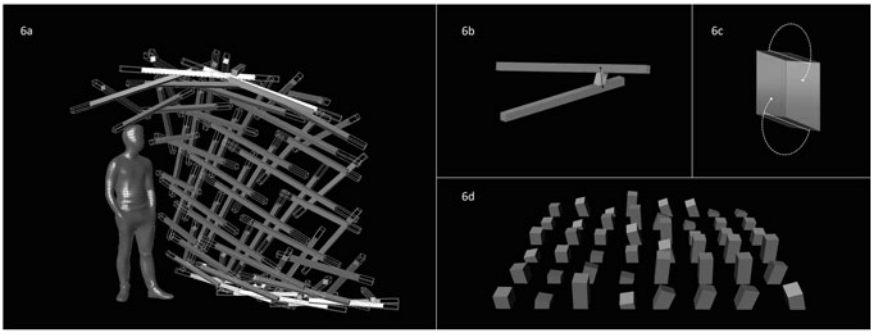


**Fig. 6** **a** Digital design process from input surface to layered structure. **b** The dimensional flexibility of elements; varies in length by 0–20%, depending on inventory availability; reducing additional labor. **c** The faces of each connector only contain simple rotations to encode the overall vector being connected

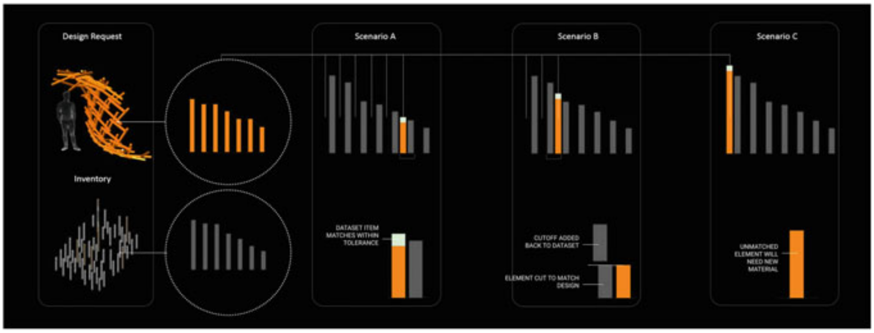


**Fig. 7** Outcomes from a design piece matching itself against the database

## *4.1 Matching Material Stock from Availability*

With this strategy for representing arbitrary surfaces with linear wooden elements, the approach needed to be realized with the available materials. With material-buyer matching already a common process for reclaimed material marketplaces, a system was developed for matching each piece to be assembled with one from the database. This was based on a top-down greedy matching system with pre-sorting by length (Fig. 7), a heuristic that generally reduces cutoff waste [9]. Each element had a degree of tolerance where it could match with elements larger than designed but never with elements shorter. As the database is arbitrarily large, the list of elements to be matched against comes from an initial reduced database selection, immediately filtering to relevant items based on dimensions, quality, or distance from storage. Particularly here, a strict quality threshold was used, given the degree of decay seen in the stock.

Each design element thus had three possible outcomes; either it was well-matched with an actual piece within tolerance, it was matched with a significantly larger piece that would need to be cut down, or no match was found and would require fulfillment with new stock. Each matching pass could then be assigned a score, with the amount of new stock and new labor required negatively impacting the viability of a particular design option given the available materials. In a larger scenario, the transport distance of each item would also serve as a negative variable.

## *4.2 Design Interface*

The design interface contains database parameters visually integrating the database's impact within the design (Fig. 8a). Information about the number of matched items is displayed; the user is informed how much alteration or new materials may be required. An optimization algorithm runs every time the selection of the database

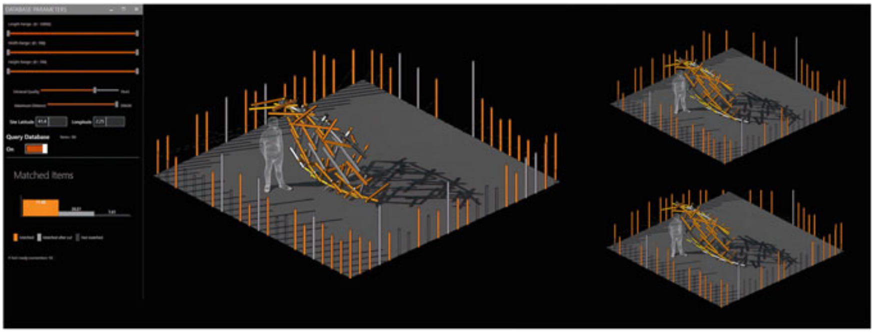


**Fig. 8** **a** Images of the UI environment. The left panel sets parameters for an initial database filtering. During the interaction, the "Matched Items" graph will adjust accordingly, showing the percentage of design elements that were matched, matched after a cut, or not matched at all

changes [10]. The fitness for the optimization is the maximization of the matched elements while reducing the labor needed; that is, reducing the amount of cutting or any modification of the pieces.

Detail design parameters like the number of mesh subdivisions and surface curvature will vary depending on the number of elements and their properties from the database. If the database is primarily composed of long elements, the resulting design will have fewer subdivisions to accommodate the specific lengths of those elements. Surrounding the model, there is a visible representation of the database, each of the elements will turn orange if the item is found and matched for the design, gray, which means it is matched, but some labor is required, or black outline, defining a no match for that particular wood batten.

The chosen design for fabrication resulted in 85% of their components being matched with the material from the inventory, from which only 10% required to be cut to size. The second objective ensures the constructability of the system, avoiding collisions between the battens and the connectors.

## 5 Digital Fabrication Methods

Following this design strategy, most of the pre-assembly work was encapsulated in the connector pieces, as they contained most of the essential measurements of the design. A fabrication system was chosen such that theoretically, all necessary operations could be carried out by a human using typical woodworking tools; the inclusion of the robotic system would increase speed, safety, and accuracy. The connectors were successfully fabricated with precision using an automated method, while the rest of the construction was handled manually with the aid of a CAD interface.

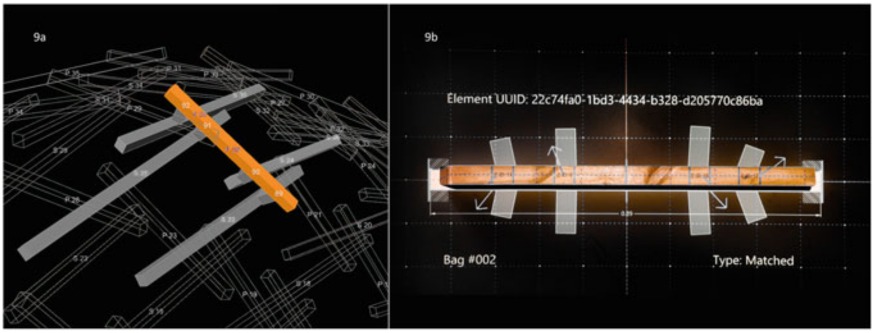


**Fig. 9** **a** The digital model for fabrication highlights the item to be assembled, indicating the connectors ID and the IDs of the other elements to which the piece is connected. **b** The projected user interface on the wood batten

A fabrication model was developed (Fig. 9a) to help during the assembly of the structure. The interface displays in the design space the location of the selected item, relevant connectors IDs, and the design IDs of the elements connected to that particular piece. The component meshes are color-coded as an extra layer of information depending on which oriented layer of the pavilion they belong to.

### *5.1 Projection Assisted Annotation*

While each structural component contained a degree of variability in its total length, the intersection and connection points within its length were highly specific. This information was applied to each component using an assistive system consisting of a work table with a projector mounted overhead and displaying the digital model [11].

The projection displayed the minimum and maximum design length, connector location, id, and orientation (Fig. 9b). The connector locations were traced for all primary-layer components, and each connector was additionally pre-glued in place (Fig. 10b) for each secondary-layer component. Each layer component was assigned an incrementing id based on its layer (e.g. P2 or S5). Each connector piece could be uniquely identified by which layer components it is attached to (e.g. 2|5). Each connection point on a layer piece was likewise identified by the id of the opposite layer piece.

### *5.2 Demonstrator Assembly*

Final assembly was performed by hand, using wood screws for all connections. Starting from the bottom diamond required multiple workers and clamping to hold

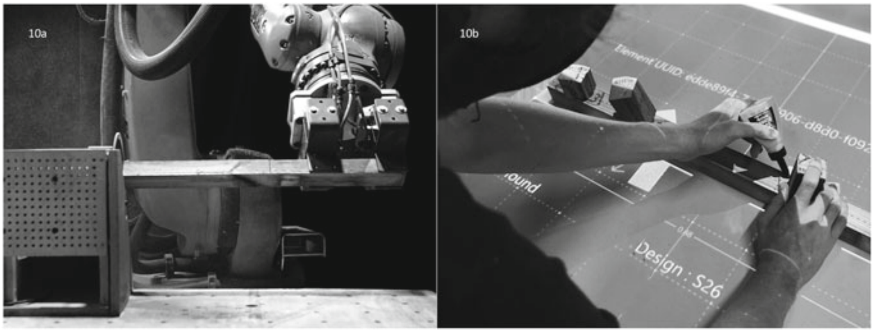


**Fig. 10** **a** Photograph of the robotic cutting process for the connectors. **b** Pre-gluing connectors for all secondary-layer structure components

the slightly twisted quad in place (Fig. 11a). However, from there, each layer of diamonds was added progressively, with the screws at the top of each diamond added last in order to pull tension into the system if necessary. Due to the density of labeling applied during the setup phase, upcoming pieces and their orientation could be found by reading the current raw edge of the structure, reducing the need to review against the computer model often.

After the structure was completed (Fig. 11b), a point cloud was created through photogrammetry and compared to the original geometry (Fig. 12). The results from the deviation analysis showed that 85% of the area of the structure was completed within 10 mm tolerance.

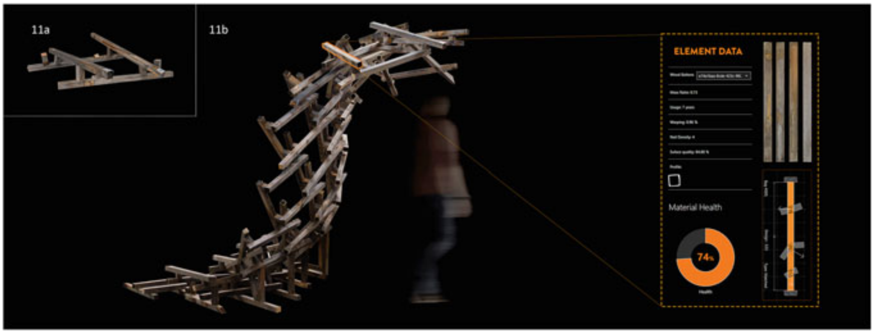


**Fig. 11** **a** The initial diamond module requires the most manual labor. **b** Image composition showcasing the material intelligence behind each fabricated item. Digital layers help improve the reliability of reclaimed materials

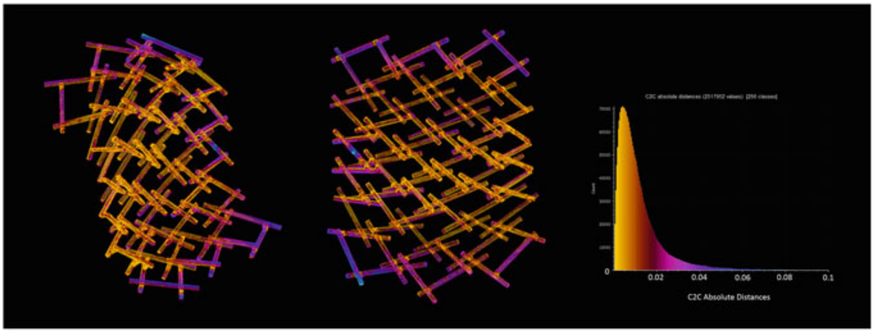


**Fig. 12** Deviation analysis

## 6 Conclusions

This project has developed a total-lifespan set of methods and technologies for applying digitization to mass re-use construction and demolition waste. Each stage contains both an operational base for new value or greater efficiency and many opportunities for further development.

The research understands the complexity of ensuring local material banks from unused buildings and focuses intensely on one source of irregular material: wood battens from a previous pavilion. It recognizes the challenge to introduce, promote and pair the capture and serving of relevant information through databases to planners and architects. Several iterations of user interfaces create a communication channel between the profoundly technical and the creative and discovery nature of design environments, stating that a mental model shift needs to occur to create an environmentally conscious design from a material intelligence perspective.

The results obtained from the demonstrator optimized repurposed material utilization and fabrication efficiency, promoting locally sourced, readily available, and reclaimed materials in a circular approach. Ultimately, the demonstrator was a highly specific case, with a focus on realizing the form and aesthetic. The application and testing of these technologies in progressively more practical constructions will uncover further structural, spatial, and regulatory constraints to be met by the optimization and design of communication systems.

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# Impact and Challenges of Design and Sustainability in the Industry 4.0 Era: Co-Designing the Next Generation of Urban Beekeeping

**Marina Ricci, Annalisa Di Roma, Alessandra Scarcelli, and Michele Fiorentino**

**Abstract** In the era of Industry 4.0, designers are expected to use new tools and approaches to innovate the design of products and services. From this perspective, the integration of design practices and technologies of the 4.0 transition can have positive implications for sustainability. Several current issues can be addressed and among them, honeybee death is relevant. Honeybees are fundamental to the ecosystem and human life. Nevertheless, their lives are extremely at risk due to exposure to several disease factors. After conducting expert interviews, the paper presents a conceptual model of intelligent beekeeping to monitor the health status of honeybees. Furthermore, after user research, the paper proposes a co-design model for urban beekeeping, scaled up to a condominium dimension, to allow condominiums and expert beekeepers to be part of an integrated design model. The critical proposition of this model is to raise awareness of the problem of honeybee death to achieve 3 out of 17 United Nations' Sustainable Development Goals: Good Health and Well-Being, Sustainable Cities and Community, and Life on Land. Early results report positive values of acceptance of the urban beekeeping practice by users and the use of IoT in managing beehives and their health status by expert beekeepers.

**Keywords** Urban beekeeping · Industry 4.0 · Industrial design · IoT technology · Design for sustainability · Co-design

**United Nations' Sustainable Development Goals** 3. Good Health and Well-Being · 11. Sustainable Cities and Community · 15. Life on Land

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_21

## 1 Introduction

The industry 4.0 paradigm is moving forward quickly, increasingly changing our world and the way we live and work [1]. This digital transition provides tools to address urgent issues with the help of new and emerging technologies.

The 4.0 model affects the way designers *design* as in any industrial revolution. The exponential development of digital technologies is certainly increasing the virtual component of our experience [2]. In this ever-changing scenario, design can indeed gather input, tools, and procedures that can be used to solve critical issues.

In the twenty-first century, designers must think of products and services differently from their ancestors. In Industry 4.0 enabling technologies such as the Internet of Things (IoT) provide new design opportunities to empower people and enrich their daily lives, in real-time and smart connecting people.

On the other hand, the impact of Industry 4.0 on sustainability and the way it can contribute to sustainable economic, environmental, and social development is increasingly gaining attention [1]. The 4.0 paradigm may offer opportunities for sustainability, by helping to achieve the United Nations' Sustainable Development Goals (SDGs) outlined in the 2030 Agenda. This document provides a set of guidelines for sustainable development, adopted by all United Nations member states to promote effective design for sustainability.

Thus, the paper aims to stimulate 4.0 awareness for designers who must solve real and compelling issues related to this era. Also, the paper defines the role of design in the 4.0 paradigm to achieve and disseminate innovative solutions and projects according to the 17 United Nations Sustainable Development Goals.

The honeybee can benefit from this digital 4.0 transition with the help of design, and its well-being can have positive implications for sustainability. Indeed, honeybees are the most effective pollinators of crops and are crucial in order to achieve sustainable development [3, 4]. Since the end of the twentieth century, honeybees are suffering from increasing stress factors, leading domesticated colonies to die or at least be less productive [5]. Also, several factors including parasites, bacterial and fungal infections, and pesticides [3] have been identified as drivers of honeybee death and this phenomenon triggered the need to rethink beekeeping and its tools.

Many plant species would become extinct without them, and current levels of productivity could only be maintained at great cost through artificial pollination. Domestic and wild honeybees are responsible for about 70% of the pollination of all living plant species on the planet and provide about 35% of global food production.

The future of beekeeping is to implement smart 4.0 beehive management using automated and remote tools for monitoring honeybee colonies along with beehive control mechanisms to safeguard honeybees' well-being and improve colony productivity [6].

There is also a growing awareness of beekeeping, particularly in metropolises and cities [7], called *urban beekeeping*. This practice of raising honeybees in an urban environment is blended with the co-design perspective and the creation of communities of experts and non-experts for the safeguarding of honeybees. We use co-design in a broader sense to refer to the creativity of designers and people not trained in design working together in the design development process [8].

Not all the reasons for honeybee death are fully known, and as a result, it is essential to obtain all possible information on the environmental conditions surrounding the beehives [9].

The digitalization of beekeeping first involves systems from the field of the IoT, with the development of sensors to collect and transfer honeybee-related data [5]. Then, data analysis comes into play, providing models that connect the data with the biological states of beehives. The speed and scale of IoT provide new design opportunities to empower people and enrich their everyday lives [10].

Thus, in this paper, we want to address the following Research Questions (RQs):

RQ1. What is the urban beekeeping' acceptance level of users?

RQ2. How IoT can be an appropriate tool to help beekeepers in managing and control beekeeping systems?

Through semi-structured questionnaires, we surveyed a sample of 463 participants to figure out their knowledge and awareness about beekeeping and honeybees' safeguard and to survey their acceptance of the urban beekeeping model. Also, we conducted expert interviews with expert beekeepers to survey their needs, knowledge, and acceptance of 4.0 tools for beekeeping.

The remaining paper is structured in four sections. The first describes the state-of-the-art related to smart monitoring systems for beekeeping. The second describes the methods adopted to answer the RQs. The third relates to the discussion about the role of design within the 4.0 era and its potential to reach three sustainable development goals through the conceptual model. Lastly, we report our conclusions and future works.

## 2 Related Work

Beekeeping has a huge impact on all agricultural field, as honeybees are the main insect pollinators and plays the important role in whole crop production and the survival of plants [11].

Recently, urban beekeeping is a rapidly developing model, involving beekeeping *in*, *of,* and *for* the city [12]. Beekeeping *in* the city concerns the importation of traditionally rural beekeeping practices into urban spaces on behalf of the beekeeper. Beekeeping *of* the city describes beekeeping consciously adapted to the urban context, often accompanied by (semi)professionalization of beekeepers and the formation of local expert communities (i. e., beekeeping associations, and communities). Beekeeping *for* the city describes a shift in mindset that addresses beekeeping for civic purposes beyond the beekeeping community itself.

Beehive monitoring is fundamental to monitoring different parameters, such as the temperature and humidity levels inside the beehives and the weight, sounds, and gases produced, which can generate important information. For example, these data can inform whether the beehives are swarming based on the temperature, whether any action is required from the beekeeper, whether the honeybees are affected by any disease, or even whether the beehives are affected moving. This last application is very useful in areas where beehives can be stolen.

Different technologies can be applied to monitor the beehives [9]. A smart beehive is a connected beehive with some intelligence, for example, a beehive capable of diagnosing health issues [5, 13].

Phillips et al. [14] encouraged the "Bee Lab project" that blends citizen science and open design with beekeeping. Their objective was to enable participants to construct monitoring devices gathering reciprocal data, motivating them and third parties. They used design workshops to provide insight into the design of kits, and user motivations, promoting reciprocal interests and addressing community problems.

Murphy et al. [15, 16] developed a fully autonomous beehive monitoring system. Their objective was to use Wireless Sensor Network (WSN) technology to monitor a colony within the beehive by collecting image and audio data and developing a multi-data source beehive monitoring system. WSN technology includes sensors, low-power processing, mobile networking, and energy harvesting. In this way, the beekeeper will obtain recorded information about in-hive conditions (e. g., during the night, winter months, etc.). The contributions of this work also include the unobtrusive monitoring of the beehive during times when the beekeeper is unable to open it.

Zacepins et al. [6] introduced and analyzed different bee colony monitoring and control systems and their combinations within the ERA-NET ICT-Agri project 'ITAPIC'. Also, they presented their vision for the implementation of Precision Beekeeping together with the smart apiary concept system based on temperature, sound, and video monitoring.

Gil-Lebrero et al. [9] designed a remote monitoring system for honeybee colonies (i. e., WBee) based on a hierarchical three-level model formed by the wireless node, a local data server, and a cloud data server. WBee is a low-cost, fully scalable, easily deployable system for the number and types of sensors and the number of hives, and their geographical distribution.

Lyu et al. [17] designed an intelligent beehive system with a real-time monitoring function of the status information of the inside and outside of the beehive (e. g., weight, attitude, etc.). The beekeeper can check the status of the beehive in real time in the monitoring center. The system reduces beekeepers' labor and improves the quality of honey.

Kontogiannis [18] developed a holistic management and control system for the apiculture industry called the Integrated Beekeeping System of holistic Management and Control (IBSMC). This system allows honeybee living conditions regulation, aiming at minimizing honeybee swarm mortality, and maximizing productivity. Within the proposed system architecture, additional security functionalities are implemented for honeybee monitoring, low energy consumption, and incident response.

Existing beehive control and management systems allow for critical thinking and rethinking of smart beehive models thanks to design approaches and 4.0 technological tools.

# 3 Methods

Beekeeping can be innovated and conceived as a co-design activity that can involve not only expert beekeepers but also ordinary citizens. By broadening the knowledge about beekeeping to the urban level, a series of actions can be performed that can benefit honeybees and cause benefits, combined with IoT technology.

The two research questions were explored through user research and expert interviews to answer needs, expectations, and problems and subsequently formulate a model.

## *3.1 User Research*

We analyze the context of use by investigating the user awareness concerning honeybee importance and their behavior. Thus, we create a questionnaire using Google Forms distributed to a sample of potential users for 12 days ($n = 306$; 59,3% female and 40,7% male). The questionnaire provides quantitative data about user knowledge and user behavior regarding honeybees through 13 open and closed questions. As an interesting result, the user analysis demonstrates that most of the users are aware of the phenomenon of honeybee death (82,8%). Also, many users know that honeybees are fundamental to human life and sustainability (84%), but most of them have never heard of urban beekeeping (58%). A mere 30.1% have observed a beehive up close previously and most are unaware of the possibility of being able to adopt a beehive (68%) and monitor its health (82%).

Interestingly, most of the users would like to have a condominium beehive to raise honeybees in their condominiums ($M = 6$; $SD = 0,4$ on a 7-point Likert scale).

In addition, users were asked about their agreement related to the listed requirements to have a condominium beehive using a 7-point Likert Scale. The results were compiled into a graph (see Fig. 1).

## *3.2 Expert Interviews*

We conducted expert interviews to gain information about beekeepers' IoT adoption and explore their knowledge and expectations. Expert interviews are a widely used qualitative interview method often aiming at gaining information about or exploring a


**Fig. 1** Condominium beehive requirements preferences according to users on a 7-point Likert Scale

specific field of action [19] (i. e., beekeeping). Those were semi-structured interviews based on the use of a questionnaire covering the following topics:

- Generic knowledge:
  - Threats to traditional beekeeping: climate change, immoderate use of pesticides, lack of food due to excessive plowing and extensive monocultures, and spread of beehive diseases (e. g., Varroa).
  - Actual problems of urban beekeeping: swarming. For the urban environment, swarms can become a nuisance and a fright for the citizens, both for citizens' lack of knowledge about them, but also the inconvenience concerning the places where the swarming families decide to settle (e.g., inhabited places, schools, etc.).

- IoT beehive adoption: according to the expert beekeepers, there is not a wide knowledge of commercially available smart beehives and their possibilities for the environment. In their opinion, if technology could help beekeepers to manage their beehives, intelligent beehives equipped with sensors are useful. Helping beekeepers manage their beehives more conveniently, quickly, and effectively is an advantage. For example, those beekeepers with lots of beehives could optimize their intervention time and be able to intervene while helping their honeybees grow and thrive. Expert beekeepers will be willing to use intelligent beehives, based on two dependent variables: costs and ease to use.

Also, beekeepers expect IoT-intelligent beehives to:

- Remotely control the beehive's temperature, humidity, and weight to understand how the health status of the family from these parameters.
- Manage to predict swarming, and consequently avoid or control it. An abrupt decrease in weight indicates that swarming has occurred, but at that point, it is too late, at most, if possible, the beekeeper could intervene earlier to recover the swarm before it moves too far from the beehive.

The possibility of monitoring the health status of honeybees remotely, by a device (e.g., smartphone, tablet, laptop), would facilitate and improve the work of beekeepers.

- Urban beekeeping with a co-design approach: the idea of implementing smart condominium beehives as a co-design for beekeeping is very interesting according to beekeepers. However, there are some limitations and aspects to consider in the design phase:
  - Fear of condominiums.
  - Allergies of the condominiums.
  - Swarming: In the city, they can become annoying and even dangerous.
  - Distance From a legislative point of view beehives must be placed at least ten meters from public roads and at least five meters from the borders of the neighborhood, unless there is a natural barrier (e.g., hedges) or artificial (e.g., walls) at least 2 m high. In this case, the distance is nullified because the honeybees would be forced to fly above human height.
  - The non-training of condos.

  Also, the smart beehive will need to have several features:

- Anti-theft system.
- Honeybee health monitoring.
- Weight of beehives.
- Swarming prediction.

### 3.3 The Conceptual Model

User research and expert interviews allow us to collect useful data to develop a conceptual model of a smart beehive (see Fig. 2) and to predict from a co-design perspective a useful application for the communication between condominiums and expert beekeepers.

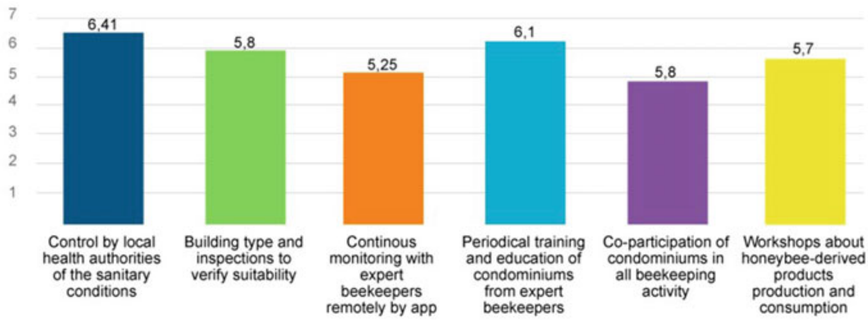


**Fig. 2** IoT technology management. From honeybees to sensors, from the Internet to devices

Different parameters of the honeybee colony can be monitored: temperature, humidity, gas content, sound, vibration, etc. Continuous monitoring of some honeybee colony parameters is very challenging and not user-friendly, using it only for research purposes, not for practical implementation by the beekeepers [6].

### 3.3.1 Types of Sensors‘

In the IoT field, the choice of appropriate sensors is essential to produce a solid base before data analysis since sensors can capture beehive-related data [5].

The design of a wireless sensor network and IoT sensors involved in this are:

– Temperature and humidity sensors: honeybees need temperatures (90–95 F) and humidity levels (50–60%) to raise their brood optimally and promote overall colony wellbeing. Below 50% humidity, eggs won't even hatch because they dry out. Additionally, higher humidity levels significantly decrease Varroa mite reproduction levels and are desirable during the brood-rearing season.
– Accelerometer: registered data about frequencies and their variations in the beehive allow for to prediction of swarming phenomena [20].
– Weight: indicates the activity level of a colony and is a good indicator of honey flow evolution and flowering.
– Geo-localization: to localize the beehive to be reached by expert beekeepers and send data via the Internet to be visualized on the application.
– Anti-theft: a tracking device consisting of a GPS tracker, a battery, a SIM card, and a motion detector. It can be placed inside the beehive (e. g., at the lid, the bottom, the body, or even inside a honeycomb). The device will stay off, without draining its battery or disturbing the honeybees via cell phone radiation. With the slightest wiggling of the beehive, the device turns on and informs users with an SMS sent to their cell phones.

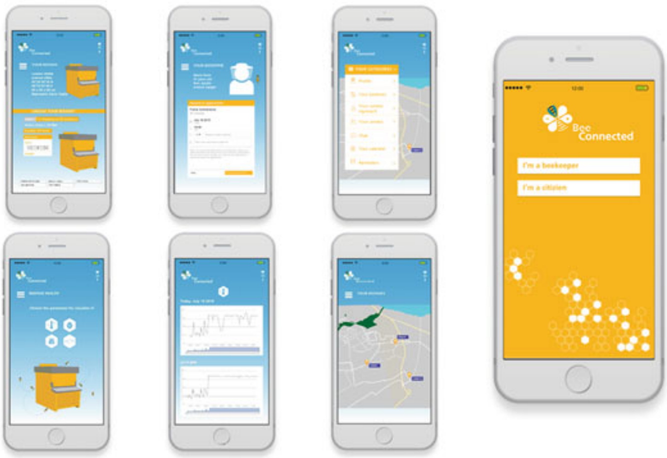


**Fig. 3** Mockup of the mobile app from an expert beekeeper and condominiums point of view

All data about honeybee health could be transmitted to an application (see Fig. 3) through which users, both condominiums and expert beekeepers, can be informed about their health status and any urgent problems.

### 3.3.2 Co-Design Approach

Co-design is an approach to designing with, not for, people. Especially in areas where technologies mature, designers have been moving increasingly closer to the future users of what they design [8]. Co-design typically works best when people, communities, and professionals work together to improve something they all care about.

From this perspective, the co-design approach could potentially be extended to urban beekeeping. The process includes several parts and starts with "Build the conditions" (see Fig. 4) for the genuine and safe involvement of people (i. e. condominium requirements).

The reference community includes ordinary citizens grouped in condominiums, supported by expert beekeepers to carry out co-creation activities. The tools employed include IoT for controlled and shared co-design for the beehive management.

## 4 Discussion

Design plays a key role in achieving sustainable goals because, by leveraging design culture approaches (i. e., co-design approach) and Industry 4.0 transition tools (i. e., IoT technology), it can solve current critical problems.

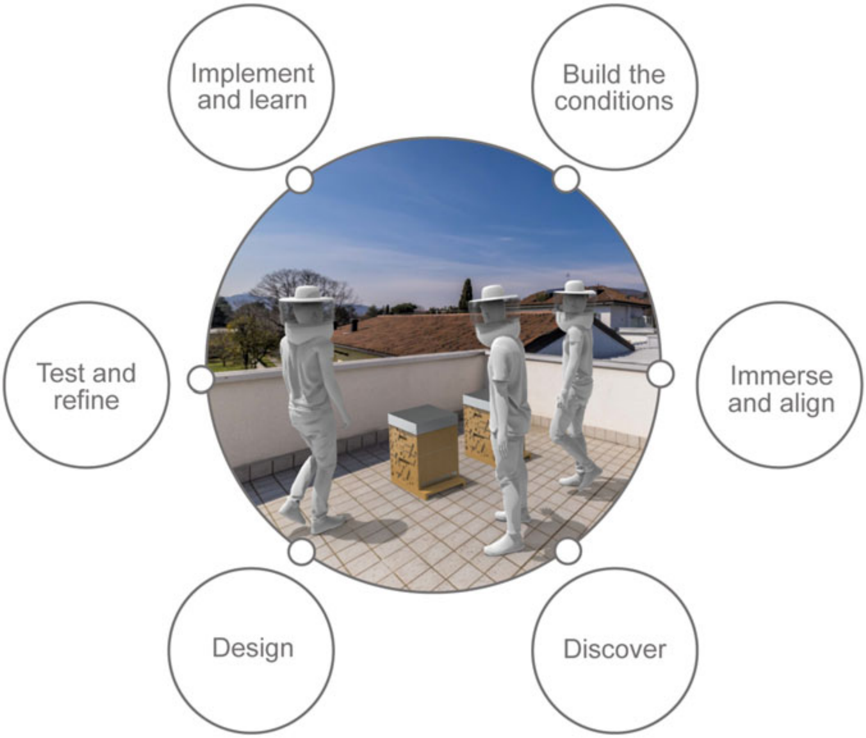


**Fig. 4** The co-design process for the urban beekeeping

In this specific case, (e.g., the death of honeybees), the design allows for achieving three United Nations SDGs.

**SD 3. Good Health and Well-Being**

One of the sustainable goals relates to ensuring healthy lives and promoting well-being. The human being's health depends on the honeybee's health. This insect, thanks to pollination, enables new plants to be born and humans to breathe. Honeybees increase the possibility of a plant making more fruits and food for human beings.

The conceptual model developed allows for monitoring the health of honeybees in real-time, h24, to ensure their well-being, with positive implications for humans and the city. Intelligent beehives allow the recording of many variables such as:

1. Honeybee ecological variables
   - Colony life history: health monitoring, collapse events, requeening events (e.g., swarming), beekeeping tasks.
   - Colony dynamics: colony size, brood area, drone brood area, food reserve mass.

- Resource use: harvested pollen species composition, honey-embedded pollen species composition.

2. Environmental variables

- Floral resource phenology monitoring.
- Land use monitoring.
- Climatic data.

**SD 11. Sustainable Cities and Community**

The sustainable challenges cities face can be overcome to allow them to thrive and grow by improving resource use and reducing pollution.

Urban beekeeping would allow environmental monitoring, particularly related to air quality in cities. It is necessary to constantly monitor the presence of air pollutants to allow honeybees to live and reproduce in city environments. By observing the behavior of honeybees, it is possible to evaluate the presence of heavy metals, microplastics, and fine dust in the atmosphere. All these substances are as dangerous as they are unfortunately present in the air we breathe in large and small cities.

**SD 15. Life on Land**

From an ecological perspective, honeybees provide a source of both direct and indirect food to a whole host of organisms, including humans [15].

Protecting the population of honeybees worldwide and enabling them to maximize their productivity is an important concern [16] since they are fundamental not only for their well-being but also for humans and vegetation.

## 5 Conclusions

Design is constantly evolving and using new tools and approaches to design useful products and services to solve current problems. This paper shows how a relevant problem such as honeybee death could be addressed through the integration of the 4.0 paradigm and design.

User research shows that acceptance of urban beekeeping is high among many users (RQ1). This finding is important and encouraging for the development of conceptual models scaled to the urban dimension and, more specifically, to the condominium dimension. In addition, co-design could be a potential approach to innovate the practice of beekeeping, making it accessible not only to the expert beekeeper but also to the ordinary citizen.

Interviews with experts show that IoT is an appropriate tool to help beekeepers in the management and control of beekeeping systems (RQ2). Although there is no established knowledge of smart systems for beekeeping, there is a great interest in adopting technological systems to facilitate several tasks for beekeepers.

The first step in the future would be to set up the model and design in a real beehive to see how the system responds in a real-world deployment. Future tests would also provide valuable real-world data from the beehive, which can be used for further beekeeping research.

Furthermore, it is important to test the dimension of the co-design approach within one or more apartment buildings to collect data on their involvement in activities, and use of the mobile app and the IoT management model.

**Acknowledgements** We would like to thank the beekeepers Nicola Ignomeriello and Cristian Scalise involved in the project DontBEEScared—stai sen'APEnsieri which concerns urban educational beekeeping in Bari, Italy. They helped us recruit participants for the expert interviews and allowed us to discover the world of urban beekeeping deeply.

Also, we would like to thank the industrial designers Federica Gentile and Adriana Romeo for their valuable effort, who developed the concept together with their colleague, Marina Ricci, during the Master's degree course in Industrial Design at the Polytechnic University of Bari (2019/2020).

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# Resolve Once—Output Many (ROOM): Digital Design and Fabrication at the Service of Social Equity

**Blair Gardiner and Sofia Colabella**

**Abstract** Digital technologies have focused much attention on promoting industrial efficiencies, interoperability, and decentralisation, facilitating design possibilities via complex geometries whilst eliciting precision, and embedding supply chain sustainability practice and connectivity in the ubiquity of *Smart* agency. The *Industry 4.0* proposition identifies the beneficial outcomes of technological advancement. Its basis and, by extension, the subset of digital design and fabrication, in part, is premised by an application in a market-driven competitive model approach. However, such underlying precepts may be equally applicable to invert the context to suit internal socio-economic conditions other than the economic activity to which they are directed but to which they may provide beneficial service. Less often referred to is how digital design and fabrication may be harnessed to benefit disadvantaged communities or those sectors where current or projected economic and industrial structures limit access to social equity. Leveraging the utilisation of digital technologies at play or developing within the construction industry, one may bypass some of the broader challenges of *Industry 4.0* by including an opportunity focus application to addressing social disadvantage and social equity. This chapter makes a case for performance-based and circular architecture in bringing together digital design and digital fabrication tools to enhance social equity and self-agency. It demonstrates this potential in a connected response mechanism to the housing affordability debate, which does not always include young people, particularly those at risk of homelessness. The investigation lens is the parameters for temporary independent accommodation for at-risk youth to remain within an existing support unit or family. The process mode extends by integrating a self-capacity facility. In the Australian housing sector, the historical aspects of prefabrication, land subdivision, dependant units and self-build, still supported by regulatory regimes, resonate with the potential of digital design and fabrication tools. Opportunities arise in scalability and decentralisation, upstream embedment for performance enhancement and sustainable practice, portative flexible modularity, and transformation permutation. Self-capacity lies with personalisation via participatory design customisation and engagement with fabrication and

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_22

assembly, serving as a training program to support employability and empowerment. By taking advantage of supply chain features of the Australian construction sector and technological advancement, one may look at the coeval opportunities that lie in applications that support social equity and inclusive responses to addressing real-world issues of social disadvantage.

**Keywords** Computational and Parametric design · Didactics · Circular architecture · Performance-based architecture · Digital fabrication and Social equity · Creativity · Design thinking and human–computer interaction

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 1. End poverty in all its forms everywhere

## 1 Introduction

Amongst the foundations of *Industry 4.0*, with its avidity for digital technology uptake in design and production, one may trace some of its precepts to the resonance articulated in 1776 by Adam Smith in *The Wealth of Nations* [1]. These include the notions of production efficiencies garnered by the division of labour, cross-boundary exchange and the positive but unintended outcomes of 'the invisible hand' for a collective economic and industrial benefit. So was raised 'das Adam Smith problem', for Smith had contributed an earlier seemingly contrary position in his 1759 publication in *The Theory of Moral Sentiments* [2, 3]. Whereas *The Wealth of Nations* is heralded as a seminal work in economic theory, *The Theory of Moral Sentiments* is less acclaimed. The former is seen as a validation of economic efficiencies derived from self-interest. However, the latter argued for the ethical and social dimensions of such actions.

Herein lies a potential merging, elucidation and leveraging of the Adam Smith problem for technological advancement broadened to social-economic conditions other than the economic activity to which they are directed. Innovation geared towards industrial efficiencies rarely filters beyond the self-referential domains from which they are targeted. The underlying precepts of *Industry 4.0* are less often directed to how digital design and fabrication may be harnessed to benefit disadvantaged communities or those sectors where current or projected economic and industrial structures limit access to social equity. Leveraging digital technologies presently used or developing within the construction industry, one may bypass some of the broader challenges of *Industry 4.0* by including an opportunity to address social disadvantage and social equity.

An increasingly ineluctable condition of the bespoke and customisation is to foreground output at the expense of upstream or end-use factors. The construction industry tends to adopt a reductive approach to this condition. It focuses on output processes seeking to minimise time and costs, reduce complexity and adopt conventional production modes. A consequence to design is its potential approbation to prêt-à-porter relegation. The adoption of standardisation and deemed-to-comply prescription is prefaced as desirable industrial management pursuits for time, cost and quality whilst simultaneously animadvert the construction industry on innovation and productivity. In recognition of this approach's limits, regulatory jurisdictions such as those in Australia retained deemed-to-comply provisions but also included a performance-based compliance approach. The shift from on-site to off-site manufacturing is an additional construction management response mechanism to resource and temporal management. Some regulatory jurisdictions, such as Singapore, encourage this approach in their design for manufacturing and assembly regimes, such as those promoted by its Code of Practice on Buildability, with high building design scores for standardisation, repetition, and prefabrication [4].

Amongst the consequences of these approaches is that as formal expression becomes unbounded, the upstream effort of response strategising and planning increases. However, design conception's intellectual and strategic capital is undervalued with a synonymist appropriation of consequential processes predicated on construction management, as exemplified by the uptake of *Building Information Modelling*.

The outcome's bespoke nature, the construction industry's fragmentation, with an *anything can be built* mindset, demonstrates a highly flexible sector. There are limitations to a reductivist premise of the *order from stock* myth. Is there a way to internalise capitalised costs associated with upstream design conception whilst responding to downstream production geared towards output? May we reconnect firmitas and utilitas to venustas? Is there a way to embed performance responsiveness whilst freeing design capacity beyond the design professional?

Industry processes seek to direct various permutations of commercial advantage and potential. Similar cross-utilisation to other sectors that do not offer a commercial return is rarely picked up by the funding authorities with whom the eventual cost is transferred—the public purse. In undertaking the task of a stream of *Industry 4* geared towards social equity, one must also trace the cultural roots of emergent technologies connected to geographies of place to recognise and suggest that antecedents may be discovered to certain design and technological strategies.

The project proposal outlined here lies in applying digital design to fabrication tools for an accommodation unit as a possible response to preventing youth homelessness in Australia. It identifies the questions and objectives of the project, suggests that cultural precedents backgrounds, and supports the approach adopted.

## 2 Youth Homelessness

An area of contention is the lack of a consistent international definition of homelessness; however, commonality occurs in aspects of stable and secure housing [5]. For statistical purposes, the *Australian Bureau of Statistics* (ABS) defines homelessness in terms of three criteria 1. that the dwelling is inadequate, 2. a lack of tenure or tenure is short and not extendable, and 3. the living arrangement does not allow control of and access to space for social relations [6]. The exaptation and co-opting potential of digital-based technologies and a co-design process offer a means by which one may address the three categories of statistical definition. The locus is a customised independent accommodation unit, utilising digital design to digital fabrication methods.

Homeless persons numbers have been steadily increasing, registering a 22% increase between 2001 and 2016 [7]. As with the definition of homelessness, youth homelessness is ill-defined [6]. The ABS refers to an age group of 12−18 or 12 to 24. The findings of the 2016 Australian Census found that the numbers of homeless youth (aged 12−24 years) were consistent across Australia, with Victoria being 26% of the total homeless population, with the range being from 21 to 26% in other Australian states and territories. Youth made up 32% of total homeless persons in severely crowded dwellings, 23% of those in supported homeless accommodation, and 15% in boarding houses. One of the features of the upward trend of the homeless population suggestive of the potential of youth homeless to become structural is that "nearly 60% of homeless people in 2016 were under 35 years and 43% of the increase in homelessness was in the 25−34 age group" [7]. The result is increased demand for support services and coincides with the lack of affordable housing.

### *2.1 Affordable Affordability*

The project does not try to offer a solution to affordability as one of Australia's most significant housing challenges [7, 8]. Instead, it focuses on how digital design and prefabrication can maximise construction process efficiency, reducing the cost of small temporary accommodation units that users can customise. The focus is on people at risk of homelessness who cannot afford affordable housing. Young persons and those experiencing short-term financial stress cannot engage with the question of housing affordability. The proposal attempts to reconcile gaps and opportunities in the formal regulations with informal building practices providing independent temporary accommodation to remain within an existing family or support network. The application aligns with government policy shifts to keep youth within support networks and avoid structural homelessness. An example is the Australian government initiative *Reconnect Program*, a community-based early intervention to prevent youth homelessness by targeted support of families and young persons who are homeless or at risk [9, 10].

### 2.2 Tiny House Models, Open-Source Customisation and Homelessness

The project *Resolve Once, Output Many* (*ROOM*) adopts the *Tiny House* or *Micro-House* model. Adherents of this form of housing argue for its responsible environmental awareness, economical housing entrée and facility as a community housing model for social interaction and support [9, 10]. It has many variations, such as those profiled in 2008 in the New York Museum of Modern Arts exhibition *Home Delivery: Fabricating the Modern Dwelling* to the open-source customisation of the *WikiHouse.* The application of independent housing units in response to homelessness is not new. The Tiny House model, either as moveable or static units, have been used as a response mechanism to access affordable home ownership or rental option. The Tiny House provides a stable, supported housing option in the *Housing First* approach to addressing homelessness in the United States and is witnessed by the advent of tiny house villages [11]. In Australia, not-for-profit organisations such as *Kids Under Cover* have been operating its *Studio Program*, which provides relocatable "one or two-bedroom studios with bathroom, built in a family or carer's home as secure and stable accommodation for young people at risk of homelessness" [12].

These approaches follow conventional systems of building and prefabrication. *ROOM* takes a similar (still very different) approach by adapting conventional building practices to digital production. It also proposes collaborative design input by including the end-user to participate in a customised output at the initial design stage.

In addition, through flat-packed delivery of simply constructed components, it facilitates self-built assembly or in conjunction with other young persons who have undertaken assembly training. This aspect of the system is seen as significant in providing the end-user with some buy-in to the unit they will occupy. It empowers the young person and provides a training mechanism which may be used for future employment or to demonstrate an individual's capacity to a prospective employer.

## 3 Resolve Once, Output Many

The proposition of *ROOM* (Resolve Once Output Many) is for independent secondary accommodation for a dependant young person on a property. Its integrated parametric design and CNC fabrication facilitate a customisable, cost-effective, and time-efficient housing option, lending itself to prefabrication and self-build assembly.

*ROOM* is in the formative stages of design and application modelling. It proposes to investigate customisation through participatory design and fabrication using digital-based technologies, aiming to produce a small housing unit incorporating ease of assembly and disassembly that is not over-reliant on technical construction skills. Its approach has commenced with the most common and familiar Australian domestic construction method of timber-framed building. It then reappraises this system to meet project objectives and, in so doing, reconfigures it as an unconventional consolidated, but conventional timber frame. The method is to recreate the frame structure using small plywood sheet sections spliced to form nodes and internodes. Design testing and verification are done by prototyping through digital modelling and structural analysis and review testing by physical scale models.

Its application is directed to vulnerable community sectors such as youth at risk of homelessness. Youth at risk of homelessness have very few housing options and reliant on private support housing providers who are under severe strain in a system that cannot meet demand. The permutations of use are extensive in addressing community disadvantage and broader housing options, such as community or cooperative housing. Key factors for the project are a minimum cost option, responsiveness to user needs and short lead times for use availability.

## *3.1 Adapting and Learning from Conventional Building Practice in Digital Production*

Operating in the refined non-bounded space of the digital environment can only take one so far. The first stage is, therefore, to learn from conventional building practice and adapt it to digital production. The approach is not to propose retooling the construction industry, though this may eventuate. It does not offer a radical shift in industry practice but recognises that there are advantages to an industry sector considered to be overly fragmented or lacking industrial or innovation capacity in being made up of small to medium enterprises (SME). Fragmentations in the supply chain may not require each link to be connected to the initial design formulation and communication nor to a final bespoke product. A variety of dispersed SME constituents may have flexibility and rapid delivery advantages at various levels of scale and location, promoting innovation at the points where intellectual capital is best held. One construction industry sector has fully embraced digital-based design for digital fabrication capacity. It has permeated joinery manufacturing and is ubiquitous as a production method. The shift to the use of sheet materials and a fully integrated supply chain with its use of CNC machines, its move to factory production and site installation and a focus on ease of installation is not an unreasonable first port of call for prototyping. Digital craftsmanship and CNC production appear to be allied to the logic of self-sufficiency and DIY and could potentially form a new iteration on the theoretical reflections on tacit and explicit knowledge.

## *3.2 Enabling and Empowerment*

The enabling capacity of digital technologies potentially facilitates a 'bottom-up' approach to design and education. Emergent technologies offer a means by which the end-user obtains a support mechanism to substantiate and realise their design vision to suit individual circumstances through customisation. The designer's role is adaptable to include professional design and co-design engagement through the architects being the users themselves [13].

Empowerment is a concept garnering currency in addressing homelessness. At the individual level, it is put forward as a method to rebuild self-confidence, promote social engagement, develop personal capacity and awareness of resource mobilisation, and accept consequential responsibility [33]. Adopting an empowerment process is a major factor in breaking the cycle of homelessness, as it could potentially support building resilience and providing a pathway of positive change by helping youth to help themselves. The alternative is the risk of structural homelessness and institutionalisation, negatively impacting youth self-confidence and autonomy. Additional benefits may include an informal design and construction education. Formulating an education pathway through involvement in the design and assembly process makes education a vehicle for shared community development. Self-assembly will embed training and work opportunities for youth through participation in the construction process. While it is not argued that applying digital design and fabrication is a solution to youth homelessness, it is possible that this system may provide beneficial outcomes in (1) preventing youth homelessness; (2) making the homelessness services less expensive; (3) shortening the time people will require support.

### *3.3 Conditional Objectives*

The initial design process has adopted several challenges and conditional objectives. Although aspirational, they also aim to focus the project on the issues raised in the testing process of the design stage, construction methods, systems, fabrication, and assembly. These include:

1.1. How may readily available technologies in the construction industry be used to reduce cost, retooling and retraining, promote scalability to support housing alternatives, and reduce the impact of disadvantage vulnerability? An option is to use CNC systems available in the joinery sector of the construction industry.

    Therefore, the starting point is sheet-based material components common to contemporary commercial joinery production, using plywood for the project.

    Incorporating an existing construction sector operative method has benefits in not retooling or retraining the industry and extending market reach. It also provides a scalability method by using a current but underutilised production capacity.

    The restriction, at present, to plywood limits accounting for the anisotropic properties of timber, providing some known attributes in structural behaviour.

The project, therefore, is limited at this stage to the structural frame and its analysis. However, even given this limitation, by necessity, it has had to encompass broader project implications.

2.2. What issues are raised in adopting an integrated approach to design iteration? How may one bring the end-user upstream into the design process, and how well may one engage in front-end design with downstream supply chain issues? What degree of customisation capacity is attainable through aggregating and embedding response conditions upstream into the design stage. These include user preference, site conditions, structural behaviour, regulatory compliance, transportation, building performance and whole-of-life considerations. Digital design and fabrication were chosen to display that a given domain of variation and personalisation is available to a layperson.

It takes advantage of a fragmented construction industry. It does not require those in a construction supply chain to be knowledgeable about input application into a bespoke product and uses simple methods of assembly.

In addition, it acknowledges aspects of off-site production and integrated assembly. Such an approach has been adopted in the commercial construction sector, the most obvious example being fully finished service pods such as bathrooms or kitchens.

3.3. How far may the bourne of optimisation be pursued? It commences on the assumption that customisation is requisite on a participatory design and assembly methodology. In addition, as the outcome is seen as transition support, it facilitates a feedback loop for in-use testing and further refinement.

The digital design optioning allows wide-ranging customisation of material systems and overall formal design, including external and internal appearance. It permits user input into personal amenities, such as exterior covered space and furniture. In addition, it may include the aggregation of units for other uses or the extension of the facility where planning regulations or exemptions may apply. Optioning extends to single, aggregated, or multiple uses, such as servicing provisioning kitchens, bathrooms, and shared spaces.

Other project permutations of optimisation include the components, as the modular unit derived from standard sheet materials reduces material waste or promotes labour efficiencies and ease of assembly.

4.4. To what degree may ease of construction, material accessibility and cost and labour reduction be pursued using environmentally responsible off-the-shelf or processing sourcing geared towards circularity? The approach maximises the use of building systems and components that are commercially available off the shelf. The structural system's use of small, interdigitated components configured to form the primary framing allows for the use of material sections that may be commercially discarded. Its approach is in 'not wasting, the waste.'

In addition, the project seeks the inclusion of local recycled and repurposed materials and components. Given the current developments in material processing technology, the capacity exists to incorporate the utilisation of processed waste into 'green materials' that may be used in the construction or fitout.

5.5. To what extent can ease of assembly and disassembly not reliant on specialist construction expertise but geared towards the youth who occupy the unit be a viable self-build option? Design for Disassembly (DfD) objectives stem from acknowledging that such units are not put forward as a long-term housing solution. They are a temporary proposition as an attainable and immediate relief to permit other factors to support transit out of an at-risk situation.

DfD is geared to the components being reassembled or repurposed, thereby promoting circularity. Its endeavour to promote ease of construction minimises mechanical fastening systems. The system uses jointing precision afforded by CNC cutting, assembly, and disassembly, reducing reliance on specialist trade skills. Such a system permits the components to be used multiple times, subject to verification for structural integrity, durability, site conditions and alternate uses to that directed initially.

## 4 Cultural Precedents

It is premature to describe the detailed technical aspects of project conception and delivery of the *ROOM* project. Let us set aside the arguments for digital design and fabrication as a new emergent form of technology but look at it through a local historical lens. It is essential to understand the historical context of places such as Australia that may lend themselves to such technologies and the conceptual cultural framing of the approach adopted. In the Australian housing sector, the historical aspects of prefabrication, residential land tenure and an engagement with self-design and self-build, still supported by regulatory regimes, resonate with the potential of digital design and fabrication tools to be used as a temporary accommodation model.

### *4.1 Prefabrication*

The European occupation of Australia in its housing commenced by leveraging technology and construction innovation with the importation of prefabricated buildings. Early uptake of prefabrication during the 1830s, saw British and Australian fabricators producing prefabricated timber houses for private occupation [14]. The globalisation of timber prefabrication is a feature of colonisation [16] and supply shortage arising from economic pressures and is witnessed in its transposition from the Californian Gold Rush of 1849 to the Australian context [17]. Australia's colonial history, in its urban development and response to building pressures generated in the Australian Gold Rush booms of the 1850s, is deeply connected to 'portable' buildings, often shipped from overseas fabricators based in Germany, India, New Zealand and Singapore, as well as those locally produced [15].

In Australia, an example of the recurrence of prefabrication as a housing solution may be found following the Second World War. To address the consequential privations and post-war housing shortage, the largest public housing provider, the Housing Commission of Victoria, turned to import prefabricated timber housing for one of its regional estates [18]. Local architects took up the gauntlet in design-driven output, utilising the perceived material and cost benefits derived from various forms of prefabrication. Notable during this period was the architect Best Overends' proposal for timber prefabrication in his 1946 prototype design of the *Indus House*. The Australian Navy in 1951 resorted to prefabricated housing through the importation from the Swedish manufacturer Åmåls Sågverks Aktiebolag of flat-packed houses [19]. However, the 1946 *Romcke* plywood house by the Australian plywood and timber veneer merchants Romcke Pty Ltd, and the contracting firm A V Jennings is considered the first wholly prefabricated house in Australia. Such efforts reflect an interest in precision fabrication and resource efficiency to alternate forms of housing supply [20].

This background suggests that awareness, adoption and acceptance of remote design and fabrication methods in construction have a cultural basis as a housing solution tracing back to the colonial development of European occupation in Australia. Innovation born as a response to circumstances, including housing shortage, resource access, labour and material optimisation, and the derived economic advantages has a genealogy that connects to the recent interest in the potential of digital fabrication.

## *4.2 Land Subdivision*

The early planning history of colonial Australia through its urban demarcation of land subdivision from its European roots has left an imprint on the Australian residential suburban form. The 1788 founding of European Australia in New South Wales and its early town plan proposal decreed that "land will be granted with a clause that will prevent more than one house being built on the allotment, which will be sixty feet in front and one hundred and fifty feet in depth" [21]. Linking the foundation of white Australia to the Australian attachment for a housing form connected to a model of low-density single houses on a substantial landholding commonly identified as the 'quarter-acre' block may be tenuous [10]. However, such an attachment to this basic model of residential land tenure remains a feature of the Australian suburb. In Melbourne, Australia, although increasingly rare, residential allotments of 1,000 sqm may still be encountered, with some outer suburbs featuring larger block sizes. A 2016 study identifies the median block size for the inner city to be under 300 sqm with pockets at 300 to 500 sqm, similar to the median of the middle suburbs' [22]. However, land size and the low density that arises from the feature of single-dwelling development are further supported by the historical self-sufficiency view of residential land in its production capacity [23]. Although this model is transitioning in two ways, firstly via Australia's domestic housing market shifting to larger houses, and secondly, through its inverse by increased housing yield by land subdivision. Residential densities for Melbourne remain low, with the Victorian Planning Authority in 2018 identifying it to be 16.5 dwellings per hectare [24]. This low density suggests that capacity exists within developed residential land to provide a different form of housing accommodation supply. The approach is not to look to the further subdivision of land, with its restrictive concomitant costs and time delay, as the solution but to provide increased capacity flexibility and immediacy for existing occupiers and thereby respond to social disadvantage and accommodation stress. Therefore, in seeking response strategies to reduce potential youth homelessness, a solution may already be available in utilising available land to retain youth within existing housing environments connected to support networks.

## *4.3 The* Granny Flat

Australian planning regulations are not unique in having a model for existing developed land to provide limited housing supply flexibility. The United States model of elder cottage (Echo) housing follows a similar model, having obtained a measure of impetus through the Australian Planner Barry Cooper's presentation in 1981 of the Australian programs at an American Association of Retired Persons forum held in Washington, D.C., [25]. The Australian concept is said to have been derived, in 1963, from a practitioner Dr Hubert Bauer working at the state mental health authority, the Victorian Mental Hygiene Department, as his response to enhancing support and housing choices for aged persons. Bauer proposed a moveable, self-contained unit that may be temporarily placed on an existing property. A key aspect of Bauer's approach was that the units be independent and autonomous, not part of an existing house but located adjacent to it, to facilitate an environment of independence and familial support. The other key feature of Bauers proposition was that the units be architect-designed. The Victorian Council for the Aged and the Rotary Club of Melbourne strongly advocated with the public housing authority, the Housing Commission of Victoria, to develop the idea. The first portable unit was built in 1975 by the Commission and was provided on favourable rental terms to a couple on their daughters' property in suburban Melbourne [26]. Bauer's concerns regarding senior person's mental health resonate today in the mental health and wellbeing of at-risk of homelessness and youth homelessness. Studies suggest that over half of young persons who have experienced homelessness have indicated some form of psychological distress, more than double that of those who have never experienced homelessness. Coping with stress is seen as a significant issue of personal concern, as are mental health, financial security, and suicide, all being reported in far higher proportions than those young persons who have never experienced homelessness [27].

The basic planning approach of dependent person's unit (*Granny Flat*) remains in local Council Planning Regulations. The property must be larger than 450 sqm, and the unit must be moveable but not be a caravan and be occupied by a dependent person. Between August 2020 and March 2021, a local government pilot program was instigated, trialling loosening restrictions to permit the construction of a secondary dwelling subject to certain conditions. These included a height limit of 5 m, a maximum floor area of 60 m, garden provisioning and no capacity to subdivide the land. As of April 2022, the pilot remains in review [28].

Therefore, a solution presents itself in providing accommodation supply to a vulnerable community sector and potentially avoiding the risk for a young homeless person's trajectory of structural homelessness. The ability to deliver the design where structural integrity and regulatory compliance are embedded into its parametric conditions facilitates a resolved customisable output. Customisable site-responsive units may be developed using digital technologies with the young person's participation as the end-user. The nature of the construction system geared towards non-technical assembly methods and the minimisation of specialist trades permits a self-build approach of assembling parts by an end-user. This approach offers a labour cost reduction and a potential training avenue for young persons.

### *4.4 Self-build and Self-assembly*

The notion of a right to build one's own home for owner occupancy is entrenched in the Australian construction regulations [29]. Its genesis lies in the post-World War 2 period in Australia. House construction fell dramatically during the war as resources were deployed to support the war effort, resulting in a chronic shortage of housing availability. Presently, the deficiency lies in affordable housing. The proportion of total houses built annually in Australia by owner-builders steadily increased from 20% in 1948, culminating in a peak in 1954 of over 40% [30]. The Australian Bureau of Statistics estimates that in 2002–2003, the proportion of owner building as a proportion of total work done on private sector houses was 13% [31]. Although originating from a lack of housing supply, the notion of self-built housing is still perceived as advantageous through the cost savings in sweat equity and builders margin, greater project flexibility and project control, particularly at the design and design implementation stages [32].

*ROOM* accommodates a self-built option available under existing building regulations. Customisation through participatory design and fabrication, progressing to self-assembly, provides a potential cost–benefit and a feedback loop for the review of the process. It enables rapid and cost-effective construction, which is easy to assemble, dismantle, and reusable.

## 5 Australian Housing Antecedents, Digital Design and Fabrication and Social Equity

The use of emergent technologies such as those that are derived from digital design and fabrication may be a development which may lend itself to contemporary application to ongoing issues in the Australian housing sector. Such technologies may provide a quick, customisable, and accessible temporary housing option for community sectors experiencing disadvantage or as a housing adjunct for at-risk youth of homelessness. Australian historical precedents in housing include the utilisation of prefabrication as a response to construction material resources and housing supply shortages. By leveraging historical residential land plot size patterns, it facilitates the provision of temporary dependant accommodation to provide housing options for youth. Capacity lies in digital design methodologies to engage the end-user upstream in the design process, whilst parametric modelling may support customisation and optimisation. The ability to embed performance and output using readily available materials without high-level specialist construction skills lends itself to labour cost reductions via a self-build assembly method. These benefits contribute to providing affordable and quick housing options to disadvantaged sectors of the community. One tributary of the *Industry 4.0* proposition may be to use the advantages that emergent technologies provide or may already exist but are underutilised in the construction industry to address social equity in housing.

**Acknowledgements** This work was supported by a 2019 research development grant issued by the Faculty of Architecture, Building and Planning at the University of Melbourne, Australia.

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# From Analogue to Digital: Evolution of Building Machines Towards Reforming Production and Customization of Housing

**Carlo Carbone and Basem Eid Mohamed**

**Abstract** The construction of edifices is all about lifting, moving and setting components according to predefined patterns. The magnitude of nineteenth century industrialization produced all manner of machines, lifts and earthmovers to facilitate construction, in addition to easing the pressures on manual labor. Along the same tactical interests, the Bessemer converter and gantry cranes were invented for advancing manufacturing and facilitating standardization of building parts. Robert Le Tourneaux's Tournalayer, perhaps the most unique building machine, made it possible to mold buildings like a mega-cookie cutter by casting reinforced concrete in moveable steel formwork. The outcome of such experiments cultivated transformations in the building process, even if they were not widely utilized. Recent advancements in digital fabrication machines in the form of Computer Numerically Controlled (CNC) cutting and milling tools, bricklaying drones, and large-scale 3D printing robots, coupled with computational design processes, are driving new possibilities in design and construction. Multiple levels of design variation are feasible, reforming standardized industrial models into user-centric, and contextually driven singular designs. The chapter aims to critically examine how contemporary digitally controlled building machines are part of a spectrum of devices linked to mechanization and how they present potentials for the democratization of housing provision. Accompanied by an analysis of how the fourth industrial revolution is impacting construction, we present a detailed overview of the evolution of building machines, with a specific focus on concrete casting machines used to produce dwellings. Then, we critically analyze the parallels between traditional casting equipment invented for mass production and today's robotic fabrication to deliver inhabitable prototypes. As a conclusion to the chapter and an opening to further research, a generative framework that stems from linking digital design with production machines is proposed

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_23

for implementing customization in the industrialized housing sector, one that has long been connoted by the lack of design personalization.

**Keywords** Architecture · Building machines · Customization · Large-scale 3D printing · Additive manufacturing · Construction 4.0

**United Nations' Sustainable Development Goals** 9. Industry, Innovation, and Infrastructure · 11. Sustainable cities and communities

**The submitted contribution must highlight the relevance of the research/project presented in respect of one or more key technologies of Industry 4.0.**

## 1 Introduction: Industrialization from Machines to Construction 4.0

From Mechanization (1765) to Mass production (1870) to Automation (1969) and to the evolving concept of Digital Objects (2016), all four stages of industrialization radically changed how things were made previously. Industry 4.0 relates to the digitization of every economic sector including building design and construction. Kagermann and Wahlster's [31] definition of «data added value creation» includes technologies and practices circumscribed by information used as parameters and criteria to trace and interact with all stages, methods and tools in the building process. The use of modelling and data managing technologies in every phase of a project's development dramatically increases the rapidity and the extensive way performance criteria and intelligence can be shared, manipulated and deployed to streamline everything from design to operation.

While professionals have been quicker than builders in adopting concepts like Building Information Modeling, Virtual Design and Construction or even Design for Manufacturing principles, the uptake of 4.0 principles within the construction industry globally is asymmetrical at best. Nonetheless, architecture and construction are greatly influenced by these changes in fabrication and production methods. In design, generative data manipulation creates potential for customizing and multiplying iterations. Within fabrication, robots and cobots can be programmed to quickly output changes and design iterations to prototype shapes unthinkable until recently. Further, the link between design and fabrication increases the appetite and potential for Offsite/Smart Factory building methodologies. Within the construction phase of projects, information sharing, Ai and digital twin modelling facilitate systemic coordination and the potential to monitor every aspect of an edifice: its building, its operation and even its end of service life.

Digitalization of the building industry encompasses and streamlines the process making it possible to envision a type of file to factory to site and to operation model applied to any scope and scale of building task. A segment of industry 4.0 that is sure to further develop through these tools and methods is the complete data-informed autonomation of construction machines. It is this segment of Construction 4.0 that will be further analysed.

In every civilization, the construction of edifices, large and small, great and ordinary, has implied the development of machines to assemble buildings from heavy and sizeable components whose lifting or moving would otherwise be impossible. For instance, the treadwheel crane became an important accoutrement in the construction of gothic cathedrals for setting materials in their final positions. Machines are part of building culture [10] and in some respects even define building cultures. The steel skyscraper or the timber balloon frame would not have been possible if not for the development of steel refinement through the Bessemer converter [5] or the mechanized timber mill. Both inventions democratized technology and completely transformed cities [42, 44].

Pulleys, ropes, rollers, lifts, earth movers, chariots or wagons are just a few implements which have alleviated human effort and have forever contributed to building. Instruments rigged for lifting were first propelled by human or animal power and this defined construction capacity [25]. Industrialization converted these machines to steam, fuel or electricity and from traditional building materials to iron and steel. Self-propelled mechanization, the first industrial revolution, improved capacity and transformed building sites into veritable open-air factories.

Mechanization, then mass production and automation, influence of all these trends on building culture in general and manufactured building culture in particular was fundamental as machines enhanced division of labor and overtook manufacturing. Large components, complete subassemblies or completed building sections could be manufactured offsite and then carried to and integrated into edifices. Further, mechanization allowed building sites to be managed as ready to assemble kits. Mass production's influence on architecture and construction still impacts our current building culture through the classification and cataloguing of every type of component required in the building process. A third industrial revolution, automation, first introduced in Japan after the second world-war was as equally disruptive to production processes as Henry Ford's assembly line had been. All three eras of industrialization had machines as their central figures in advancing construction: the gantry crane, the conveyor and automatic robotic arms demonstrated how objects of every scope and size could benefit from industrial processes.

During industrialization's first three phases, an intense time of technological advancements, the building itself was also theorized increasingly as a type of integrated machine. The "*Mobile housing unit*" patented by John Hays Hammond Jr in 1947 [27] explored suspending monolithic units from two central gallow beams as shown in Fig. 1. The supporting structure served as a crane and scaffolding during construction making it possible to anchor each concrete box onto the tower. The crane also made it plausible to remove and relocate the dwelling units over time. The building as a support structure and crane essential in the building's erection is perhaps one of the most experimental visions of building to come out of the machine age.

Machines in the factory also determined dimensional standardization, repetition or normalization as each area unit of the factory participated in a serial making process. Contrary to this, on site machines made singularity possible. The tension in architecture between standardization and singularity is longstanding [9]. The connection from machines to customized or standardized or even mass customized architecture is the topic of this chapter, which looks at the links between production and customization through the lens of machines capable of generating unique architecture.

Currently machine capacity and potentials are being determined by a complete link to information technology. Artifical Intelligence (AI) in particular is being explored to define a particular breed of machines that can generate, react, engineer, design in relation to their connectivity and integrated logistical data sets. This fourth industrial

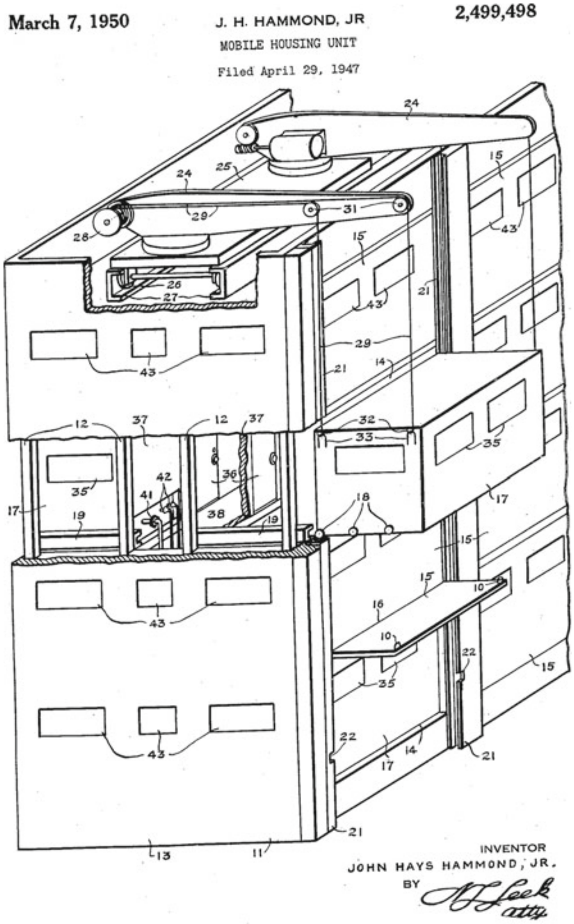


**Fig. 1** Mobile housing unit (1947) John Hays Hammond. US Patent no. 2499498 (*source* Public domain)

revolution is being promoted as a new way forward for improving construction in general and driving a new era of industrialized construction experiments.

### 1.1 Construction 4.0

From planning to design, to procurement, to management and to off- or on-site production of edifices, every part of construction is being reformed by information technology. The literature on construction's digitization is expanding almost as quickly as information technology. Both theory and practice are understanding and accepting how its potential can federate all stakeholders to increase construction's lagging productivity and transform construction's traditional ways of making buildings. Perrier et al. [47] have made the argument that 4.0 is not only about technology but also about reviewing age old management processes that are wasteful, time consuming, fragmented and littered with too much conflict.

Many have referred to Industry 4.0 as a new digital age. The concept of 4.0 has been defined as "a new digital age for manufacturing that uses cyber-physical systems, IoT, data and services to connect production technologies with smart production processes" [19]. Although it implies newness, the novelty of 4.0 in the architecture and construction industries is certainly disrupting previous methodologies but also harmonizing and nuancing the three previous phases of industrialization though a comprehensive exchange of big data.

In the systematic literature review proposed by [4], the authors discuss drivers of construction 4.0 and indicate three principle elements that are linked to information sharing, through connectivity of devices and management processes. BIM, Big data, IoT are the three topics that together have the potential to completely reform construction's organization from a intensely disjointed process to using digital twins as the hub for all information about edifices and their service life. Processes like DfMA, Lean construction, and PLA that previously were absent from architecture and construction are being proposed though the extensive use of digital information sharing platforms. Equally as disruptive as Ford's assembly line or Taylor's task division had been to early twentieth century car production, the digital construction of the built environment is making the building process not only more efficient but increasingly metric and performance based though information toning and monitoring.

This exchange of information between people, process and tools is driving 4.0 and is enhanced by our totally connected lifestyle and culture. It is the «tool» portion of the equation that lead us to study the relationship between machines and building processes and understand if a new generation of connected tools could also reform the relationship between design, production and customization.

Paolini et al. [46] and Sartipi [49] proposed a comprehensive review of Additive Manufacturing in relation to construction 4.0 and outlined its potential to create more complex forms and buildings while simplifying the construction process. Bos et al. [7] identifies certain challenges that are all linked to machine's output. Based on previous literature and the objective of unifying design with production the present chapter looks more specifically at the issue of customization and how it related to mechanization or industrialization 1.0 and how it is being reformed toward a digital mechanization through the digitally controlled layering of material leveraged toward the potential democratization of the 3D printed building.

Developments in concrete depositing machines or 3D printers are being employed to produce completely customized homes and buildings which to date has not been possible. The links between twentieth century machinery and 3d printing are discussed as concepts in a similar spectrum of production: Using mechanization to produce architecture quickly, uniformly, and with possible complete customization. From the entire field of possibilities the link between reinforced concrete construction and numerically controlled machines that deposit it in layers to produce any form or shape truly exemplifies how two distinct eras with access to different industrial typologies examined the same subject of generating dwellings through concrete depositing machines. The recognized strength, flexibility and malleability of concrete made it a truly modern and globalized material, however the complexity associated with its casting has always fascinated and driven inventors to propose new ways of facilitating its use. The links between mechanization and concrete casting serve as an interesting case study in how material constraints influence manufacturing, design and construction.

### *1.2 Reinforced Concrete, Moveable Formwork and Machinery for Casting*

Through three previous eras of industrialization, reinforced concrete, has commanded machines to transport, deliver, mold and set it. Mechanization 4.0 is no different, as digital tools are outlining casting machines that continue to address concrete's potentials and challenges.

Reinforced concrete is a cast artificial stone that can be conveyed and poured at variable consistencies and in any shape. This versatility inspired industrialists, architects and engineers to identify ways to integrate concrete in modern construction. From Lambot [34] and Monier [43] to Hennebique [28], much literature is dedicated to the establishment of skeletal concrete structures, esteemed as fireproof and monolithic. Hennebique's patent, an evolution from the more densely reinforced flowerpots of Monier became the most commercially available. Hennebique established a veritable concrete empire licensing his structures all over Europe and North America [51]. From these preliminary experiments, Robert Maillart's bridges and Pier Luigi Nervi's airplane hangars invoked concrete's use to reform construction and build any shape, scope and scale imaginable both by on site casting or by prefabrication. Nervi's work on prefabricated structures can be read as a manifesto on mass customization before its time. Using a process that is repeated and perfected but that could be nuanced to form multiple shapes [45]. As shown in Fig. 2, his shapes and compositions for a roof in Torre in Pietra represents a prototype of his more

**Fig. 2** Agricultural Shed Roof (1946) Torre in Pietra, Pier-Luigi Nervi (*source* Authors)

well-known cupolas, using a type of geometric and modular repetition to create a process for all manner of roof structures. Further his explorations of sliding formwork allowed him to build some of the most recognized large-scale concrete slabs of the twentieth century.

Others including Felix Candela and eventually Santiago Calatrava showcased the unique potential of a magnificent material capable of any shape. Reinforced concrete and novel casting processes inspired increased productivity and affordability with the advantage of the fire protection and the durability of stone. All advantages of reinforced concrete construction, are however, mitigated by the complex formwork and temporary scaffolding that has to be edified and often removed and hauled away as waste after casting. In reaction to the time consuming nature and often wastefulness of disposable formwork, inventors such as Pier Luigi Nervi and Wallace Neff reimagined formwork as a structural and constructive process. Neff's Airform houses (Wallace, Building construction 1941) employed inflatable and pressurized plastic domes as geometric formwork onto which concrete was cast. Once cured the inflatable material could be removed and reused on another house eliminating both waste and rigid geometry. This type of inflatable formwork is still used today. Neff's airform process employed shotcrete, a process by which concrete is sprayed through a hose at a specific consistency to stick to irregular and vertical shapes.

## *1.3 Weight as a Constraint Outlining a Need for Machinery*

At 2400 kg/m$^3$ conventional reinforced concrete is not only prohibitive because of wasteful formwork but also since it usually requires some form of complex mechanical process to bring it to site and deliver it into forms. Imagining a process that would reuse forms and simplify the building process was the object of two processes that in some respects can be analyzed as the predecessors to today's 3D printing machines. Thomas Edison's one pour house [17] as shown in Fig. 3, explored the potential to convey concrete vertically onto the top of a ready-made formwork and let gravity force the fluid material into the various parts of the structure. Ornamentation

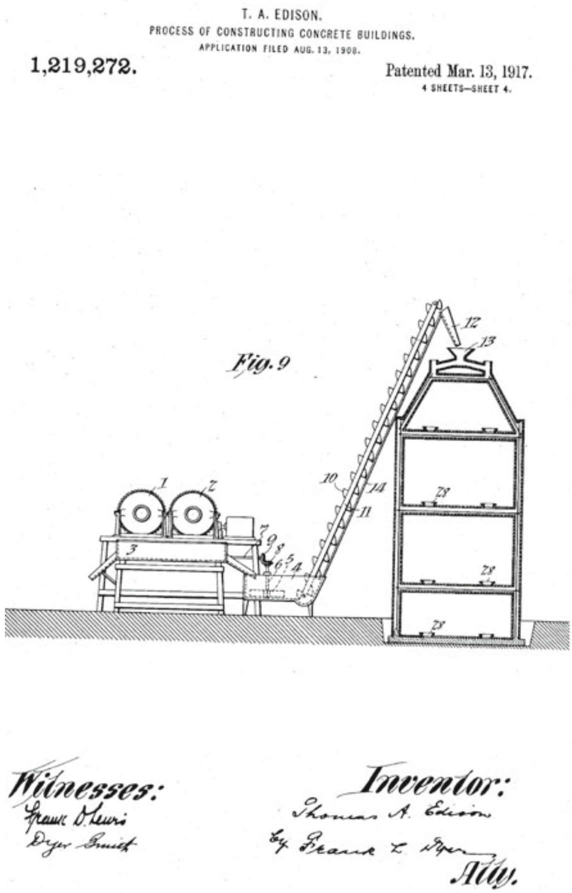


**Fig. 3** Process of constructing concrete buildings (1917) Thomas A. Edison. US Patent 1,219,272 (*source* Public domain)

was shaped in the casting mold and openings distributed throughout enabled quality control and correct compacting and vibration eliminating any air pockets. A marginal number of houses were built using this system and the published advantages of a one-cast-pour would not eliminate any complexities associated with disassembling the formwork and then reassembling it on another site.

## *1.4 The Tournalayer*

Investigating further into the idea of reusable, moveable and integrated formwork to build a type of instant structure, The Tournalayer [38] is a massive machine invented to cast houses onsite as shown in Fig. 4. A two-part house-sized form was fabricated out of steel components. Either one- story or two- story forms included networks for

**Fig. 4** Tournalayer—Outer Form for house form assembly (1955) R.G. Le Tourneau (*source* Carlo Carbone private collection)

mechanical distribution and openings for windows and doors. The steel formwork was moved on-site by a tractor like machine that would then deposit the forms over a site-cast slab with infrastructure connections. Once laid over the slab, concrete was poured. The form was then lifted and removed as a cake mold once the concrete developed its initial cure. The Tournalayer was used to deliver houses in the United States, Brazil, Israel and Morocco [54]. This mega-machine was inspired by production methods used in parallel industries that were simply scaled for building production. This type of invention linked to industrialists' fascination with machinery that proposed alternatives for an optimized site casting of concrete have not changed much since the early twentieth century; Slip forms, tunnel forms [54], continue to be applied where sufficient repetition justifies the machinery's use and cost. What has changed considerably is our ability to numerically control the concrete's casting in precise ways helping to develop another generation of similar tools inspired by additive manufacturing to introduce customization to mechanization.

## 2 Numerically Controlled Machines

During the last two decades, advancements in digital design software and fabrication devices have outlined powerful options for implementing numerous iterations in design and predetermined variations in production towards the customization of building components. For instance, parametric design is being used to tweak and adapt parameters to simplify made-to-measure or engineered-to-order supply chain management. As early explorations reveal, precast concrete panel producers have been the first to explore how information technology could be used to numerically produce personalized details, profiles and thicknesses according to specific needs. For instance, a wide variation of possibilities could be developed using CNC milling machines for subtractive fabrication of molds for casting concrete. This technique was employed to produce the façade of the 290 Mulberry Street, a residential building in New York City designed by SHoP (2007). The architects materialized a reinterpretation of traditional brick detailing through the application of parametric design processes, coupled with advanced fabrication [50]. This process considered innovative at the time would be thought conventional compared to emerging applications of Additive Manufacturing. The project details could be viewed on architect's website.

Additive Manufacturing, and specifically 3D printing, is based on gradually layering material following a specific path to the level of building up a complete structure. The process is controlled digitally, and its quality directly related to composition and quantity of placed material.

As small-scale filament 3D printers have become common, the building industry has sought through academic and industrial partnerships to explore the potential application of AM machines in construction, with specific interest in scaling processes to envisage large-scale 3D printing. Further, based on the same principles percolating form parallel manufacturing industries including but not limited to DfMA (Design for Manufacturing and Assembly) or integrated product development, collaborative teams including architects, engineers and fabrication specialists have been experimenting with 3D printing of large building components like façade elements, structural components, and even full buildings as completely integrated processes from design to fabrication and construction. Both in academia and practice 3D printing machines are being used to conceive and make singular components, a radical change from what the manufactured architecture space has produced during more than a century of exploration. The result has been a fascinating amount of work investigating multiple processes and material possibilities in a relatively short period of time.

### *2.1 Concrete 3D Printing Machines*

Development of concrete 3D printing could be traced back to mid-1990s, specifically in California, USA. The technique addresses several shortcomings in conventional concrete construction: complex and costly formwork, material procurement, simplified delivery, safety, and environmental impact. It is also argued that combining digital design process with 3D printing could foster the development of highly customized building components, and complex geometry [53]. While offering an opportunity to produce customized building with little labor and man power, 3D printing of concrete remains a complex undertaking, involving coordination of various parameters from machine size, information transfer to material consistency, resource availability and building system integration,most current systems have simply extruded walls without imagining the coordination of other systems.

Khoshnevis and Dutton (Khoshnevis and Dutton, Innovative Rapid Prototyping Process Makes Large Sized, Smooth Surfaced Complex Shapes in a Wide Variety of Materials 1998), Khoshnevis (Khoshnevis, Automated Construction by Contour Crafting—Related Robotics and Information Technologies 2004) introduced, then elaborated on the technique defined as Contour Crafting (CC), basically a concrete pump attached to a gantry-based system that involves the sedimentation of a fluid concrete filament. One of the unique features is the use of trowels attached to the deposition nozzles for production of accurate and smooth surfaces. This research inspired many subsequent attempts.

In 2009, Dini developed and presented D-Shape, a 3D printing machine that uses binder jetting, a powder-based technique to strengthen certain and precise areas of a large-scale sand-bed by depositing of a binding agent over these areas. The subsequent bound, calcified or cemented areas define a hardened object layer by layer. Dini filed his first patent in 2006/published in 2008 (Dini, Method and Device for the automatic construction of conglomerate building structures 2008). The potential of such a machine and technique enables the integration of voids and overhanging features towards developing complex shapes, with relatively high-resolution or smoothness [53]. Dini continued working on a wide range of objects since then.

Following these attempts, 3D printing in the building industry expanded rapidly. Langenberg's provided a comprehensive review of the remarkable growth in exploring 3D printing in architecture in the article "mapping 20 years of 3D printing in Architecture [35] where he provided a detailed infographic. An illustrated list of market available printers is provided at the end of the chapter to showcase the amount of current marketable exploration of the topic.

Tay et al. [53] published a review on 3D printing trends in building and construction, comprising a classification of different techniques based on technology, machines, materials, and scale. The paper highlighted that 3D printing full-scale building components is still emerging and is gathering notable attention in both academia and practice. The main challenge, shared in the literature, is synchronizing material consistency with the machine speed to extrude continuous layers without any deformations. Later, El-Sayedgh et al. [20] presented a comprehensive review of relevant literature exploring various 3D printing techniques in construction, while relating the benefits and challenges of each technique. Their analysis was also focused on risks but limited in terms of other challenges we have mentioned including systemic integration required in architecture.

There is a wealth of publications exploring the topic of 3D printing in construction, and any review of existing techniques would be out−dated almost as soon as it is published. The following section proposes a series of projects that were realized using 3D printing machines. The selected projects are not cited and described in an attempt to circumscribe the amount of research but to address the spectrum of possibilities all linked by the issue of mechanization and architectural singularity; the ability to deploy a machine in any context and shape any form exempt from modular constraints that have come to describe the manufactured housing undertones.

**3D Printed Office, Dubai, UAE**. One of the earliest projects built in 2016 by Chinese company Winsun. The building measuring 36 × 12 × 6m was assembled as a set of 3D printed modular components as seen in Fig. 8. The printing machine is composed of an automated robotic arm fitted on a cartesian type portal grantry crane, and uses a proprietary cement mixture. The 3D printed modules were printed in China then delivered and assembled onsite on a granular foundation, making it possible to relocate them if necessary. Produced from 3D printed volumetric units, the office can be customized with any mechanical system and for any particular use, as it is basically an open volume. Figure 5 represents recent photos of the buildings.

**3D Printed House, the University of Nantes, France**. An experimental 3D printed house by Batiprint3d at the University of Nantes, the project has caught attention for its use of polyurethane expandable foam as a customizable formwork into which reinforced concrete is poured as shown in Fig. 9. The hybrid system is relatively inexpensive and avoids costly and specifically rectilinear formwork, which is usually discarded. The 3d printed formwork is deposited in any shape and once cured with the concrete infill creates a strong bond and a superior insulated wall. Even though it is particularly suited to contexts where material procurement and delivery are difficult, this simple construction method can be deployed in any setting. The robot is mounted on an automated vehicle and precisely controlled with laser precision for making any

**Fig. 5** Office of the future, Dubai, UAE, produced by company Winsun (*source* Basem Mohamed private collection)

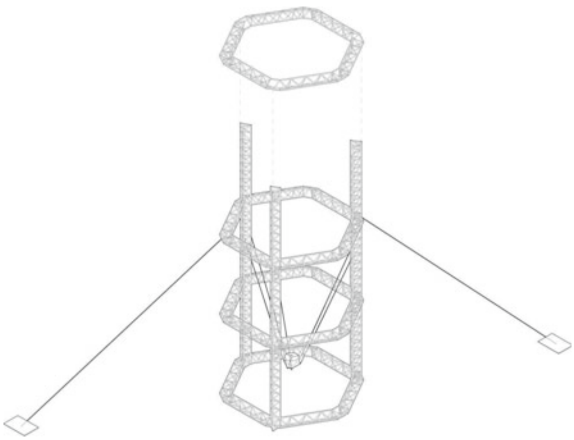

**Fig. 6** Illustration of the WASP big delta structure (2012) WASP (*source* Authors)

vertically extruded shape where compression is maintained as the principle acting force.

## 3 BigDelta, WASP

The additive manufacturing process is interpreted as a cultural and contextual endeavor through an organization known as WASP (World's advanced Saving Project). The organization has been developing and researching giant 3D printers such as their Big Delta; the 12 m, scaled Delta type tall printer uses a robotic nozzle equipped with a mechanical mixer, which combines material into a paste and extrudes it through a nozzle. The material is a mixture of cement and mud, similar to a daub clay composite but with an extrudable consistency. The nozzle deposits layer upon layer of material in a precisely digitally controlled pattern, extruding shapes as the layers increase. The Big Delta's printing format impedes linear forms that are possible with Gantry systems, however it offers more flexibility in terms of topology and forms (Fig. 6).

**Municipality building, Dubai, UAE**. Apis Cor, an innovative startup company is complementing the extensive list of onsite casting inventions and has garnered remarkable interest, thanks to its innovative printing machine; a telescopic robotic arm mounted onto a central rotating crane. The company has to date produced one 38$m^2$ dwelling structure in a small Russian town, a municipal building in Dubai that is considered the largest on-site 3D printed building as shown in Fig. 7, and a competition proposal for Mars habitat. The Apis Cor printer shown in Fig. 7 is based on a flexible machine that could be transported and positioned on any site. The machine uses a moveable column crane that has a circular printing range of 132 $m^2$. Analogous to a computer controlled concrete pump, the printer's nozzle is controlled to deposit a lightweight concrete mixture in horizontal strata. The company argues in favor of their lean construction process, which reduces material use and waste as material is mixed, generated and used on-site and as needed. A small mixing plant is located in the printer's range and material is transferred to the printing nozzle. A cellular truss matrix maximizes voids in the structure reducing both mass and volume. These voids could theoretically be used as a network for passing cables and mechanical systems.

**Quake Column**. Printing buildings as a whole can be dimensionally and logistically prohibitive. A more feasible avenue for 3D printing in construction is making personalized components that can be easily assembled and scaled toward larger structures. Architectural components can be produced with intricate geometries and made-to-order. *Emerging Objects* has been exploring 3D printing for construction as a way of giving new life to age-old construction methods. They have developed a masonry unit, which requires no mortar. The 3D printed mixture of sand, sawdust, ground-up tires, salt, pulverized bone are bound into a type of concrete piece that fits together precisely into a giant 3D puzzle. The firm was inspired by ashlar stonework in which each stone is precisely cut and dry bedded to form a robust structural system for walls or columns (Emerging objects n.d.).

Informed by the study and analysis of ancient Incan stonework, the Quake Column combines precisely defined, printed and numbered elements to facilitate assembly as shown in Fig. 8. Various geometric patterns are possible and could be modified as needed, improved through generative design parameters and shared with the click of a mouse. As complex geometry no longer requires the steady hand of the stonemason, each individual unit didactically displays its shape relating to a whole individualized pattern. Each chunk's geometry is completely self-locking.

This type of file to component production method nuances the traditional debate between on and offsite construction as a large-scale 3d printer produces project specific components reforming the ideals of normalization and standardization normally associated with architectural production.

**ICON: Housing For The Homeless**. ICON is a US based construction technology company focused on large format concrete 3D printing. The company has developed

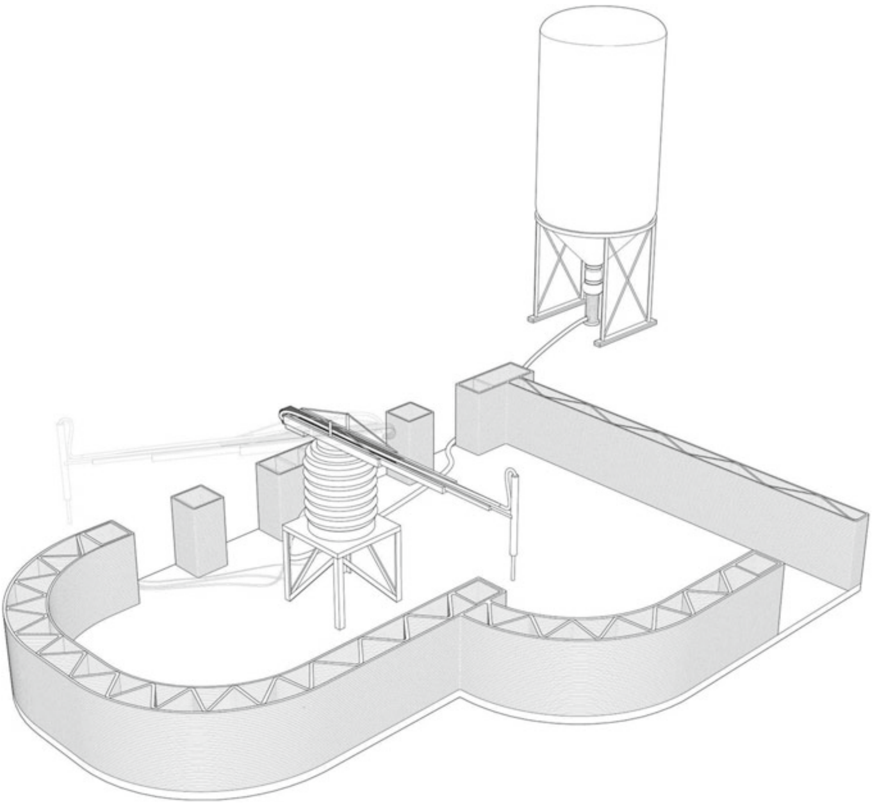

**Fig. 7** An illustration of the Apis cor 3D printing machine (*source* Authors)

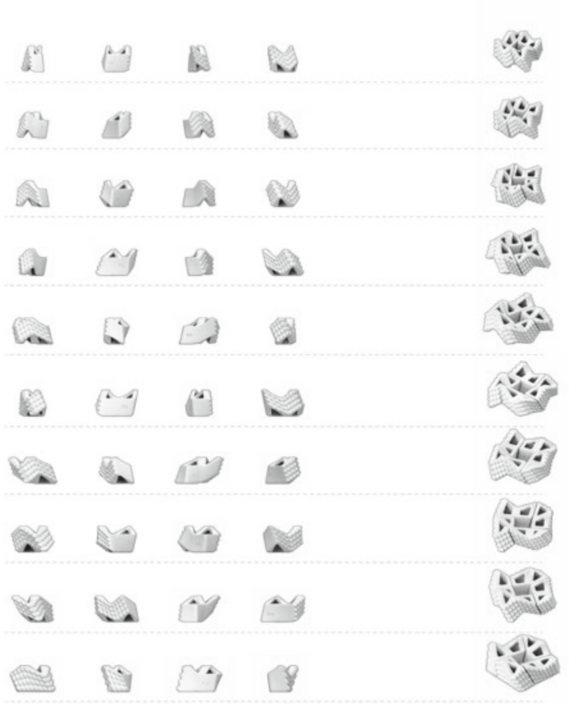

**Fig. 8** An illustration of quake column morphology by Emerging Objects (2014) (*source* Authors)

an advanced 3D printing model that employs a gantry system designed specifically for deposition of concrete, and operated through an interface-based software system to print structures using a cement-based mix designed to be extruded without slumping, increase bonding between layers, and that hardens quickly.

In 2018, ICON delivered its first 3D printed house prototype in Austin, Texas using the Vulcan printer. The hope is that this could be leveraged towards a wider utilization for building housing for the homeless. Later in 2019, the company introduced its first 3D printed community project in Tabasco, Mexico. In collaboration with New Story and Echale, the project delivered 50 housing units, each was printed in 24 h.

## 4 Towards Reforming Construction: Open Source Customization, and Rationalized Manufacturing

As 3D printing technology is brought to mainstream building, Edison's dream of a one-cast concrete house seems conventional. The very idea of production in architecture has been inspired by the multiple perspectives and evolutions of parallel industries. From mass production, to lean production and then digital fabrication, the ability to make architecture a commodity would reform construction culture, thus

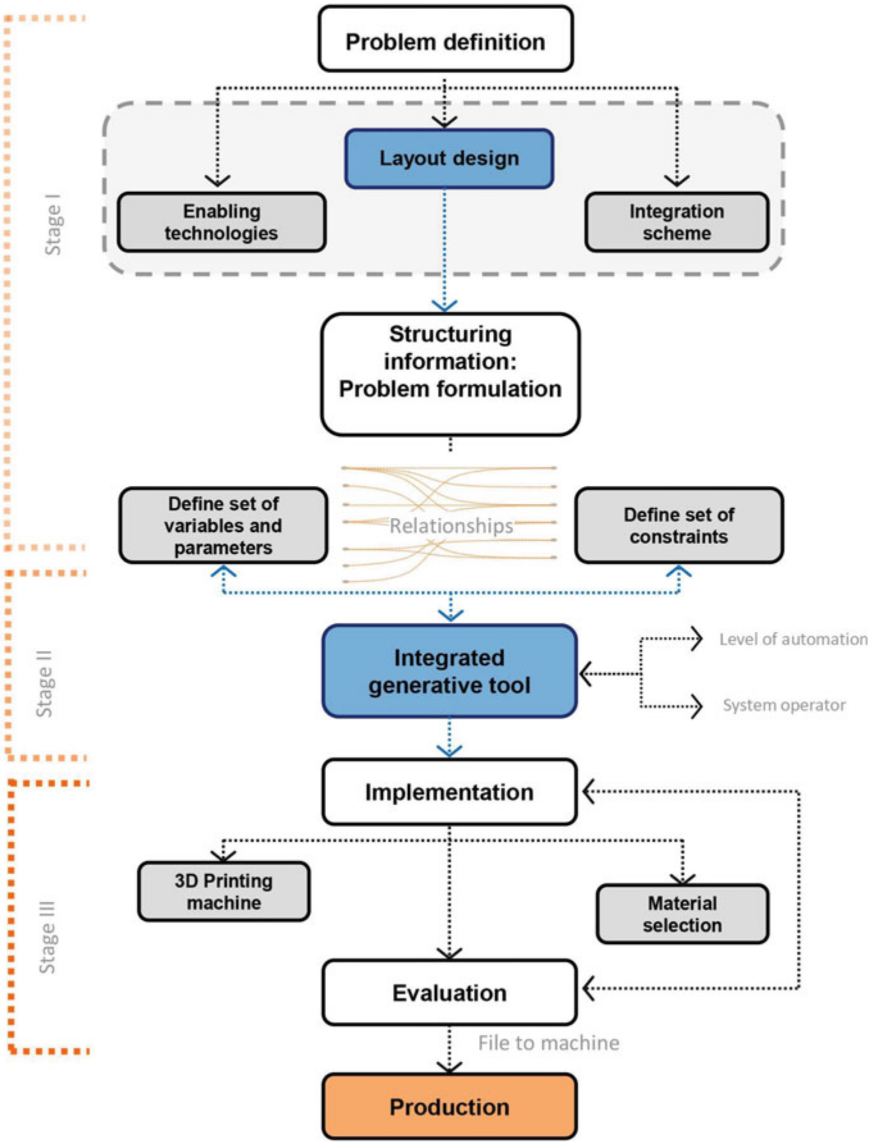


**Fig. 9** A diagrammatic representation of a proposed mass customization framework (*source* Eid M., B. 2022)

allowing for alternatives to address issues of productivity and affordability. The implications for traditional industrialized construction ideas are significant. The dream of the factory-made building or house consistently rested on manufacturing models that placed an importance on modularity and repeatability to achieve some type of cost effectiveness. The conventional paradigm of mechanization and mass production only ever attained marginal competitiveness with onsite fabrication, which has always been argued as offering greater flexibility. Connected, transportable, and moveable machines such as 3D printers offer a new paradigm to reform traditional archetypes of manufactured building as the process is controlled through a digital workflow. The fabrication process is streamlined from a collaboratively detailed 3D design model to a machine code that is then translated into a physical object which can be produced multiple times or just once without substantially changing the work-flow as would be the case for producing a one-off house in a modular factory.

Moving from mass customization to a type of individualized production is at the heart of this budding business model for architecture. Age old prefabrication theories are being challenged by the possibilities of bringing a unique vision of mechanization to the construction site. The tension between design, production and fabrication is in a sense erased in favor of a digital design thread, which weaves new architectural potentials. Further this digital thread can be invested by anyone with the capacity to share or harvest crowd knowledge in favor of multiple iterations. Streamlined 3D printing has already brought the factory into the home. It now has the potential to bring the factory to the construction site.

Additive Manufacturing combined with reinforced concrete eliminates the need for costly formwork and the requisite orthogonal geometries that are easier to shape. The nozzle head could be controlled to deposit or spray a material in any direction or angle. Further using horizontal or arched or vaulted decking as part of the final structure makes it possible to envision structures that are more than just vertical extrusions but that arrange continuity of form from walls to floors and roofs, which until now remain absent for 3D printing explorations applied to building. Most explorations in this sense offer a very narrow spectrum of architectural possibilities. This opens an area for future research in matters of how machines and materials could be used to complete more comprehensive and complex forms.

To speak to the advancements of pioneers in reinforced concrete construction the reduction of weight compensated by resistant shapes finds in 3D printing new possibilities of geometrical matrices optimizing material use. Each wall or surface can be realized with an efficient infill pattern to make use of geometric patterns' and material strength. Analogous to trussed elements in a structural steel trellis framework or spaceframe or even in a tightly weaved fabric pattern, concrete can be deposited to reproduce such patterns largely increasing strength per unit of weight ratio. Furthermore contextually informed parameters can be used to generate shapes that are filled according to site conditions, seismic or climatic constraints. The same shaped building could have a 70% infill in the arctic while only a 40% infill would be required in another context.

Along with these structural possibilities, specialized mixtures, even from localized volcanic ash or industrial waste such as slag, creating a greener concrete, can be harvested locally, mixed on site and localized in every corner of the globe with minimal site disturbance.

### *4.1 Mass Customization of Housing: New Systems and Machines*

When looking at recently completed attempts in employing 3D printing in construction it is evident that housing as a typology has gained particular focus given its appropriate scale for experimentation, in addition to the continuous call for exploring new ideas to tackle issues of quality, affordability, sustainability and customization. While most projects we studied are clear with regard to the type of machine used for production, whether a gantry system or a robotic machine, very little information is provided about the design process, and how it could be configured to deliver customized designs. Primary constraints relate to the machine or printable area, and material deposition characteristics. Accordingly, we believe that further developments in orchestrating a relationship between a novel design process and 3D printing machines could lead to new production protocols, and dimensional parameters that could inform the process from design to delivery.

To give a broader perspective, the growing role of Artificial Intelligence (AI) in architecture, coupled with the capacities of adaptive generative design tools, and supported by new modes of fabrication in the form of large-format 3D printing, are all promising to offer a new opportunity for implementing customization in architecture, and specifically housing, thus potentially reforming current models towards addressing many of the contemporary challenges. Appropriately, a design to production workflow could offer an alternative to conventional industrialized housing models that has faced obstacles with regard to perceived quality, and customization. Whether 3D printing of a whole housing unit, or components to be assembled on site, the process transforms the prefabricated housing production paradigm.

It is evident that customization in the housing industry has always been connected to advancements in design and fabrication technologies. Following every new wave of techniques and machines, the interest in mass customization arises. One of the early efforts to explore enabling technologies for mass customization of housing is the work by House_n [36]. This former digital media and housing research group at MIT's Department of Architecture defined three necessary elements for the mass customization of housing. First, a preference engine for customer profiling. Second, a design engine that employs computational set of rules encoded into a shape grammar to generate design solutions in response to the profiling process. Finally, a production system that relies on digitally controlled machines for construction. Powered by the rise of more accessible computational tools and digital fabrication machines in architecture, much of the research efforts explored mass customization of housing from three different angles [48].

As a response to rethinking a model to integrate all three levels, rather than only highlighting the potential of computational design tools or digital fabrication machines, we propose open framework for mass customization of housing that builds on previous efforts, while taking advantage of recent technologies. The framework is outlined by integrating large-format 3D printing, redefining the traditional relationship between design and production. Figure 9 represents a schematic diagram for a proposed mass customization framework, one that is enabled by the utilization of large- format 3D printing machine for production.

The framework is structured based on the following three stages:

- Stage I: Identifies the various levels and activities that are required to implement mass customization of housing. The initial objective is to define the level of customization based on a company's readiness with regard to available design and production technologies with the means by which communication with home-buyers will take place. This could happen on two levels: first, configuration of pre-defined designs with framed limitations and second, spatial layout following particular design rules and criteria.
- Stage II: Explores the process of selecting a design methodology to formulate a solution space. The framework that relates to the 3D concrete printing machines proposes exploring the integration of adaptive generative design tools towards developing design solutions. Adaptive generative design tools, such as Finch3D (Finch3D n.d.) [41], given its potential in extending current parametric CAD/ BIM tools through advanced computational design logic and AI, Such tools offer to automate the design process through a well- informed decision support model. Given that the framework is structured to capitalize on large-format 3D printing capacities, the generative tool could be programmed to comply with inputs describing user profiling, while being controlled by the parameters and constraints of the 3D printing machine.
- Stage III: Proposes the implementation of the framework and validating its capability to deliver customized designs in response to the requirements defined in the preceding stages, this stage would require deciding on the production process and device, orchestrating the relationship between the design system and production machine, and testing various material options before prototyping a final design.

### *4.2 Challenges and Potentials*

The idea of a customized inhabitable prototype certainly transforms traditional industrialized housing. Further, linking design parameters with generative design solutions and programming an automated output is symbolic of construction 4.0's potential. The digital process integrates design with production relating fields that are normally discordant and that in itself is transformative in a fragmented industry. Architecture and construction remain however, deeply material-based and any advances in technology are often mitigated by entrenched material constraints.

As is the case for reinforced concrete in general and 3D printed concrete, systems that have been explored require layering of material creating structures that are based on massive construction as opposed to filigree construction. As this becomes an advantage with respect to thermal inertia and mass, it is a complete transference from modernity's penchant for the skeletal structures and their intrinsic flexibility and adaptability. In massive bearing structures changes are difficult to make over time; structures become obsolete more rapidly. If the structures become obsolete the question of their end of service life becomes significant. Concrete can be dismantled then crushed or pulverized to be reused in concrete over and over again, however it is a time and resource intensive process making it unlikely to be used in contexts that lack the necessary tools or resources.

Change is a permanent need in residential structures. From minor adjustments to major retrofits, adapting to the need for variation is a fundamental requirement of architecture. Looking at 3D printing from this perspective opens avenues for further research. For the moment, cable network channels, service integration or structural matrices have been studied for optimizing current construction. It is possible to reimagine 3D printing from the perspective of making structures more adaptable. Concrete deposited in interrupted layers or channeling for service replacement, can be designed in the patterns but still monolithic construction impedes disassembly of certain components at the end of their service life. Such a challenge also relates the discussion regarding machine size, and choosing a technique that offers greater efficiencies; on-site 3D printing, or 3D printing in a factory-like facility then assembly on site. While most of the recent projects were 3D printed on site, production in a controlled environment addresses the notion of quality control that has always been considered an advantage of industrialized building. In fact, the first 3D printed office in Dubai was 3D printed in parts and assembled on site. Additionally, one of the recently completed projects, 3D printed house in Sharjah, UAE, was 3D printed on-site, yet within a specially built tent to control the printing environment [6].

## 5 Discussion and Conclusion

Even with the high-tech nature of Additive Manufacturing, sourcing local materials to be deposited according to contextual traditions or patterns paves the way for an interesting union between information technology and traditional construction, thus potentially inducing a type of site-specific manufacturability. From mass-production to a type of customized manufacturing model, unlocks a new era of building machines.

The geneology from the Tournalayer, gantry crane and other modern experiments to large scale 3d printers is clear. Machines were central to the modernization of building culture and to the development of modern construction methods. Experiments in fabricating architecture through mechanization, to automation and robotization often are linked to normalization and repetitive production, but 3d printing offers a different path forward. The democratization of 3D printers puts fabrication in the laps of the many—as was the case for prototypes such as the Robo-hand [39] sourcing the needs and sharing knowledge on how to respond to them—with a basic understanding information technology. The issue of customization, a longstanding burden on the fabrication of architecture is being turned on its head with the help of machines that can address a type of intrinsic singularity programmed into a nozzle moved in any direction depositing concrete layers onto any surface in any context.

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# Virtual, Augmented and Mixed Reality as Communication and Verification Tools in a Digitized Design and File-To-Factory Process for Temporary Housing in CFS

**Monica Rossi-Schwarzenbeck and Giovangiuseppe Vannelli**

**Abstract** This work presents a research project in which Cold-Formed Steel building components for temporary post-emergency housing are developed and realized with a digitalized workflow. This starts from early design ideas (peacetime), includes file-to-factory production and assembly processes (emergency relief/early recovery) and leads to the disassembly of building components and their reuse (reconstruction). The key element of the entire process is the Information Model. This is the place of the interoperability that, during the different stages, interfaces with different devices including Virtual, Augmented and Mixed Reality tools as well as file-to-factory processes for the industrial production. Aim of the paper is to show how visualization tools (like interactive Whiteboard, Tablet, Cardboard, Oculus Rift, Hololens 2, and Cave) can be used not only to realistically and immersively represent the project, but also to optimize design, production and construction processes. Indeed, these devices can also be used to improve the communication between the involved stakeholders, to enhance participatory processes, to help in decision-making, to verify a digitalized design and manufacturing process and to train workers. To achieve this goal, the innovative workflow is presented in chronological order, highlighting the purposes for which the selected tools were applied, analyzing their characteristics, potential, limits, software, interfaces, involved users and costs. The results comprise not only the application itself, but in particular the advantages and challenges evaluation of the use of the selected tools in a design project in order to improve future applications.

**Keywords** VR AR and MR · BIM and interoperability · File-to-factory · Cold-formed steel · Temporary housing

**United Nations' Sustainable Development Goals** 9. Industry Innovation and Infrastructure · 11. Sustainable Cities and Communities · 13. Climate Action

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_24

# 1 Introduction and State-of-the-Art

## 1.1 Industry 4.0 and the Architecture, Engineering and Construction Sector

During the Hannover Fair in 2013, the German Federal Ministry for Economic Affairs and Climate Action and that one for Education and Research, together with other partners, established the Industry 4.0 platform to support industrial production with innovative information and communication techniques in order to make it faster, more efficient and more flexible [1, 2]. The platform has been a huge success and a driving force not only in Germany, but also in the rest of Europe, in the digitization also of sectors outside manufacturing. Industry 4.0 has now taken an important place in the economy. Companies see this as an opportunity to increase their competitiveness, drive technological development and, in particular, optimize production and business processes. On the contrary, in the AEC sector the digitization of building design, production, construction and more generally of processes is taking place in a slow and uneven manner [3]. This is attributable to several factors including two main ones: the high number of involved stakeholders (often characterized by different interests, applied workflows and used tools) and the fact that each building is a unique piece often made on site and with wet technologies, so that an industrial production (either serial or customized) is not always applicable. In order to reduce this gap, numerous initiatives such as Planen und Bauen 4.0, started in 2015, have been set up with the aim to introduce digital construction processes in the AEC, to consider the entire life cycle of buildings and transform new business models for real estate projects [4].

Therefore, the application of innovative paradigms and digitized processes has become more widespread in recent years. However, this is often done in a fragmented manner, only at certain stages of the process or by only some of the involved stakeholders. Industry 4.0 in AEC is a challenge, but also a big opportunity, which, in order to work efficiently, must cover with a collaborative and holistic approach the entire designing, construction and management process.

## 1.2 Digitization in the AEC: Challenge and Opportunity

Digitization in the AEC sector is taking shape particularly in the following applications: Building Information Modelling (BIM), digitized production (file-to-factory) and buildings project representation (Virtual, Augmented and Mixed Reality).

The use of BIM—consisting of an innovative collaborative method of design, construction and management that allows integrating all information about a building in one single three-dimensional digital model—is becoming increasingly widespread, particularly in complex and large-scale building projects for public clients [5, 6]. The creation of a digital twin of the to-be-built/built building facilitates communication between the involved stakeholders, reduces the possibility of design and construction mistakes, limits unforeseen cost increases, and can also be subsequently used for Facility Management [7, 8].

The digitized production of components using the file-to-factory method is nowadays customary in many sectors where the entire production takes place in the factory, such as the automotive industry. In the AEC, building realization mainly takes place on the construction site, and file-to-factory manufacturing is limited to components that can be produced in the factory and then assembled on the construction site. Not all building materials are suitable for this type of production, although interesting applications in concrete, steel, brick, plastic, wood and fiber materials have been realized in recent years [9, 10]. The most significant difference between this type of production and the traditional industrial one is the ease in making unique pieces. According to the 2030 Vision for Industry 4.0, digitized manufacturing is becoming increasingly more customized and less serial [11].

In recent years, the rapid spread of three-dimensional representation software and visualization tools has meant that these have reached the general public. Initially, users were almost exclusively video game players, now immersive representation tools are also routinely used in completely different sectors such as museums, education, medical, military, robotics, marketing, tourism, urban planning and civil engineering [12]. In the AEC these tools are generally applied for realistic, experimental and immersive visualization of urban, architectural or industrial design projects, although they have great potential in improving the design process by being applied in the stakeholder engagement, design support, design review, construction support, operation and management and workers training [13].

### *1.3 Virtual, Augmented Und Mixed Reality: Typologies and Characteristics*

The above mentioned digital technologies for the representation of an architectural project are all based on a three-dimensional model of buildings and/or components. A 3D representation can take place on a two-dimensional medium (such as paper, tablet or screen) or the third dimension can be rendered more realistically with, for example, the aid of 3D glasses and the screen of a cinema or of a special television. When this third dimension comes to life, it becomes another type of representation such as Virtual, Augmented and Mixed Reality.

Virtual Reality (VR) is a technology that provides a 360-degree world in which the viewer can look in all directions and can also change his perspective by bending down or walking towards something. VR needs a tool (e.g. VR-glasses) and is immersive. This means that the user is totally immersed in the virtual world and perceives no other space outside this environment [14].

Augmented Reality (AR) is used to describe a combination of technologies that enable real-time mixing of computer-generated content with live video display. AR inserts additional objects or information into the real field of view and can be immersive (e.g. using Hololens 2) but also not (e.g. using a tablet or smart phone) [15].

Mixed Reality (MR) is an extension of the AR. The user is able to move and perform actions at the same time and in an integrated manner, in both the real and digital worlds, interacting and manipulating physical and virtual objects [16].

## 2 Research Purpose, Methodology and Case Study

### *2.1 Workflow Development: Information Model as Place of Interoperability*

BIM, file-to factory production and VR, AR and MR are certainly important resources for the AEC, but at present, they are often used independently of each other, without exploiting their synergies. In order to better exploit the potential of these tools in the AEC sector, the aim of this paper is to specifically develop for a real case study an appropriate workflow able to improve the entire design, production, construction and management process using different types of representation tools as well as file-to factory production devices. A key element in digitized processes is the interoperability. In the glossary of the Industry 4.0 it is defined as the ability of different components, systems, technologies, or organizations to actively work together for a specific purpose [17]. In the proposed workflow, the place of interoperability is the Information Model. It is able to interface with different devices, it is the common element between representation tools and digitized production one (Fig. 1) and can be used by the different stakeholders, facilitating their communication and interaction. The Information Model is able to filter the information and provide the user with only the needed information for example, it provides the representation tools with information like form, materials, surfaces, colors, and the production one with information like processes, procedures, thicknesses [18].

### *2.2 Case Study: Design, Production, Construction and Implementation Process of Post-Disaster Temporary Housing in CFS*

With the aim to develop and test a workflow that is capable of exploiting the full potential of the information model, of the various immersive and non-immersive visualization tools and of the file-to-factory production, a complex project is essential as case study. It must be characterized by a high level of complexity and a long time-span and in which interoperability and communication play an important role (because of the many stakeholders involved). Due to that the design of modular [19], incremental, flexible, dry-assembled, easily removable and reusable temporary

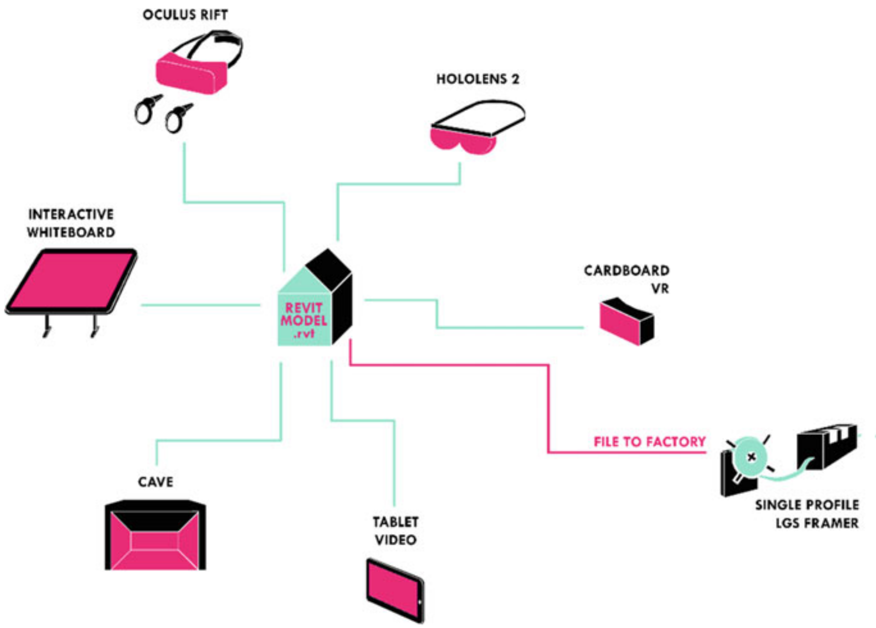


**Fig. 1** Building information model as place of the interoperability. Visualization and file-to-factory tools that interface with the information model in the workflow developed

housing, using a construction system in Cold-Formed Steel (CFS) [20–22], for the construction of residential settlements to be built quickly following a disaster [23] (Fig. 2) was chosen as case study. These dwellings are conceived, according to the "building by layers" [24] logic, to be flexible and expandable over time, and at the end of their use, which is planned to be temporary, the wall-panels can be reused both to build new structures and to redevelop existing architecture by improving their seismic and energy performances [25].

The design of the housing units is part of a more complex process in which time plays an important role and is carried out in three phases: Peacetime (before the disaster, which as such is unpredictable), Emergency Relief/Early Recovery (following the disaster) and Reconstruction (Fig. 3).

The simulated process is characterized by a large number of involved stakeholders—that vary over time—and by different time phases whose duration is difficult to predict in advance as they are linked to unpredictable circumstances. In order to develop a workflow appropriate to the specific case study, it is necessary to analyze and predict the roles and relationships that stakeholders play during the process. These are the Italian Department of Civil Protection, designer (architects and engineers), university research centers, enterprises, local administrations, workers and inhabitants.

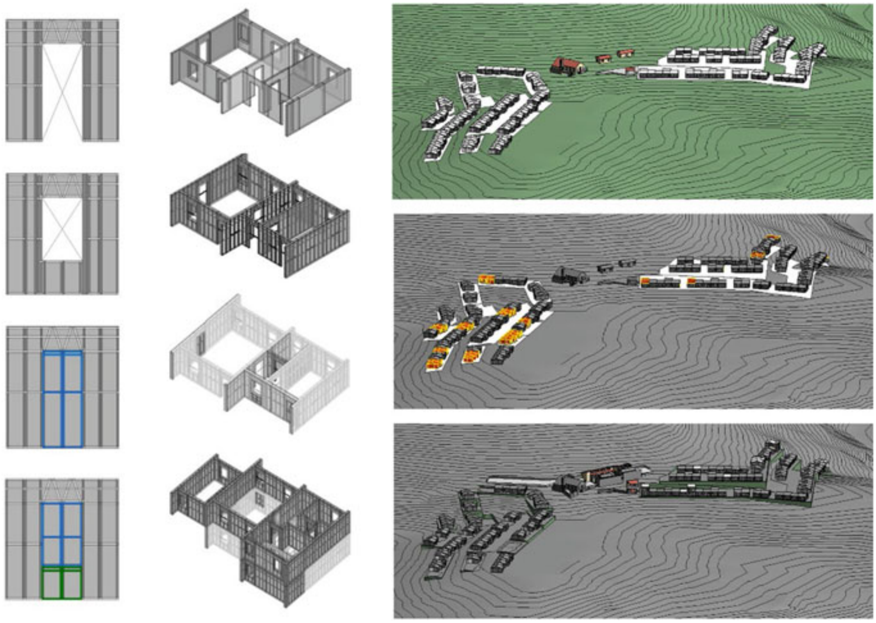

**Fig. 2** Application case study. Design of the panel as building element, of the housing system and of the housing settlement in Sant'Eusanio Forconese (L'Aquila, Italy)


**Fig. 3** Timeline of the design, production and implementation process: Peacetime, emergency relief/early recovery and reconstruction

# 3 Experimentation

## *3.1 Peacetime*

In the first phase of the simulated process—called Peacetime, since it takes place in a timeframe prior to a possible emergency—the Italian Department of Civil Protection (DPC), supported by a university research center, is issuing a call for proposals for post emergency housing. The best proposal is chosen and optimized until it is ready to be manufactured and built immediately succeeding the emergency (see Fig. 4).

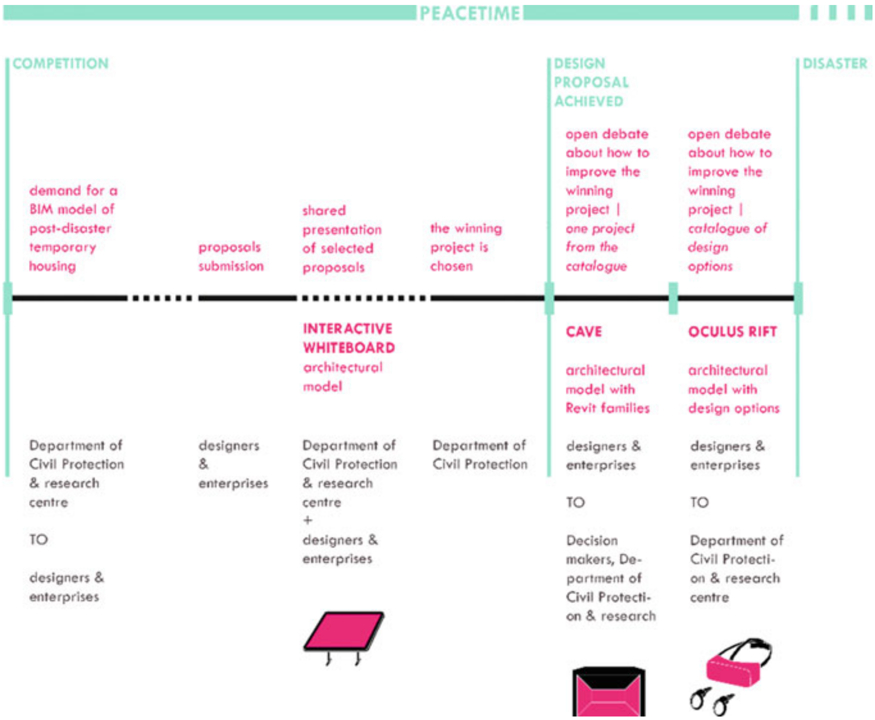


**Fig. 4** Workflow and tools in the peacetime

The DPC is the national body that deals with post-disaster recovery and relief and in the simulated experimentation process constitutes the contracting and bidding body. The partner that could scientifically support the entire process should have a BIM laboratory equipped with the applied visualization tools, as it is the case for the Leipzig University of Applied Sciences (HTWK Leipzig, Germany). The call also requires that design proposals contain not only the project of modular dwellings, but also the design of dry-assembled and easily removable and reusable building components for their construction.

Then, design proposals must be submitted jointly by designers and enterprises that will be responsible for manufacturing the components. Additionally, the design must be presented in form of an Information Model able to be managed with a BIM working methodology. In this regard, the contracting authority also provides in the call an accurate Employer´s Information Requirement (EIR) [18] based on which the participants in the competition develop an appropriate Building Execution Plan (BEP).

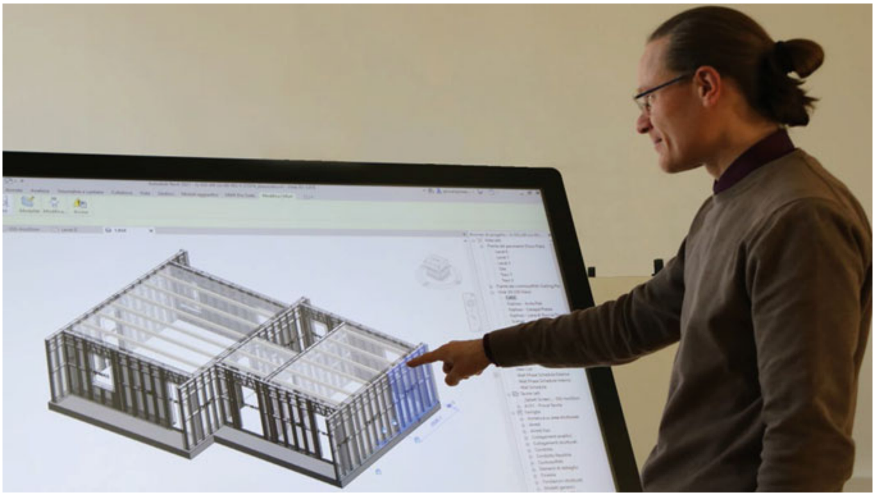

**Fig. 5** Mobile interactive whiteboard with multi-touch display applied for the presentation as well as for the improvement of selected proposals (3D visualization)

After the submission of design proposals, designers and enterprises of the selected projects present their proposals to the principals with the support of a mobile interactive whiteboard with multi-touch display. This whiteboard constitutes a useful visualization tool for presenting the project to a small number of people, facilitating communication and interaction through the model (Fig. 5). The informative architecture model can be opened in the proprietary format in the modeling software (e.g. Revit or ArchiCAD) as well as Industry Foundation Classes (IFC) file in a checking software (e.g. Solibri Model Checker) and can be verified and superimposed on specialized models (e.g. technical building equipment or constructive model).

Following the selection of the winning project, open debates can be held in which the DPC, designers, enterprises, and decision makers participate. These meetings could take place at the university research center and aim at optimizing the winning design in order to make it executable. Therefore, following a disaster, the housing units to be built can be quickly chosen and/or adapted to the specific situation and the necessary building components can quickly go into production.

Then, the proposed experimentation simulates a possible process using a project developed as part of a doctoral thesis elaborated within a collaboration between the University of Naples "Federico II" and the HTWK Leipzig while Irondom srl—a CFS component producing company—has been the manufacturer enterprise partner.

Two representation tools could be used in the open debates: a Cave Automatic Virtual Environment and the Oculus rift. The Cave is a VR Space in which a discrete number of people (up to about 30) with the support of special 3D glasses can simultaneously immerse themselves in the virtual reality of the design proposal so that they can discuss it and possibly optimize it together (Figs. 6 and 7). The Oculus Rift is an immersive VR tool in which the moving around and interaction with the building elements (thanks to the two touch controllers) is greater. The model is editable and it is possible to write issues and to see model information. However, this is an experience that an individual performs alone and there is no interaction with the rest of the stakeholders, who see the model on the screen (Fig. 8).

**Fig. 6** Cave automatic virtual environment and associated 3D glasses applied for the open debate between designers, enterprises and members of department of civil protection to improve the winning project (VR space)

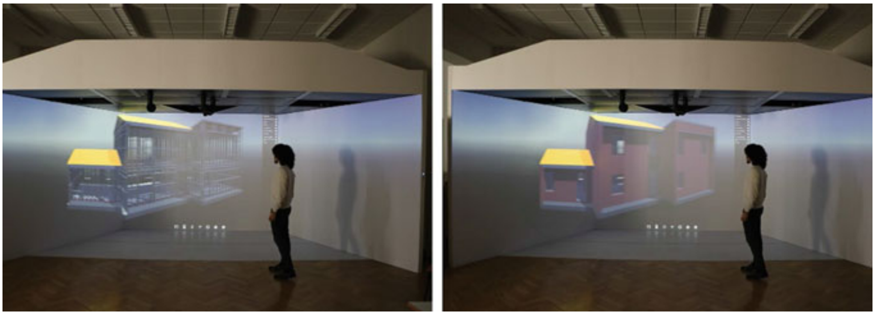

**Fig. 7** Cave. View with and without building envelope

**Fig. 8** Oculus rift (immersive VR). One person has a VR vision and people can see the 3D model on the screen

## *3.2 Emergency Relief and Early Recovery*

Following the disaster—in case of the simulation an earthquake that occurred in central Italy (a seismic prone area, struck by several events in recent decades (1997, 2009 and 2016))—the process for the rapid construction of housing units starts (Fig. 9).

In the emergency relief phase, the site where the housing could be built is identified with the support of the local public administration. Within the experimentation an area located in the municipality of Sant'Eusanio Forconese (L'Aquila, Italy) was chosen. With the support of Hololens 2 it is possible to visualize the information model with different design options in the lot chosen for the settlement. DPC and the local government in order to define the exact placement of housing units in the lot can use this immersive AR tool, which can also be called MR as it allows interactions with both the real and virtual worlds (Fig. 10). At this stage, the quantity and types of housing units to be built and consequently the CFS building components to be produced are defined, based on number and needs of the future inhabitants.

A non-immersive AR visualization is also possible with the use of a tablet or iPad. This inexpensive tool, which even non-technicians often already have, can be used e.g. by workers (who may also be non-specialists and volunteers participating in the post-emergency construction) and future inhabitants to visualize the dwellings on the site. Unlike with the Hololens 2, the model is only partially editable with the tablet (Fig. 11).

In order to involve future inhabitants in the process and allow them to move virtually into their future homes, Cardboard VR glasses can be used. These are extremely inexpensive VR visualization tools that can be used with any type of smartphone,

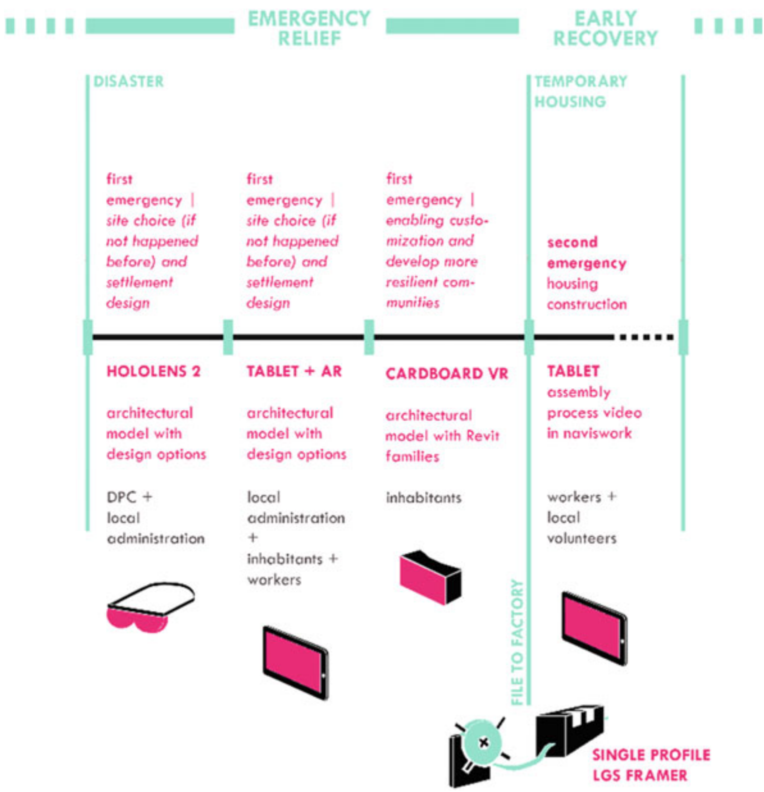


**Fig. 9** Workflow and tools in the energy relief and early recovery

**Fig. 10** Hololens 2 used to visualize the dwelling in the lot (immersive AR)

**Fig. 11** Tablet used to visualize the dwelling in the lot (non-immersive AR)

a device currently owned by any type of user. This visualization is immersive but not interactive and does not allow you to edit the model, view information or write issues (Fig. 12).

As soon as the exact needs are defined, production based on file-to-factory processes can start. Panel-walls and other CFS elements can be produced by the enterprise—Irondom srl, in case of the simulated process—using a CNC machine (e.g. Arkitech AF I 200P Framer (Fig. 13)). This is a single profile LGS framer that is able to read the information of the building components from the information model and produce them through a digitized process based on customization and on-demand production (Fig. 14). Such a light production system opens the possibility of structuring flying factories [26] where to pre-assemble the building components. Moreover, this approach to the production process ensures—in accordance with Industry 4.0 goals—a high mass customization capability [27] and combines

**Fig. 12** Cardboard VR-glasses used with the smartphone by future inhabitants

process flexibility, resource saving and high productivity. In post-disaster condition, also considering the amount and the variety of needs (variables over time) and of involved stakeholders, this is a meaningful workflow.

At this point, assembly and construction can begin on the construction site, carried out by skilled workers as well as volunteers. To assist the training of volunteers, videos made from the information model and viewable on a tablet or iPad can be prepared to illustrate the assembly of prefabricated elements (Fig. 15).

**Fig. 13** Arkitech AF I 200P framer. Manufacturing process file to factory

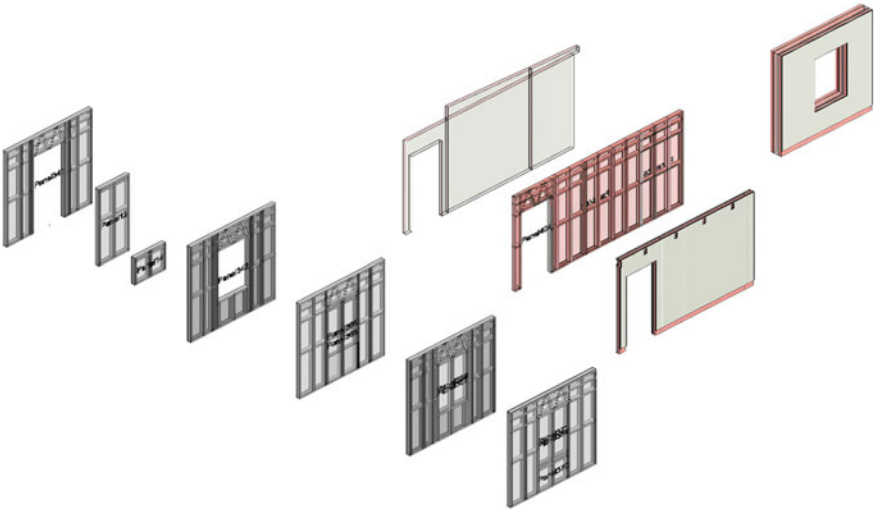

**Fig. 14** Example of CFS customized panels/wall produced with a single profile lgs framer in a file-to-factory process

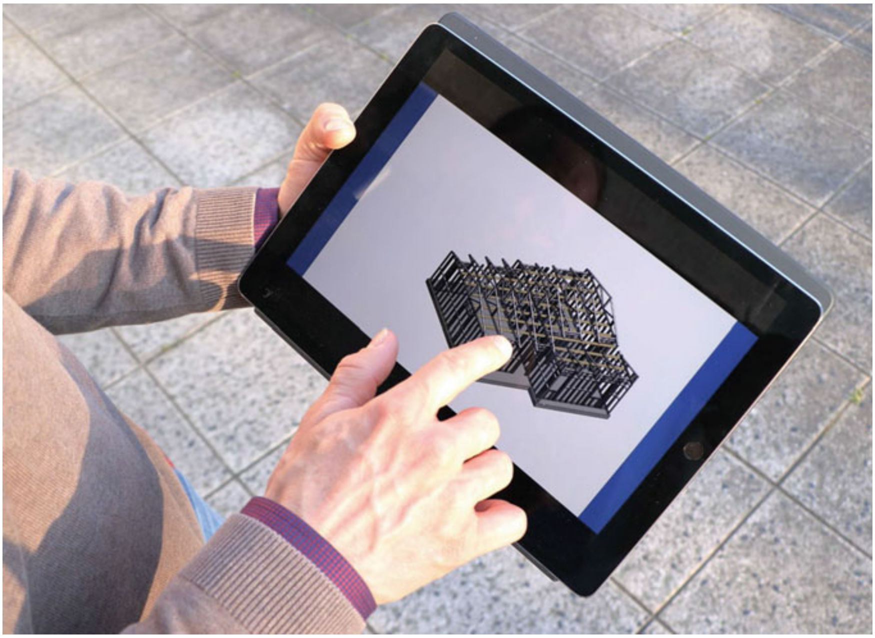

**Fig. 15** Tablet displaying assembly process videos used by workers (3D visualization)

### *3.3 Reconstruction*

While displaced communities are living in temporary housing, the reconstruction begins and includes rehabilitation and seismic improvement of lightly damaged buildings and demolition and reconstruction of severely damaged or collapsed buildings (Fig. 16).

At this stage, Virtual, Augmented and Mixed Reality tools (particularly the Cave and the Hololens 2) can be useful devices for stakeholders to jointly make decisions regarding future developments (Figs. 17 and 18).

The duration of this phase is difficult to predict as it depends widely on reconstruction policies and other external factors. Thus dwellings—which were intended to be temporary—are sometimes used for a longer period than expected and in the meantime the needs of the inhabitants may change (e.g. the number of members of a household increases). Otherwise, it may happen that two temporary housing units adjacent to each other, become vacant at different times, because inhabitants of different households may return to their permanent (redeveloped or reconstructed) home at different times. These changes in requirements over time may result in the need to expand one housing unit or to disassemble two adjacent ones at different times.

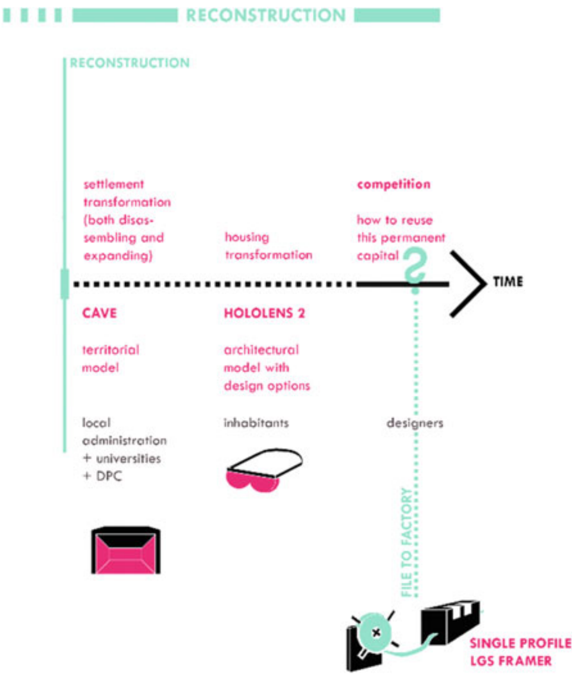


**Fig. 16** Workflow and tools in the reconstruction

**Fig. 17** Meeting in the cave using the urban model to identify housing units that need to be expanded, modified or disassembled/removed

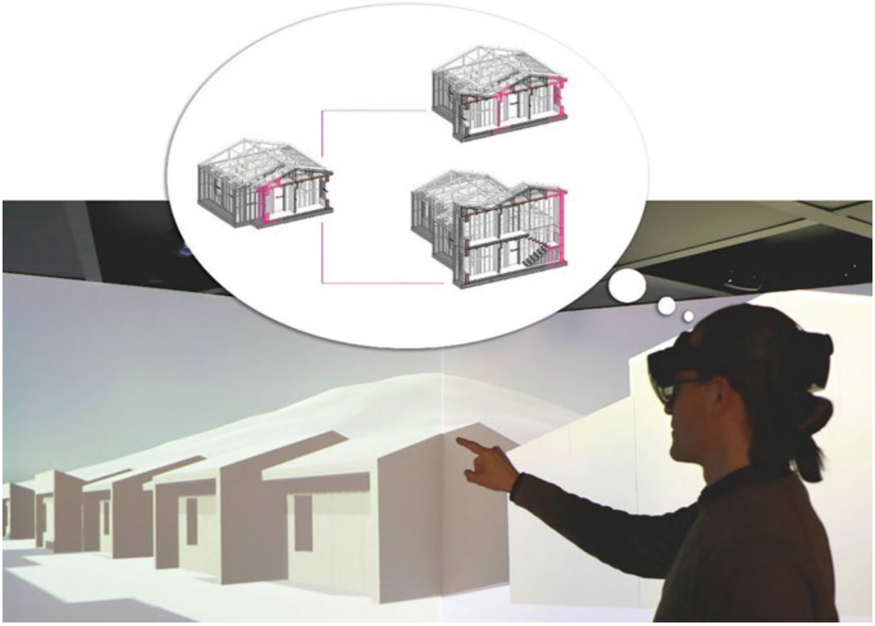

**Fig. 18** Meeting in the cave. Evaluation of possible extensions of a housing unit

To respond quickly and easily to such needs, the housing units as well as the construction system in CFS components are designed with a high level of transformability and reversibility. Additionally, the reuse of CFS components, disassembled from temporary housings at the end of their use, for seismic improvement of pre-existing damaged buildings is conceivable. The reuse and recycling of materials and components makes the entire developed process part of a circular economy approach [28].

## 4 Results and Discussion

The outlined experimentation achieved several results on three different levels: process innovations (development of a digitized workflow that includes the use of VR, AR and MR tools and file-to-factory processes), design innovations (design of a catalogue of flexible, extendable, transformable and removable residential buildings) and product innovations (fine-tuning of different types of customized CFS panels, dry-assembled on site, removable and reusable).

In relation to the topic of this chapter, the development of the workflow is the most interesting result. Indeed, the case study demonstrated how it is possible to manage a complex, time-extensive process with numerous stakeholders based on an information model capable of interacting with different AR, VR and MR devices as well as with customized file-to-factory production tools. The application also showed that visualization devices could be used not only to realistically and immersively represent an architectural project, but also to optimize design, production and construction process.

For this process to work best, it is necessary for the client to define the Employer´s Information Requirements (EIR) in detail, as well as for the designers to develop an appropriate Building Execution Plan (BEP). The Level of Definition (Level of Geometry and Level of Information), as well as the software and the exchange formats between them, are important points that must be defined in advance so that communication takes place without errors and the stakeholders receive only the information that is relevant to them.

The choice of which visualization tools to apply, at which stage, for which purpose and with which stakeholders must also be based on an understanding of their peculiarities. The tools used in the experimentation differ from each other in some fundamental characteristics such as typology, involved people (both in terms of amount and skills), possibility to check the model information, ability to modify the model, possibility to write issues, used software, formats and costs.

In particular, the number of users who can simultaneously use a device influences its application in a meeting among decision makers (even 20–30 people) or, for example, for solving a problem by an expert who is working alone. The ability to modify the model as well as the ability to write issues are key features at the stage in which the building system or design still need to be optimized, while they have no importance at the presentation stage of the project itself. Costs of the devices are also important: these range from €1.00 for Cardboard VR glasses to around €300,000 for the Cave. The Cardboard can be a gadget that can be distributed free of charge to residents; the cost of the Cave can be met by, for example, a university research center that rents it out to design groups to conduct their meetings or presentations. Other tools such as Hololens or Oculus Rift have costs that are also affordable for design firms or enterprises.

In fact, this research, in addition to testing, intends to analyze the potential and limitations of the visualization tools in order to facilitate their selection for possible future applications. To this end, their characteristics are presented in detail in Figs. 19 and 20.

In relation to design innovation and product innovation, it is possible to say that the use of a digitized workflow, in accordance with the principles of Industry 4.0, based on an information model, or rather on the overlay of specific information models (architectural model, structural model, plant engineering model, etc.) has certainly facilitated the development of a housing and a construction system capable of reacting to changing conditions and needs as well as a file-to-factory production. In fact, the use of the BIM methodology makes it possible to highlight any problems and collisions in advance. This is a fundamental requirement for a complex project such as the experiment performed, which has a high degree of flexibility and unpredictability due to a disaster event and uncertain development over time. On the production side, the information model also plays an important role by providing inputs to the CNC machine and allowing easy customization.

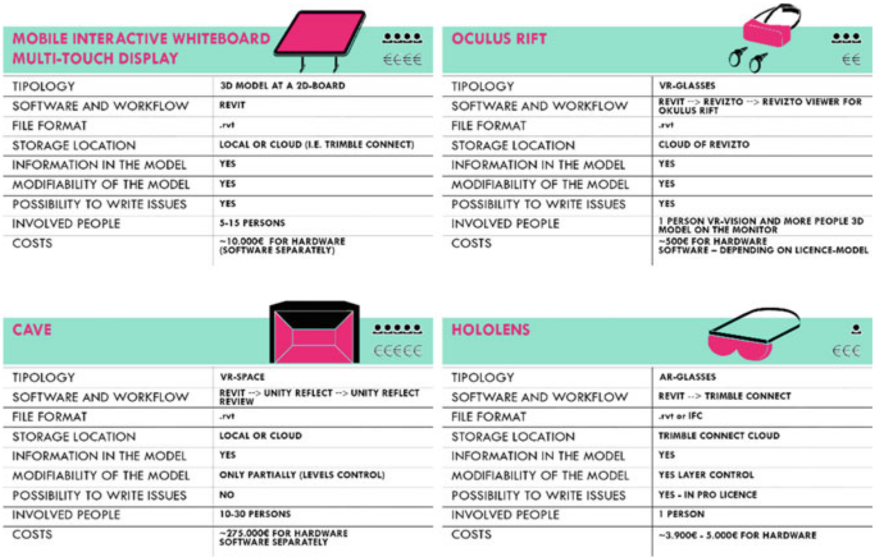


**Fig. 19** Used visualization and production tools and their characteristics


**Fig. 20** Used visualization and production tools and their characteristics

In conclusion, the developed workflow certainly yielded positive results that—after an appropriate adaptation to the specific situation as well as the needs of stakeholders and their relations—could be also applied to other complex projects. To this end, the digital information model becomes the place of interoperability and communication, while AR, VR and MR devices play an important role as facilitators for example in communication, in problem identification and resolution, in worker training, and in on-site assembly. Additionally, it is certainly desirable for future applications to extend the workflow of the digitized process to other phases such as facility management.

**Acknowledgements** The presented research is by its nature characterized by the interaction of numerous partners. In this context, we would like to thank the people and institutions that in various ways contributed to its success. We would therefore like to thank the team of Irondom srl with whom a fruitful two-way transfer of knowledge took place. We also thank the Department of Civil Protection and the mayor of the municipality of Sant'Eusanio Forconese for the exchange of information and materials necessary for the success of the research. We would like to thank Christian Irmscher (BIM employee at the HTWK Leipzig) for sharing his knowledge on BIM, Virtual and Augmented Reality. We would also like to thank Sergio Russo Ermolli and Angela D'Agostino, supervisors—together with Monica Rossi-Schwarzenbeck—of the doctoral thesis conducted by Giovangiuseppe Vannelli at the University of Naples "Federico II" in collaboration with HTWK Leipzig and Irondom srl. The research has been carried out the framework of a PhD with Industrial Characterization financed with P.O.R. funds Campania region FSE 2014/2020, Axis III—Specific Objective 14 Action 10.4.5.

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# Digital Processes for Wood Innovation Design

**Fabio Bianconi, Marco Filippucci, and Giulia Pelliccia**

**Abstract** The study reports the outcomes of a research activity focused on digitization techniques and in particular on the value of computational design, with the aim of implementing innovative product and process solutions resulting from an integrated design approach. The digitization paths focused on representative strategies for digital optimization of the architectural form of wooden houses as a function of context, based on research on generative modelling and evolutionary algorithms for multi-objective optimization applied to the architecture of wooden houses. With such an approach, centered on artificial intelligence or at least on augmented computational intelligence, it was possible to achieve a process of mass customization of meta-planning solutions of wooden architectures, based on the morphological and energetic selection of the best configurations, identified according to the context. These results were made accessible through a web-based configurator that provides the designer with initial configurations from which starting the real project. The studies are projected to the definition of a prototype of the "breathing house," characterized by its moisture-responsive wooden panels, with the identification of innovative solutions capable of reacting passively to changes in humidity according to the "natural intelligence" of the material, whose morphological transformation, empirically studied and digitally transcribed to identify performance solutions, generates well-being for living.

**Keywords** Meta-design · Energy optimization · Responsive architecture · Timber construction · Digital representation

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_25

innovation · 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns

## 1 Introduction

The digitization processes accompanying the recent industrial revolution, in the context of AEC (Architecture, Engineering and Construction), are based on representation: the design of form and enrichment through multiple information are amplified with the interactivity, modifiability and multimedia inherent in digital [1]. The goal is to make the information implicit in the form visible [2, 3]. The design is asked first and foremost for a total freedom but also for a full awareness, as validation tools for the construction phase, to the point of generating a digital clone that replicates reality to continuously derive information in the dynamic integration between hardware and software [4]. The built does not become an object in itself, but stands precisely through its digital replication in relation to its environment, through the processing of causal associations used to create predictions [5], in a cycle marked by data-information-knowledge [6]. Data, defined as the new oil [7], promotes the architecture's resilience.

Such processes result in multiubiquity [8] arising from enabling technologies [4, 9] that lead to a "Cyber-Physical Production System" [4, 10] inherent in the "Smart Factory" [11], which are bringing interesting substantial benefits in terms of digital production [12] and automation [13], but also in what concerns mass customization [14] and stimulating innovation [15]. This activates a digital thread [16] where design becomes a continuous process overlapping the built.

The field of research has thus increasingly shifted from the physical to the virtual space: the morphogenesis from which the model is originated, where the multiple information converges, changes the relationship between sign and image as well as the way of reading and interpreting reality, observing it from different points of view, analyzing it with integrated skills, studying its multiple variables and their mutual interaction. In Industry 4.0 [13], the new paradigm of digital tectonics is developing a new coincidence between virtual representations and their fabrication (Fig. 1), in what appears to be a true cultural revolution [17, 18], because "fabrication is not a modelling technique, but a new way of doing architecture" [19].

Profoundly affecting this transformation are the advances in computational design [20] and in particular parametric logics [21], all based on a different interpretation of the value of data: if the digital revolution has shifted the focus from models to visualization, then parametric design allows to reclaim the infinite potential of the model [1, 22] because data is not secondary but rather the main element that leads to form. "Through a well-designed system of rules, generative design systems have the capability of maintaining stylistic coherence and design identity while generating different designs" [23], rethinking relationships that are "intelligible because its members exhibit a common order resulting from the operation of the same generative principles" [24]. By varying parameters in defined but always open processes, the

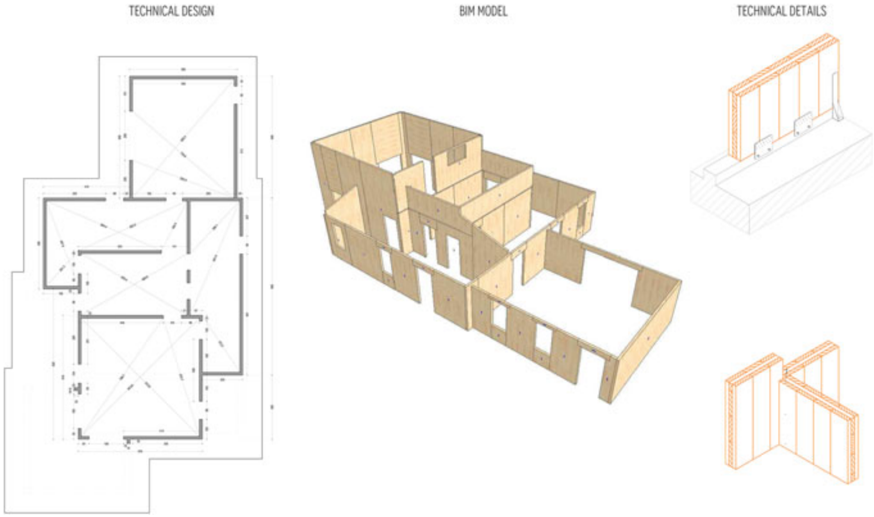


**Fig. 1** Digital wood design and digital manufacturing

algorithm is a tool for configuring, rather than a static morphology, a generative pattern characterized by diversity.

Thus, a data-driven design [25] is developed where one relates to "complex systems" not by looking for simplifications or optimal solutions, rather by creating a combinatorial explosion [26], contrasting this Evolutionary Engineering marked by Multiscale Analysis [26–28] as an alternative to the "iterative and incremental" standard. Optimization strategies [29, 30] are structurally and environmentally optimized form-finding solutions [31] that enable the designer to visualize and evaluate thousands of design options and variants [32] through the materialization of the issue of architectural complexity [33], from the perspective of mass customization [34–43].

Representation is proposed in its definition of architecture and design as "*Lineamenta*" [44], understood according to Leon Battista Alberti's diction [45] as a system of signs. Artificial intelligence [46, 47] and in particular the logic of optimization inherent in evolutionary algorithms [48] acquires a central role in this relationship: computational design is enhanced thanks to the augmented intelligence of the digital [49–51], which finds perfect exemplification in wooden constructions, from design to realization.

Thus, in this context, wood emerges as a material that is absolutely congenial to digital logics, versatile, and fully adapted to contemporary needs for performance and customization (Fig. 2). Therefore, digital representation is added to the properties of matter and its Natural Intelligence (NI) [49–51]. Nature offers not forms but processes for thinking about form [52] and teaches how to create it [53, 54] in efficient structures [55, 56] explaining how the roles of design [57, 58] are truly adaptive and optimized [59]. NI defines paradigms that could be transposed not as "ignorant copying of forms"…but in the recognition "that biomimicry teaches that

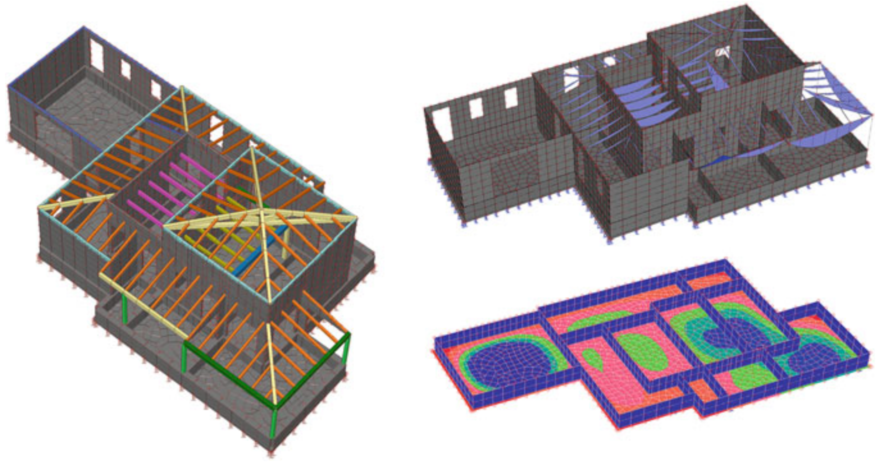

**Fig. 2** Analysis and simulation in digital wood models

form is the most important parameter of all" [60], because at all levels it builds responsive and adaptive forms to preserve material and energy resources through the use of modular components combined with low-energy structural strategies [61].

## 2 The Research

Digitization has been the focus of the entire research project started in 2016 with the then wooden construction start-up Abitare+, in the aim of achieving innovative solutions that would characterize the quality of its offerings. The study is focused on digitization techniques and, in particular, on the value of computational design, with the aim of implementing innovative product and process solutions as the result of an integrated approach to design. The digitization paths addressed various issues, starting with the identification of representative strategies for digital optimization of the architectural form of wooden houses according to the context.

The research was developed at the Department of Civil and Environmental Engineering of the University of Perugia, a path that has found an important recognition in the "BIM&DIGITAL Awards 21" promoted by CLUST-ER BUILD and DIGITAL&BIM Italia. The award was intended to report as excellent the innovative path that through the new digital techniques of representation has led to the development of solutions for new generation wooden housing, capable of responding to the multiple performances and needs of living today. This collaboration was supported by funds from the 2014–2020 POR FESR of the Regione Umbria aimed at supporting the creation and consolidation of innovative start-ups with a high intensity of knowledge application. The sustainability of innovation processes is then strengthened by the support for research guaranteed by national regulations, which provides tax credit for a significant part of the investments made.

### *2.1 Meta-design and Mass Customization of Wooden Houses*

One of the first approaches developed jointly with the company is based on computational design research to address the need to promote a design culture of wooden constructions. Indeed, the research is aimed at designers, who in the national context often face difficulties in designing wood constructions due to the absence of specific training: it is then intended to provide meta-planning solutions, a basis for then developing the project. Evolutionary principles have been applied aimed at informing the design and customization process in the early stage of design. The main goal is to design a comfortable house characterized by high energy performance taking maximum advantage of the passive use of sun and wind. For this purpose, a web-based interface has been developed allowing to explore the design alternatives of a specific construction model by visualizing and downloading a series of multimedia files.

The developed parametric process generates a wide variety of architectural solution, and each of them differs from the others mainly for their orientation, size, type of ceiling, roof slope and shape of the glazing elements. In this case, the definition of rule-based design emerges from a study of local codes and CLT construction systems; indeed, while defining the geometrical rules of the model, constraints have been encoded in a way that each solution follows codes dimensioning and affordable fabrications methods. As a result, each house in the series is unique in shape and size, even if it shares with the others the same building system characterized by CLT panels and a fixed number of manufacturing operations, in both the factory and the building side.

The integrated process proposed in this research has been entirely developed with Grasshopper, introducing in each phase of the project different add-ons for analysis, representation, and interoperability. The definition of the performance criteria started with the study of a construction model through the definition of detailed solutions and sizing of structural elements. In this phase, the construction cost was computed with the company through the definition of a series of parametric costs for the elements constituting the structural system and the envelope, while energy performances were evaluated through advanced energy analysis by estimating building energy consumption, comfort, and daylighting. The goal of an environmental optimization is to ensure a satisfactory comfort with the minimum use of energy, through the adaptation of the architectural organism to its context and its inhabitants. Natural lighting then becomes one of the major driving forces in this design process, which aims to reinforce circadian rhythms and to reduce the use of electric lighting by introducing daylight into space, and it results an effective reduction of energy consumption and comfortable spaces (USGBC, 2013) (Fig. 3). In this research, due to time constraints, 15 generations of 100 individuals were evaluated with the climate data of Perugia,

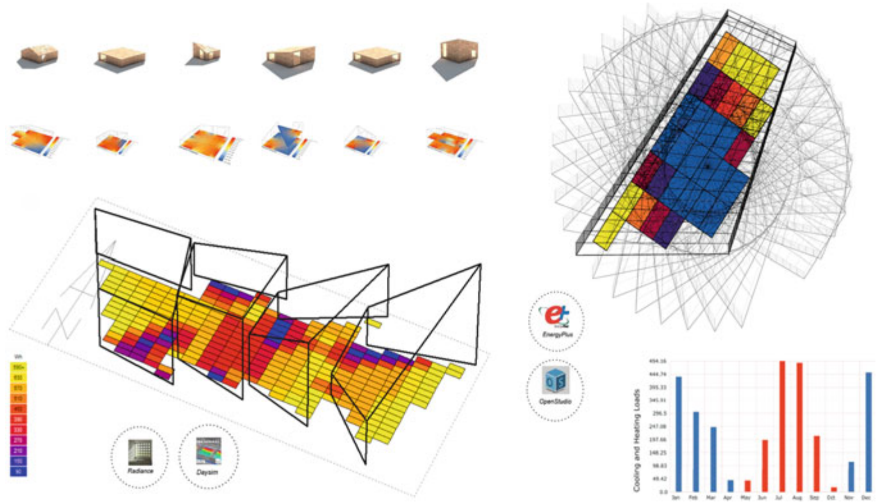


**Fig. 3** Lighting, cooling and heating loads have been analyzed for the different geometric solutions through Honeybee for Grasshopper

Italy. Comparing the less and the most efficient solutions, taking into account that they have different areas, volumes, grazing rations, orientations, the results in saving on energy consumption per square meter was 380%, and saving on construction costs per square meter was 240%.

The proposed workflow highlights the centrality of the research approach, based on computational and collaborative strategies, as a link between design teams and modern construction companies. The analyzed solutions have then been represented in a web-based catalog through which the technology owned by modern construction companies can be shared with designers to achieve an integrated approach. Within a wider collaborative workflow, encompassing smart manufacturing principles and integrated design strategies, the research and development project focuses on the analysis and representation of data. As a result, design teams can take part in the process of mass-customization and start an integrated design process to optimize the product and achieve further design customizations.

## *2.2 Multi-objective Optimization of Architectural Elements*

The logic of mass customization applied to architectural morphogenesis can be similarly applied to the design of building elements. Focusing on the envelope as an essential element of buildings, the research examines perimeter walls by analyzing them from the point of view of both winter and summer behavior and verifying the absence of the of interstitial condensation. Two building systems, Platform-Frame and X-Lam, were analyzed with the aim of optimizing, through the creation of special algorithms, their stratigraphy in order to provide the company with a set of diversified solutions that take into account both cost and energy performance [62, 63].

The combination between the thicknesses and types of materials that compose the wall is the basis of the analysis. Large amounts of data can thus be analyzed and combined and to get solutions that simultaneously present the best values of the parameters chosen as inputs, returning the required outputs. By varying the parameters, the outputs describe the summer and winter behavior of the wall through thermal transmittance $U$, periodic thermal transmittance $Y_{ie}$, decrement factor $f$ and time shift $\varphi$, according to UNI EN ISO 13786:2018 [64] in addition to the verification of interstitial condensation by Glaser diagram according to UNI EN ISO 13788:2013 [65]. The total cost was then used as a benchmark for comparison with the optimized packages. The stratigraphy optimization process was conducted using Octopus, which allows evolutionary principles to be applied to parametric modelling in order to optimize specific parameters [66, 67]. In the two cases considered, Octopus calculated about 5.000 possible solutions; among them, only those belonging to the Pareto Front [68] were selected. Packages were then divided according to performance, as defined by DM 26/6/2009 "National guidelines for energy certification of buildings" [69]: excellent performance ($\varphi > 12$ h, $f > 0.15$) and good performance ($10 < \varphi < 12$ h, $0.15 < f < 0.30$). Depending on the final cost, the most suitable walls were identified, narrowing down to those with a lower or slightly higher cost than the standard reference package (Fig. 4).

Through the proposed optimization and selection method, it was possible to obtain walls with significantly better performance than the standard ones, even at a lower cost. For Platform-Frame, in particular, a stratigraphy can be obtained with excellent

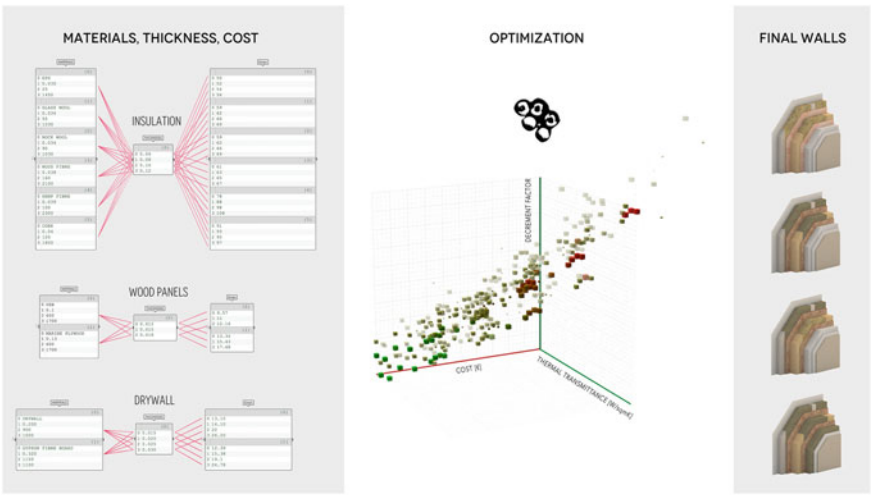


**Fig. 4** The optimization process through Octopus for Grasshopper combines materials and thicknesses while maximizing time shift and minimizing thermal transmittance, decrement factor and costs

performance with a saving of 0.7% and one with good performance with a saving of 3.8%. For X-Lam, on the other hand, an excellent stratigraphy can be obtained with a saving of 1% and a good one saving 13% of the costs as compared to the standard wall. If, instead, the improvement in energy performance is considered without limiting the cost, Platform-Frame can be improved up to 20% in transmittance and 31% in time shift, and for X-Lam up to 28% in transmittance and 22% in time shift. Thus, the parametric design and muti-parametric optimization tools proved to be, once again, essential to process a large amount of data and select the best performing solutions according to specific needs.

Experiments in digital form-finding are linked to BIM modelling, aimed at defining digital manufacturing processes. The construction is linked to representation through BIM interchange models that define the characteristics of the envelope and structural elements, which in turn find information from the algorithms developed in generative modelling.

## *2.3 The Breathing House*

Alongside digital simulations carried out to achieve the ultimate goal of improving the energy consumption of wooden buildings, solutions can also be found in exploiting the properties of the materials themselves. This is the case, for example, of technological smart materials, which have the ability to react to a particular stimulus and change some of their properties to adapt to the external conditions [70, 71]. Smart materials also include natural materials such as wood, which is a sustainable, easily available and low-cost solution [72]. In fact, thanks to its hygroscopic properties, wood expands and shrinks as ambient humidity changes. One can therefore think of exploiting these properties for the control of hygrometric well-being in indoor environments [73, 74].

A typical example of hygroscopic behavior is showed by pine cones, whose scales bend due to the different reaction to moisture of the two tissues from which they are composed (fibres and sclereids) [75–78]. It is therefore possible to replicate these properties by making an artificial composite that takes advantage of the hygroscopicity and anisotropy of wood (active layer) combined with a material that does not react to moisture or has a lower hygroscopic expansion coefficient (passive layer). A single layer of wood will always show some degree of shrinkage/expansion proportionally to changes in moisture; by coupling it with a material that does not undergo deformation, its response can be pre-programmed in order to achieve the desired configuration at a given moisture content, and from a simple dimensional change will result in bending [79, 80]. The carried tests on various specimens with different configurations and characteristics were used to create a prototype of a modular ceiling panel which is pre-programmed to bend for relative humidity other than 40% (Fig. 5). Double-layered wood panels react passively to changes in humidity and, therefore they can be considered as low-cost, low environmental impact and technological

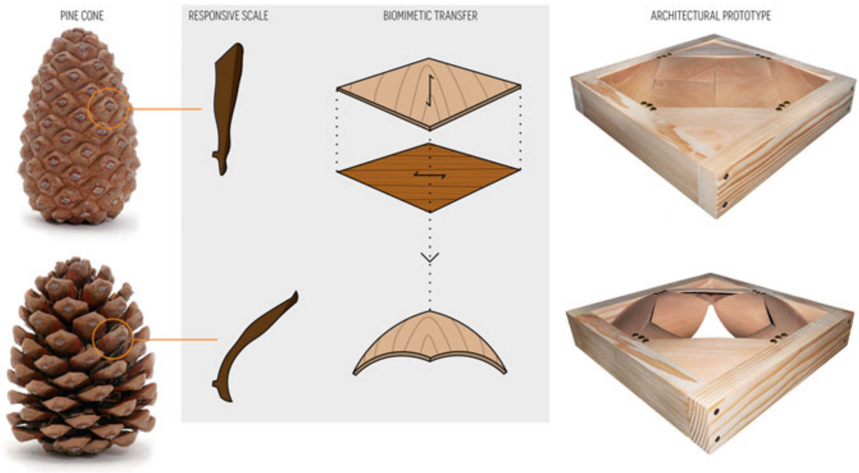


**Fig. 5** The biomimetic transfer of properties from the pine cone to an artificial prototype can be used in responsive architectures to passively react to humidity variations

elements that may be able to improve indoor hygrometric comfort without additional energy consumption. In particular, it is intended to propose a model of natural ventilation, complementary to the use of air conditioning systems, especially for the regulation of humidity, which is thus regulated thanks to bioclimatic principles that exploit the convective motions of warm and humid air and the chimney effect.

These principles and goals have since been transferred to the field of 4D printing [81–83] of wood-based filaments, joining the 3 dimensions in space with a fourth dimension, time which allows the composite to adapt to environmental humidity. Additive printing allows a total customization, making it possible to design the hygroscopic deformations. Using the commercially available filament LAYWOOD, composed of 40% recycled wood powder and 60% PLA (polylactic acid) [84], the direction of expansion of the composite is drawn by the deposition of the filament itself, which can then follow the desired pattern and result in complex deformations. Various printing properties radically affect the result obtained, from layer height to infill, feed rate to z-offset with respect to the printing plane, and so on. By varying these parameters, different curvatures and curvature velocities can be obtained for the same design (Fig. 6).

The production of multiple specimens to compare the hygroscopic deformations, both in natural and printed wood, and the research aim of applying these composites to the improvement of indoor well-being then led to the creation of a test room where these panels and optimized solutions for wood walls could be tested.

**Fig. 6** Different curvatures and velocity of curvature of similar 3D printed specimens with different printing properties

## *2.4 The Wooden Test Room*

Digitally optimized solutions as well as the idea of a "breathing house" involve multiple aspects that need to be analyzed but also verified. For this need, a temporary wooden test room was built at the Engineering Pole of the University of Perugia.

This structure was developed on a single level with Platform-Frame structure, of about 20 $m^2$ and average height 2.4 m, characterized by a glazed opening in the south direction. On the roof, about 15 $m^2$ of thin-film photovoltaic panels with a storage battery are needed for the heat pump, to cool and heat, simulating the winter and summer indoor thermo-hygrometric conditions typical of a residential environment. The north-facing wall is removable and can be replaced with other walls characterized by different stratigraphies.

The peculiarity of this Platform-Frame test room is that the monitored north-facing wall is removable for testing with different stratigraphies chosen from the various solutions optimized by the algorithm in the simulation phase. Monitoring was carried out through heat flux sensors, thermocouples, humidity and temperature probes during the summer period (Fig. 7). The acquired data were used for the determination of the in situ thermal transmittance to be compared with the one simulated by the algorithm, referring to UNI ISO 9869 [85], according to which it is possible to obtain the thermal resistance from the ratio of the summation of the surface temperature difference between outside and inside and the summation of heat fluxes.

Moisture-responsive wooden panels made of beech and larch wood were installed at the ceiling of the test room. Thanks to the convective motions of moist air rising toward the false ceiling, which causes the panels to bend due to the difference in humidity, air flows inside a cavity and is carried outside by exploiting the chimney effect.

Measurements were made on an optimized wall that best combines the most popular insulation materials on the market. Thermal transmittance was then calculated from the acquisitions, and considering the 10% uncertainty rate of the direct measurement, due to multiple factors, as well as the fact that the stated values of the


**Fig. 7** The test room has been designed and built to experiment in reality what had been digitally simulated, concerning in particular the responsive false ceiling and the optimized timber walls

thermal conductivities of the insulating materials also exhibit percentages of variability, it was concluded that the actual behavior is similar to that obtained from the simulations. The information is then returned from the built to the digital in the final section of the study, in order to build a real-time monitoring system of what is happening within the test room and integrate that data into the model, creating a digital twin in the BIM environment [86].

The test room certainly represents one of the clearest paradigms of a contemporary way of doing research, a space set up to transfer innovation to the market in which Abitare+ presents itself by offering innovative and performing solutions. At the end of this first part of the research it is interesting to highlight that the data acquired confirmed the reliability of the calculations made by the algorithm, with a small percentage of error due to field measurements.

## *2.5 Representation and Communication of the Optimized Models*

One of the key aspects of the research was the collection of data and its representation through ways that are accessible to everyone: the algorithms created have their own complexity and specificity so that even the company's engineers cannot manage the information. In fact, during optimization processes, a huge amount of data comes into play, and visualizing this data is crucial for understanding, comparing and sharing the results of the approach carried out.

In this context, the combination of data visualization became an effective way to enhance the decision-making process [87] while design space catalogs, which present a collection of different options for selection by a human designer, have become a commonplace in architecture in the perspective of the design democratisation [88]. The aim is to create an open source design [89–91] as meta-project for adaptable and mass customized housing [92]. The user interface developed in this research is based on Design Explorer, an open source project realized by CORE Studio Thornton Tomasetti, that allows to intuitively visualize and effectively navigate the design space of parametric models developed in Grasshopper, Dynamo, and Catia. These tools can support the designer in the complex problem-solving processes, through the combination of the designer's preferences with the great amount of information owned by modern construction companies, thus filling the gap between technological advances and design practice. Furthermore, their usability and effectiveness will grow along with advances in Building Information Modeling (BIM), performance simulations and parametric design and hopefully, in the next future, a similar data-driven approach will help the designer to deal with increasingly complex projects and achieve both performance and aesthetic expression.

For both the meta-planning solutions of the houses and the multi-objective optimizations of the walls, the same representative action was carried out, which allows the selection of parameter ranges for the different elements that characterize their geometry (Fig. 8). At the strategic level, the company then decided to make public the results of the mass customization of the houses while leaving for internal use the dynamic catalogs of the wall element combinations, which become a performance enhancement to the solutions of each house as a result of the executive design, in terms also of production, which the company refines at the end of the design phase.

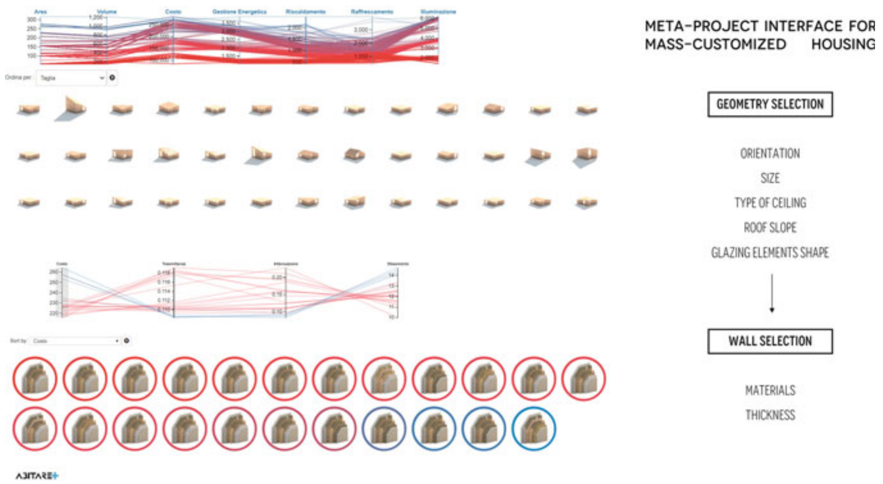


**Fig. 8** The web interface allows the users to select the optimal solutions, choosing the best geometries and walls depending on their performance requirements or budget

### 2.6 Representation and Communication of the Environmental Simulations

The data, analysis and the whole logic of performance and efficiency that is demanded of buildings today does not meet the needs of living. The design of the home must be communicated comprehensively to both engineers and clients. Technical drawings and renderings, which are the main tools for communicating design, do not guarantee customization, which instead is inherent in digital language.

The experience conducted is projected in the logic of the serious game [93–96], aimed at gathering information on the impact of simulations. In fact, the interaction between the user and the model is monitored by an analysis of the sensations related to the different configurations: in the interactive experience, sensors applied to the fingers are able to assess the galvanic skin response (GSR) [97–100] to pick up variations in its micro-sensation, including, for example, involvement and stress. This information, after the interactive visit, is cross-referenced with data collected "in game" regarding the user's location and point of view to understand what events triggered the changes recorded by the sensors.

In order to create a process of relations and communication between the user and the company, an immersive model was then created with the Unreal Engine graphics engine of a dwelling chosen from the optimized ones that is made interactive and customizable according to the client's needs.

Starting from the catalog shapes, transformed into a design, materials were applied and the interior of the building was enriched with furniture. In addition, some geometric variations to the morphology of the house were reproduced to create different configurations of the spaces to be made available later during the immersive experience. Thus, all the functions necessary for the different types of variations were programmed, as well as those that allow the user to move through the space, others for recording all the actions, movements and points in the scene on which the user focused most, the functions necessary to allow the execution of the experience with a VR visor and the logic related to the graphical interface. Finally, some numerical data and interactive graphs were included that adapt following the user's choices and describe the impact they have on some parameters related to the house (such as energy costs, construction costs, comfort parameters), with the aim of providing awareness of the effects of decisions (Fig. 9).

## 3 Conclusions

Wood constructions reverse some conceptions linked to the building processes proper to our architectural culture, which is deeply tied to craftsmanship. This issue concerns the transition between architecture and fabrication: concepts such as smart manufacturing [101], robotic fabrication [102] virtual prototyping [103], automatic rule-based design [104] and virtual building design [105] are rapidly reshaping the relationship


**Fig. 9** Starting from the design, the project can be 3D modelled and reproduced through virtual reality before the construction, to show the results and help in the decision-making phase

between architecture and construction, where we are increasingly seeing a direct transition from design to fabrication thanks to digitization and robotics [106].

Wood is naturally connected to the intelligence of biology [72]. It is a renewable resource [107] with an aesthetic value, workability, flexible, relatively light, versatility, low thermal conductivity, but it presents also undesirable characteristics for its sizing limits and deformations, anisotropy, hygroscopicity and degradation. Through its engineering aimed at the homogenization of its characteristics, wood represents a performing solution that integrates fabrication as a generative paradigm into the design process [108]. For these conditions, wood represents one of the most important field of application of parametric design [109–113] where "non-standard timber structures can be efficiently aggregated from a multitude of single timber members to foster highly versatile timber constructions" [114]. In hybridization and integration of digital wood design, the innovative tools involve a transformation of paradigm and form, connections and limits.

The processes of digitization and the value of digital techniques of representation are increasingly being contextualized in the innovations implemented in relation to the issues of contemporary building, many of which may find optimal solutions in wood. As a natural, sustainable, inexpensive, and extremely versatile material, wood is well suited not only for use as a material in construction, but also for experimenting with generative design and digital fabrication solutions.

The presented research ranges from multi-objective optimization of forms and construction details, to empirical research on responsive panels, and finally focus on forms of sharing and communicating the obtained results. The presented path thus describes the collaborative process implemented that has created a development of products, processes and services to meet the need for innovation that characterizes the new Industry 4.0 applied to architecture. The data and experiments are enriched with dynamic simulations in immersive reality, with the interactive variation of possible morphological and perceptual configurations, which can be used by the company to show the client the impact of the final project, reinforcing the full involvement of the end user, designer and/or owner, in the choices thus made aware of their impacts.

Representation presents itself as the field of existence of research: from design to construction, and beyond into the digital twin, drawing understood as a model is enhanced by the logics of digital. The transdisciplinary language of representation, open to different knowledges based on form, suited to bring out the underlying relationships, presents itself as the lifeblood of Industry 4.0 and the contemporary logics of doing architecture.

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# Technologies

# Visual Programming for Robot Control: Technology Transfer Between AEC and Industry

**Johannes Braumann, Karl Singline, and Martin Schwab**

**Abstract** For a long time, the construction sector has been considered a field with a low degree of digitization and automation with architects and designers looking for inspiration in other industries. Today, the construction sector is steadily innovating and automating, prompted by the lack of skilled labor. While robots are gradually starting to be used in situ for construction, robotic arms—also referred to as industrial robots—have already created new ways for the creative industries to develop innovative machinic processes at 1:1 scale. As the field of architecture eagerly moved towards robotics with an open mindset and little existing infrastructure or established protocols, architects and designers were quick to adapt the key themes of Industry 4.0 for their purposes. A core enabling factor has been the field's expertise in advanced, geometry-focused visual programming tools, which have since been adapted for robotic fabrication in order to enable individualized fabrication processes and mass customization. This chapter explores this development through several case studies and provides an outlook how visual programming and robotics may lead to a more sustainable, local, decentralized, and innovative post-industrial manufacturing in the creative industries and beyond.

**Keywords** Visual programming · Technology transfer · Creative industries · Robotic fabrication · Mass customization

**United Nations' Sustainable Development Goals** 9. Industry, Innovation and Infrastructure · 11. Sustainable Cities and Communities · 12. Responsible Consumption and Production

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_26

## 1 Introduction

For a long time, the construction sector has been considered a field with a low degree of digitization and automation [1], with architects and designers looking for inspiration in other industries. Today, the construction sector is steadily innovating and automating, prompted by the lack of skilled labor. While robots are gradually starting to be used in situ for construction, robotic arms—also referred to as industrial robots—have already created new ways for the creative industries to develop innovative machinic processes at 1:1 scale. Startups from the field of architecture are developing new additive fabrication technologies [2] or radically rethinking existing processes like shotcrete [3] while established construction companies innovate their fabrication workflows (Fig. 1). This innovation can partly be attributed to universities, where many architecture and design students are today exposed to those technologies during their studies.

This leap in competence, from a few key research institutions to a much wider range of users, coincided with the definition of Industry 4.0 at Hannover Fair 2011, as marked by the first conference on Robotic Fabrication in Architecture, Art, and Design, ROB|ARCH a year later in 2012.

As the field of architecture eagerly moved towards robotics with an open mindset and little existing infrastructure or established protocols, architects and designers were quick to adapt the key themes of Industry 4.0 for their purposes.

**Fig. 1** Large-scale robotic fabrication process defined in a visual programming environment at ZÜBLIN Timber, Germany

This chapter traces the connection between Industry 4.0 and robotic fabrication in architecture, with a specific focus on the role of visual, flow-based programming as a driver for algorithmic thinking, resulting in innovative robotic fabrication workflows that are today also increasingly adopted by other industries.

## 2 Industry 4.0

### *2.1 Individualization*

While research into robotic fabrication in architecture has been ongoing since as early as the 1980s [4] the results of that research did not reach the larger community of the creative industry but was primarily rooted in academic research and engineering applications. Now in the fourth industrial revolution, innovative architectural applications using robotic arms are no longer just trailing the perfectly orchestrated mass-fabrication in industry but matching or even exceeding the state of the art of industry regarding individualization and mass-customization.

While the "smart factory" as the overlaying idea of Industry 4.0 does not directly apply to many architectural applications, it contains a range of sub-topics that strongly resonate with the creative industries. Custom manufacturing enables individualization and small lot sizes, while digital twins facilitate process simulation and rapid (design) iterations.

An enabling factor for that development can be found in the repurposing of digital tools originating from the creative industries for automation and robotics, which allow architects and designers to apply their deep knowledge and understanding of working with small lot sizes to the—for them—still new field of robotics, particularly robotic arms, or industrial robots.

The development and repurposing of tools has become important because while individualization is of course actively used in industry for a variety of applications [5], these developments are mostly built on custom, purpose-built software, rather than accessible programming environments. Though there are commercial software packages for a variety of tasks like milling, 3D printing, 3D scanning, etc., they only cover the most common, commercially relevant robotic tasks.

### *2.2 Digital Twin*

Currently, a main selling point of industrial manufacturing software is the digital twin, which promises to speed up the development of new production processes as well as the quality of their output by enabling an accurate simulation of entire production lines.

When looking closer at these processes, it becomes apparent that while their scale and orchestration makes them highly complex, the individual actions making up those processes are often comparably simple, moving elements from A to B, performing spot welding, or dispensing glue along a curve.

The limitations of digital twins become apparent once non-standard processes are involved that go beyond the state of the art. Even industrially applied processes like fused filament fabrication still cannot be efficiently simulated due to the complex interactions of heat and material [6]. Thus, these fabrication processes rely on their software making viable assumptions about the process parameters, along with the process expertise of the machine operator that is often the results of years or decades of working with a given manufacturing method (Fig. 2).

### *2.3 Collaboration*

However, when working with completely new processes, no viable assumptions or simulation frameworks yet exist. In industry, interdisciplinary teams solve these challenges in a collaborative approach with each discipline contributing their expertise, from geometry to material to robotics. This approach can also be seen in the early robotics projects in the field of architecture, where mathematicians collaborated with architects to realize complex brick stacking patterns [7].

Beyond large-scale industry, it often is not feasible for smaller enterprises, especially in the creative industries, to assemble interdisciplinary teams, instead having to rely on the local process experts with a deep understanding of a given material, but less programming and robotics expertise.

Geometry-focused, visual programming like McNeel Grasshopper and Autodesk Dynamo today provides a pathway for these user groups to apply their process knowledge to a robotic process through an accessible, responsive interfaces that fosters experimentation and by design facilitates iteration and individualization.

## 3 Visual Programming

Today, visual or flow-based programming is often associated with "low-code" [8] strategies that make complex processes accessible to non-experts, such as allowing designers to create complex, parametric geometries [9] or non-coders to automate processes and workflows [10]. However, visual programming is today also frequently used in industry, from complex factory automation to the definition of robotic processes.

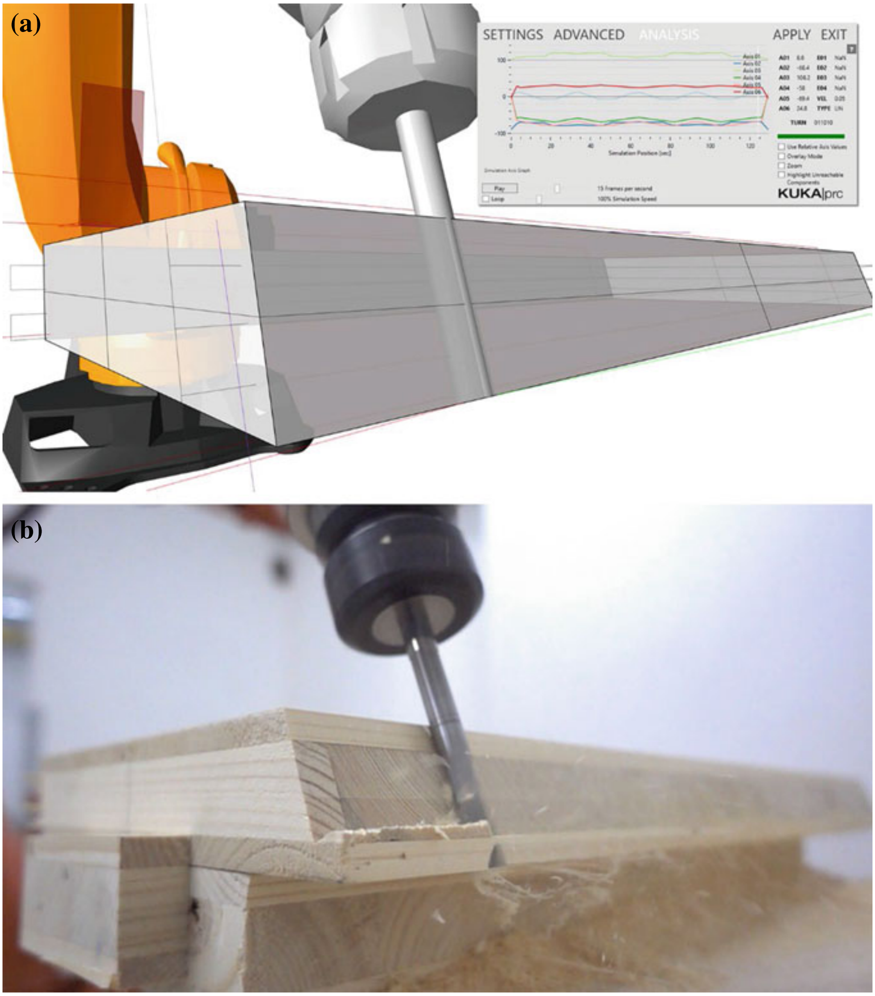


**Fig. 2** Digital, idealized representation of a robotic milling process (Fig. 2a), actual complexity of timber as a cross-laminated, anisotropic material (Fig. 2b)

### *3.1 Visual Programming in Industry*

The underlying programming paradigm of flow-based programming was first developed by Morrison [11] in the late 60 s for IBM, building upon the concept of co-routines that was sketched out even earlier [12].

The concept of flow-based programming is that the process of programming does not happen in a textual, but in a graphical way. This often results in a flowchart-like appearance, where modules, containing certain functionality or processes, are connected via lines or arrows, thus defining their parametric relationship (Fig. 3, left).

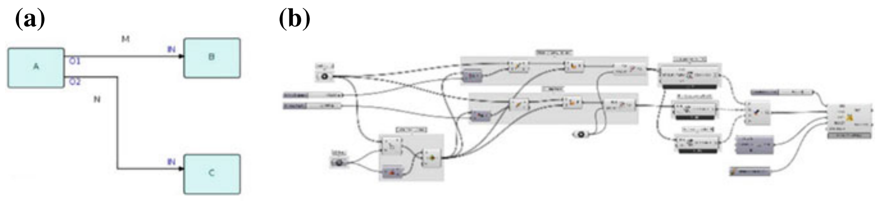


**Fig. 3** Flow-based programming by Morrison dating back to the 60 s (Fig. 3a). CAD-oriented visual programming through McNeel Grasshopper (Fig. 3b)

Within the area of robotics, a basic visual programming language for PLCs is the Function Block Diagram (FBD) which was standardized as part of IEC 1131–3 [13] and allows the user to e.g. create individual functions via ST (Structured Text) and then make them more easily useable via the graphical representation as a FBD.

More recently there has been a large number of new, visual programming environments presented within the scope of industrial robots, such as drag&bot [14], Fox|Core by Faude, and the Desk software used to program Franka Emika robots, all of which are running within the browser. Within the greater area of robotic research there are also educational environments like Scratch [15] and Blockly, whose block-based visual programming has been expanded to include industrial robots [16–18].

These environments are highly flexible and can be used to program a wide variety of tasks, even allowing the easy integration of a wide array of external sensors and data sources. However, their primary use-cases can be found in the area of pick-and-place, bin picking and assembly, as they lack CAD integration and more complex geometric functionality that would be needed to e.g., derive toolpaths from an imported surface geometry.

## *3.2 Visual Programming in Architecture, Art, and Design*

Geometry-focused approaches towards visual programming are instead often found in the creative industry. Users in the field of architecture and design utilize tools such as McNeel Grasshopper and Autodesk Dynamo to define parametric objects, artists create real-time visualization and digital art through VVVV and Max/MSP and entire video games are developed through Unreal Blueprints and Unity Visual Scripting. In the area of 3D-modelling, visual programming has been pioneered for the definition of photorealistic materials, defining how different textures are blended and linked via a node-based system, but has since been expanded to geometric operations, e.g. via Blender Animation Nodes, XPresso, Houdini and others.

A fundamental difference in these systems is whether they are real-time based or not. Programs like VVVV, but also FBDs in PLCs, are generally running in real-time, i.e., the graph is constantly being refreshed at a high rate, ideally at 60 Hz for live-visuals and potentially much more frequently for PLC-programs that might be triggered every millisecond or less, for 1000 Hz and more.

CAD-oriented programming environments like Grasshopper (Fig. 3, right) on the other hand are optimized for longer-running, more complex processes and by default not constantly updating: operations are represented as function blocks with inputs on the left and outputs on the right side, creating a directed, acyclic graph. Only when an input changes, the downstream components refresh automatically to reflect the change in input values, creating a highly reactive system that lends itself to a very intuitive interaction with data and geometry. Commonly, such function blocks include geometric operations like e.g., creating a point out of three numeric values representing its XYZ coordinates, but through plugins like KUKA|prc, HAL, RoboDK, and Robots, the range of function blocks can be expanded to include robotic fabrication, thus for example defining the robot's programmed position through a coordinate system.

### *3.3 Towards Robotics*

Since 2007 Grasshopper has established itself as the core platform for applications utilizing industrial robots within the field of architecture and design. There are several advantages of using such a platform for robotic processes: Geometry and toolpath strategies can be generated at the same time, so that it is possible to intelligently have the geometry respect certain fabrication-related parameters, while the fabrication-related data can be automatically assigned to the relevant geometric features. This automatically translates both into the potential to be used for the automated batch-generation for mass-customization, as well as providing immediate feedback on the feasibility of the developed fabrication process, thus speeding up the learning process for new users. Furthermore, as the user is defining their own fabrication strategy, the potential scope of robotic fabrication is expanded beyond the functionality offered by CAM software such as milling, wire-erosion and plasma cutting.

### *3.4 Limitations*

However, going beyond the state of the art also leads to an increased complexity for the user, as the development of such strategies requires both in-depth robotic knowledge, as well as material expertise and proficiency with the visual programming environment. Unlike many CAM environments, visual programming frameworks generally offer little official documentation and training, instead relying on third party and community-led initiatives.

A related general criticism of flow-based visual programming in Grasshopper by Davis et al. [19] is the lack of modularization to facilitate efficient code re-use as well the infrequent use of clearly named parameters.

Integrated development environments (IDE) for text-based programming like Microsoft Visual Studio support the user in creating a clear and easily readable syntax, often offering refactored code automatically. This process is based on consistent coding conventions for programming languages, which do not yet exist for visual programming.

Finally, especially within the scope of robotic fabrication, a limitation of CAD-oriented flow-based programming environments is that while they are very efficient in defining data flows, they are less optimized for process flows, i.e., conditional clauses, parallel processes [20]. This can be especially an issue for flexible fabrication processes that incorporate sensors and feedback loops (see Sect. 4.2).

## 4 Robotic Workflows and Dataflows

### *4.1 Defining a Robotic Process*

A core appeal of using robotic arms lies in the abstraction of complexity. Rather than having to design and fabricate a bespoke, complex machine, robotic arms instead allow users to deploy an extremely reliable, well-tested and readily available manipulator, that then must be equipped with a suitable tool to perform a given task. The robot therefore forms the basis of a larger, robotic setup (Fig. 4). While they may not reach the level of performance of a purpose-built machine [21], their capabilities generally exceed the tolerances required at construction sites.

Their programming consists mostly of a sequence of movement commands and IO operations, structured by conditionals and logical expressions. A movement command defines where to move in relation to the current position of the robot,

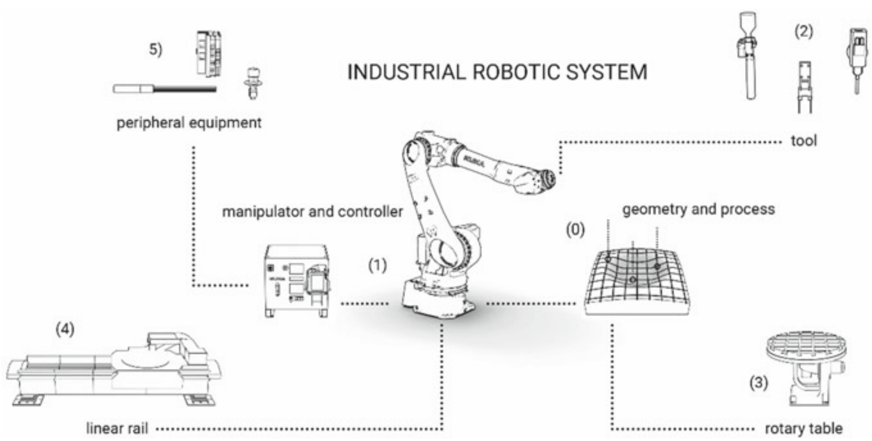


**Fig. 4** Overview industrial robotic system—schematic layout for robot-based fabrication

the speed of the movement, and how to interpolate between the current and subsequent position. The robot's position can either be expressed in axis values, with a numerical value corresponding to each of its degrees of freedom, or in a Cartesian format, expressing a coordinate system through an XYZ coordinate and three Euler angles ABC in the case of KUKA robots. Common interpolation methods are linear interpolation, that moves in a straight line, circular interpolation that creates an arc through an auxiliary point, and point-to-point interpolation that interpolates at the axis level, creating a highly efficient trajectory.

## *4.2 Robotic Fabrication Through Visual Programming*

In a visual programming environment, these movements can be represented by individual nodes. In most robotics-focused, accessible programming environments, the axis values or Cartesian position of the robot's tool is extracted from the current position of the—simulated or real—robotic arm. Therefore, the robot is moved, the position saved, and then the process repeated until the final program exists—similar to teaching by demonstration [22] done on a physical robot, but through the flow-based programming with an easier control over the structure of a program.

Within a geometry-focused visual programming environment like Grasshopper, the toolpath logic can be extracted from the underlying geometry: A NURBS curve is projected onto a free-formed surface and then segmented into a series of point objects. Based on the parametrization of the surface closest to each point, a coordinate system is defined. Along with a numerical value for the movement speed, each coordinate system results a linear movement, that is then traced by the robot, moving along the given surface while keeping the tool axis perpendicular to it.

To achieve a reliable simulation, the entire robotic setup must be known: As there are barely any standardized tools for industrial robots, calibration of each tool is required so that the robot is aware of the position and orientation of the tool center point in relation to the robot's flange. Similarly, local coordinate systems are defined in relation to the robot's world coordinate system—commonly at its base—to define the program origin and orientation. This modularity can also be well represented in a visual programming environment, coupling the robot node with different tools or external equipment to define the so-called robot cell. The typical setup for robot-based manufacturing shown in Fig. 4 consists of the product and associated geometry and process parameters (0), the industrial robot unit consisting of manipulator and controller (1), the end effector—with tools like gripper, extruder or spindle (2), a static or dynamic base for the workpiece—e.g. a rotary table for increased reachability (3), a static or dynamic robot foundation—e.g. a linear rail for expanding the working volume (4) and peripheral elements like industrial control systems, sensors, actuators and safety equipment (5).

### *4.3 Dataflows for Robotic Fabrication*

Having both the accurate robotic setup and the parametric design within a single environment allows architects and designers to constrain the toolpath generation to parametric geometry, automatically creating an individual robot control data file for each design variation and thus fostering individualization.

Thus, a robotic process in a geometry-focused visual programming environment commonly consists of three parts (Fig. 5): The generation of the parametric geometry, the extraction of toolpaths, most commonly as sets of coordinate systems, and finally the robotic simulation and code generation. This sequence forms a directed graph where the user can easily interact with a complex, parametric system that covers both design and fabrication. Once a process is free of collisions and other problems, the resulting file can be copied to the robot, or streamed to the robot in real-time.

As geometry-focused visual programming environments create acyclic, directed graphs, they are best suited for bringing parametric designs to fabrication. However, fabrication processes that incorporate sensor feedback or user interaction are challenging to represent within such a system, as it becomes necessary to differentiate between data flow and process flow. This can be achieved implementing behavior models like state machines. Recent projects have implemented Unity Visual Scripting for that purpose as it differentiates between flow-graphs—creating similar graphs like Grasshopper—and state graphs—controlling the process flow from one state to another, e.g., informed by user interaction [20].

Due to the flexibility of the paradigm of visual programming, it has become the predominant way of programming applications that go beyond the state of the art in robotic fabrication in the creative industry, at academia and startups as well as within the established industry.

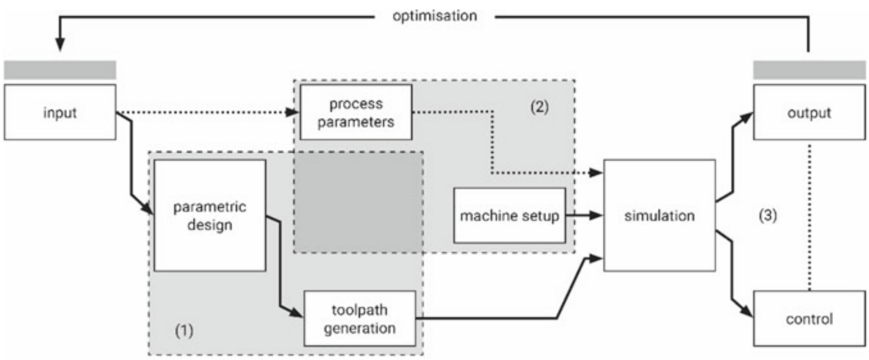


**Fig. 5** Schematic workflow diagram—visual programming setup for robot-based fabrication: (1) parametric design and toolpath generation (2) digital representation of physical machine setup and process parameters (3) simulation, code generation and manual interpretation

# 5 Case Studies

This section provides an overview of innovative robotic applications within the field of architecture, where visual programming has become a core enabling factor for the realization of innovative processes. From large-scale, multinational construction companies to architectural offices, innovative construction startups and the wide dissemination at maker spaces.

## *5.1 Architecture and Design Office: Matter Make, Malta*

Located on the island country of Malta, holistic design, and fabrication studio Matter Make identified the complexity of operating within the disconnected region regarding the lack of easy access to building materials (Fig. 6). This absence of access to a singular raw material led them to reconsider traditional architectural and interior design techniques and incorporate a workflow built upon a flexible visual programming as a core component of their working environment focused on complete processes based on the products available for import.

This approach prompted Matter Make to add value through means of design creativity that was supported by the novel workflow and flexibility of an industrial robotic arm which allowed a range of materials and processes. This meant projects could differ vastly between materials such as copper to plywood to high density foam without requiring additional software or equipment.

Within their visual programming environment, the same digital model is created and evolved from initial conception through to finalized design form can feature layered data of varying complexities which is used for a multitude of tasks such as quantifying a bill of materials, while simultaneously generating toolpaths required to produce their designs robotically.

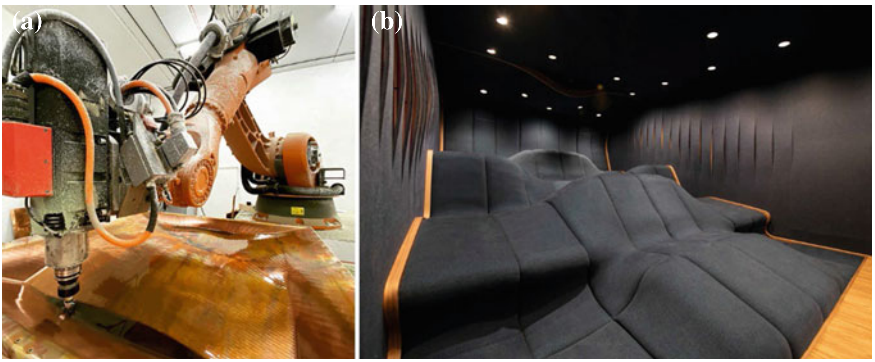


**Fig. 6** Robotic incremental sheet forming of copper (Fig. 6a), free-formed home theatre by Matter Make (Fig. 6b)

**Fig. 7** Large-scale robotically fabricated timber formwork for free-formed concrete columns

### *5.2 Large-Scale Construction Company: ZÜBLIN Timber, Germany*

ZÜBLIN Timber is a leading timber construction company based in Germany that has worked on high-end projects such as the Metropol Parasol in Sevilla and Stuttgart 21 in Germany (Fig. 7). A pioneer in robotic fabrication in architecture, ZÜBLIN Timber set up their first robotic timber fabrication setup already in 1995 and has since upgraded it to be able to cover $160m^2$ with a large robot and two linear axes.

ZÜBLIN Timber uses visual programming in-house for both general production preparation and the definition of robotic processes. This facilitates the integration of advanced algorithms coming from architects and fabrication consultation offices and greatly streamlines the workflow from design to production: Where parametric geometry is often reduced to plan drawings that are then manually processed at the fabricator, ZÜBLIN Timber can keep the entire process within a single environment.

### *5.3 Construction Startup: REPRECT, Austria*

Austrian based start-up, Reprect, is a research and development group with a focus on innovating precast concrete through adaptation of novel technologies. In 2020 Reprect explored the challenges and advantages of that the introduction of an industrial six-axis robotic arm could be for digital fabrication across multiple aspects of precast concrete manufacturing techniques. This was completed over several steps: research into existing workflows for traditional precast concrete fabrication, identifying key areas where automation could play a significant role and frameworks that would be required to support such an integration.

A significant challenge was the countless variables introduced when handling custom building components, rarely were two precast elements identical. To ensure the workflow was feasible, it had to accommodate precast panels of various dimensions, penetrations, and modifications: horizontal and vertical drilling, surface milling and contouring. The visual programming environment Grasshopper was used for its ability to process traditional CAD data that was combined with domain-specific meta-data in the form of a JSON file. Based on that, toolpaths are calculated to provide visual feedback in the form of a full robotic simulation almost immediately. This research resulted in a software solution was designed to allow for the growth of projects without a requirement of significant retooling.

### *5.4 Education*

Educational institutions take up a central role in the popularization of new technologies. Within the field of construction robotics, there are now dedicated Master programs at several universities such as RWTH Aachen, ICD Stuttgart and ETH Zurich where visual programming is used as a core tool to get students exposed to robotics.

A different approach is to specifically use robotics as a cross-sectional, interdisciplinary tool that can be applied in a wide variety of creative disciplines. At the research department Creative Robotics in Linz, Austria, students from a variety of programs such as architecture, industrial design, fashion, and interactive media take robotic courses where they are encouraged to apply robotic technologies within their own field of expertise.

Visual programming environments like Grasshopper and Unity Visual Scripting are therefore taught to students with widely varying degrees of experience in working with CAD software and digital software tools. Through that, robotics and visual programming put together become an interface that encourages interdisciplinary collaboration and experimentation, that has already resulted in several startups, such as Print-a-Drink for robotically fabricated cocktails and YOKAI Studios for innovative textile processes (Fig. 8, left). Research-led teaching also contributed to experimental projects like a mobile 3D-printing platform that was exhibited at the Ars Electronica Festival (Fig. 8, right).

That process is facilitated by the close collaboration of Creative Robotics with the Grand Garage, Europe’s largest maker space, embedding academic research in a semi-public environment that encourages interdisciplinary thinking.

### *5.5 Case Study Summary*

In summary, the collated projects described above demonstrate the discrete capabilities of incorporating visual programming and automation techniques already utilized in industry 4.0 within a contrasting range of architectural and related fields, from education to small bespoke design and large-scale fabrication for construction.


**Fig. 8** Education resulting in student-led startups, like YOKAI Studios in the field of fashion and textiles (Fig. 8a), research-led teaching for the "Wandering Factory" at Ars Electronica Festival (Fig. 8b)

Although each case study is operating at a distinct scale and output, all actively demonstrate capabilities for non-standardized and mass customization construction methods facilitated by robotics that was previously deemed unavailable due to economic and efficacy constraints [23].

## 6 Outlook

The field of architecture has taken a pioneering role in the rapid adoption of robotic technology, questioning established standards and through that realizing advanced applications that have also caught the eyes of industry. While the ultimate goal of an automated construction site still lies in the future, current projects with industrial robots have moved beyond academic research, towards creating the foundation for innovative startups in the fields of architecture and design.

An enabling factor for this process has been the critical mass of users within architecture and design, often in academia, who have laid a foundation of knowledge for new users to build upon. Achieving this critical mass can at least partly be attributed to the development of domain-specific visual programming tools that allowed architects and designers to build upon their existing knowledge of parametric and generative design but expand it to cover also robotic fabrication. This can be seen as a testament to the efficiency of peer-to-peer teaching for knowledge transfer between different fields.

Other fields in the creative industries, such as fashion and textiles or crafts, are also starting to increasingly adopt digitization and concepts of Industry 4.0. However, their fundamental knowledge as well as their goals and the scale and valorization of their output differ significantly from architecture and design. It will therefore be necessary to adapt and modify the workflows and dataflows developed by architects and designs, towards again creating bespoke, domain-specific tools that have the potential of greatly accelerating the adoption and integration of new technologies.

The underlying technologies for simulation and control can be maintained, requiring mostly the interaction metaphors and concepts, including the degree of abstraction, to be adapted to new user groups. Building on the current approach of linking functional elements that often represent only basic geometrical methods, reduced workflows can be developed that group functionalities (Fig. 9) and automatically assign data to the correct inputs and outputs, guided by intelligent assistant systems. Having a clearly defined data structure opens possibilities for an accessible, automated optimization of robotic process parameters that can consider the individual degrees of freedom provided by each production process.

This reduction in complexity and scope enables new users to focus on the domain-specific input and associated process parameters, while providing them with a pathway to extend their level of control over a process by interacting with the underlying building blocks.

Ultimately, robotics combined with powerful and accessible tools for robot programming offers startups the potential to create highly innovative, disruptive applications, but also gives the much wider field of smaller architectural offices the possibility to take control of the fabrication process with the potential to realize high-end construction processes that strongly incorporate individualization, thus bridging the gap to much larger architecture and construction firms that employ specialized, interdisciplinary teams to fabricate their designs.

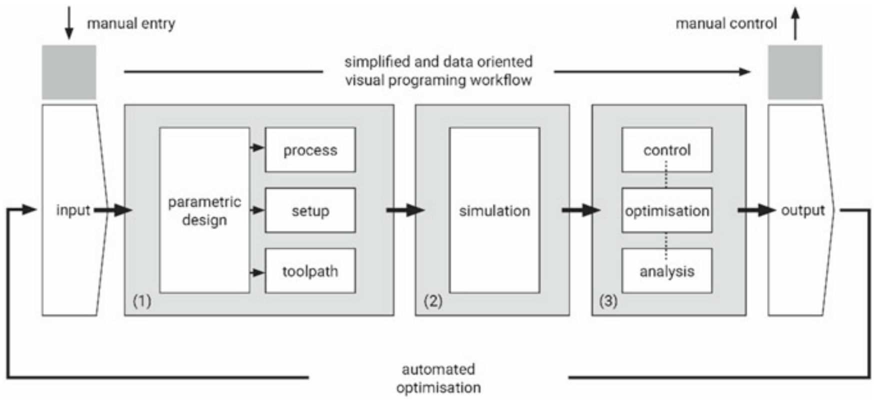


**Fig. 9** Outlook for data-based workflow approaches: design-based geometry and process parameter generation (1) process related simulation (2) computer-aided analysis and automated optimization for design and process adjustment (3)

When looking at the impact of digital fabrication combined with visual programming on a higher level, the increasing accessibility of customization and multi-level-optimization leads to a potential reduction of energy consumption and use of resources whereas the low system costs enable and support a return to local and decentralized production.

By combining high flexibility with scalability, we expect individualized robotic fabrication informed by visual programming to support the creation of sustainable and innovative post-industrial manufacturing, in architecture and beyond.

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# Design, Robotic Fabrication and Augmented Construction of Low-Carbon Concrete Slabs Through Field-Based Reaction–Diffusion

**Roberto Naboni, Alessandro Zomparelli, Anja Kunic, and Luca Breseghello**

**Abstract** Constructions have a tremendous impact on global warming and are responsible for 39% of annual carbon emissions. Designers will increasingly focus on developing design methods and solutions that mitigate the impact of buildings over the next few years. Accordingly, this chapter focuses on developing an accessible computational design method to investigate the design, engineering and construction of ribbed concrete slabs with low levels of embodied carbon by minimising the use of structural materials, maximising bending resistance and surface area for recarbonation through convoluted geometry. We discuss using a Reaction–Diffusion system for performance-driven generative structural design, informed by the outputs of Finite Element Analysis in the form of scalar and vector fields. To streamline the production of geometrically complex slabs, a field-based robotic milling approach is introduced to process styrofoam concrete formworks. Mixed Reality is used to assist construction operations and realise non-standard rebar reinforcements. The results consist of proof-of-concept ribbed-slab prototypes characterised by structural efficiency, high resolution, and low-machining time.

**Keywords** Computational design · Robotic milling · Mixed reality · Reaction–diffusion · Field-based design · Finite element analysis · Concrete slabs · Low-carbon

**United Nations' Sustainable Development Goals** 12. Responsible consumption and production

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_27

# 1 Introduction

The climate emergency has radically shifted our architecture, design and construction priorities. The mitigation of climate change is a fundamental planetary goal for the survival of our ecosystem [14]. As a reflection of this, the design focus for architects and engineers is moving towards reducing embodied carbon associated with the life cycle of building materials and structures. Carbon dioxide emissions (CO2) from the manufacturing process of buildings, including material extraction, transportation, fabrication, installation, operations and end-of-life, account for 49% of the total carbon emissions from new construction [18]. Among all building materials, concrete is still necessary to fulfil the need for construction over the following decades, already being the most used material in the world after water [19]. This extensive use of concrete significantly impacts GHG, being responsible for about 8% of global emissions [7]. Replacing structural concrete with more sustainable materials is currently not a realistic and scalable option. Designing novel structures requires embodied carbon reductions through advanced design optimisation in this context. Contemporary Construction 4.0 technologies offer vast opportunities for achieving such a goal [13]. In particular through the combined use of (i) data-driven generative design; (ii) computationally-driven design to fabrication workflows that enable strategic use of building materials; (iii) smart digital twins that streamline robotic construction and Mixed Reality (MR and enhance the level of functional integration across phases. This chapter discusses integrating such features in the context of advanced structural geometry, characterised by high material efficiency and low embodied carbon.

# 2 Carbon-Driven Design for Horizontal Structures. Precedents and State-Of-Art

Horizontal structures, such as slabs, beams and roof elements that carry perpendicular loads to their longitudinal direction, constitute about 43% of the total use of structural concrete in buildings [3]. Minimising such structures' carbon impact is critical in achieving sustainable construction, as recent studies have documented [6, 9, 10 ]. At SDU CREATE, we conducted a study on the cradle-to-cradle life-cycle assessment of 3D concrete printed beams [8], where we formulated a design strategy for achieving carbon-efficient design: maximising bending resistance, minimising the use of material (reduction of cement and steel reinforcement), maximising the surface area of concrete for recarbonation [5]. This design rationale provides a framework for exploring geometrically convoluted ribbed slabs, where material and structural efficiency is synergistically tackled. Historically, the design of such structures has been studied in connection with the use of Principle Moment Lines (PML). In 1951, Pierluigi Nervi designed the wool-factory building *Lanificio Gatti*, where a pre-compressed concrete slab was reinforced using ribbed reinforcements along the direction of primary and secondary PML [1]. A similar approach was later used to design the zoology hall at the University of Freiburg, a large-span building that was efficiently constructed with this principle [2]. More recently, the integration of Finite Element Analysis (FEA) and parametric modelling environments has allowed more accessible access to such structural patterns. However, existing workflows do not support a straightforward translation of structural analysis into structural shapes. In a recent study, we demonstrated a method to generate lightweight 3D concrete printed beam elements using PML to inform the planning of a continuous printing path. Tan and Muller (2015) developed an approach to overcome common software's inconsistent generation of stress and moment lines. In this chapter, we focus on an alternative approach, where PML and other structural analyses inform the emergent shape generation of ribbed slabs, leading to an interactive exploration of efficient structural patterns.

## 3 Approach and Methods

One of SDU CREATE´s areas of expertise is formulating computational workflows for carbon-efficient design. The opportunities for data-driven structural morphogenesis based on FE have been discussed in multiple studies from SDU CREATE [4, 11, 12]. To render such investigations more accessible, we recently conceived a field-based approach for automating the design and fabrication of concrete slab structures (Fig. 1).

This approach analyses structural, morphological and functional properties with a set of 2D plots. These are collected as multilayer performance maps, representing scalar and vector fields. We introduce a Reaction–Diffusion (RD) system to read,

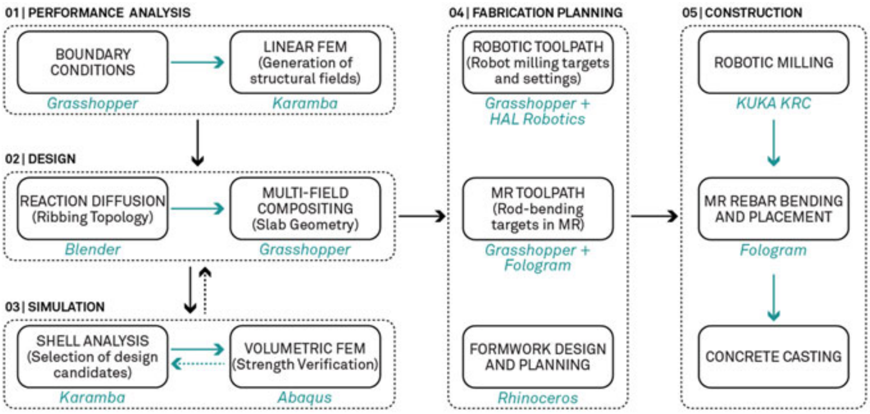


**Fig. 1** Software pipeline for field-based design and fabrication of concrete ribbed-slabs

interpret and react to such fields and output the underlying patterns to generate three-dimensional ribbed slabs. This avoids inflexible parametric modelling operations, which limit the exploration of topologically diverse design options.

# 4 Simulation and Field-Based Design

## *4.1 Generation of Structural Fields*

A computational design pipeline was developed to explore different loading and support scenarios for a 20 by 10 m rectangular slab. Starting from given input 2D shapes, the loading and support boundary conditions, and given material properties, a linear FEA was run using Karamba for Grasshopper [15]. The analysis includes primary and secondary PMLs, intensity, and sign information. Moment principals show the direction of the highest and lowest moment of inertia along the analysed surface. Through a custom exporter which translates mesh face properties into RGB colours, a series of 2D maps were stored for the following steps of the design work-flow: (i) two maps of primary and secondary moment vectors directions, where the red (R and (G channels correspond to X and Y directions of the vectors; (ii) two grayscale scalar maps showing the absolute values of the moment intensities; (iii) two grayscale scalar maps outlining the sign of the principal moments, i.e. whether it is positive or negative (Fig. 2). The analyses were applied onto two different slab cases: (01) four-point supports placed at an offset from the perimeters; (02) two diagonal linear supports evenly placed along the two axes of the rectangular slab. Both elements are calculated with their self-load and a distributed load equivalent to 6 kN/m$^2$.

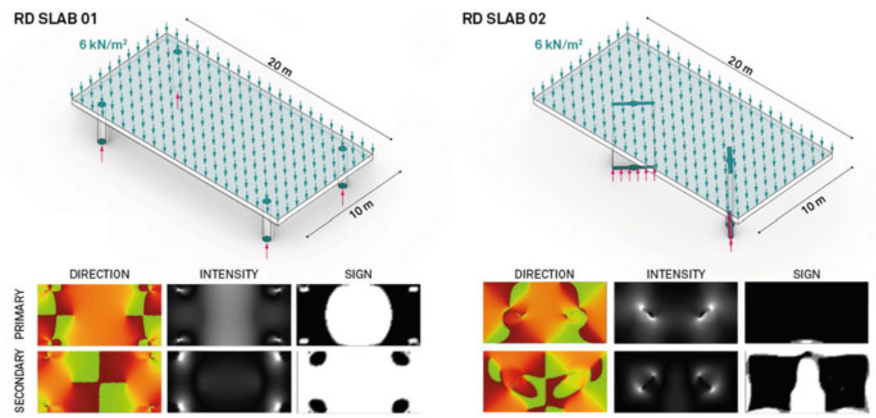


**Fig. 2** Slabs' boundary conditions and field maps for the primary and secondary PML

## 5 Isostatics Structural Patterns with Reaction–Diffusion

In this phase, structural patterns for a ribbed slab are found with a Reaction–Diffusion (RD) system. In conventional structural design, topology and load paths for a ribbed slab are determined case by case using parametric modelling with relatively low flexibility. In our approach, an RD system was developed as a generative tool for quickly and interactively exploring isostatic structural patterns which adapt to the provided input fields. RD algorithms reproduce the chemical reaction of two or more substances spreading along a surface at a different rate [17]. When in contact, the two substances react by altering their concentration values. An anisotropic version of the Gray-Scott model was deployed to describe the variation over the time of the two substances according to parameters $F$ and $k$, representing respectively the *feed* and *kill* values:

$$\frac{\partial A}{\partial t} = Diff_A \nabla^2 A - AB^2 + F(1 - A),$$
$$\frac{\partial B}{\partial t} = Diff_B \nabla^2 B - AB^2 + (F + k)B.$$

The variation of these parameters generates a highly varied range of patterns, including continuous, closed cellular, maze-like networks, and dotted configurations (Fig. 3). In this work, the growth of an RD is controlled using input fields from the preliminary structural analysis and general design to manufacturing considerations. In particular, the system needs to allow (1) the control of the directionality according to principal moments direction; (2) the variation of density according to moment intensity; (3) the dimensional control of individual rib elements according to construction and fabrication constraints. To do so, vector maps describing the principal moment curves and the scalar map of moment intensity were used to control the direction (laplacian) and diffusion rate of a pattern (F, k, and scale), respectively, obtaining anisotropic and variably dense patterns that were used as structural geometry (Fig. 4).

Using a Graphical User Interface (GUI), the students were to experiment and generate different patterns according to input images and tune the pattern scaling. The process was applied for primary and secondary principal moments to generate perpendicular ribs. Additionally, secondary design elements such as holes can be explored using additional grey-scale fields, controlling $F$ and $k$, or used as an inlet or outlet for one of the two substances. With this exploration phase, recurrent patterns have been identified.

The anisotropic RD behaviour converges to some dominant configurations according to the parameters $F$ and $k$. Independent longitudinal structural elements and a network of longitudinal structural elements (they could also be seen as one the negative of the other). For structural continuity, the network is considered a more convenient choice (Fig. 5).

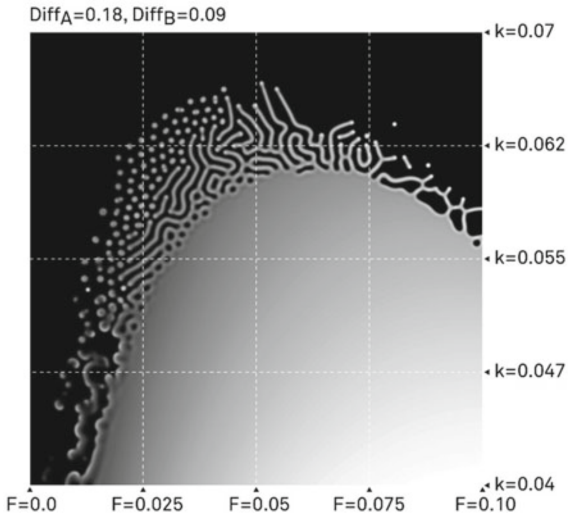


**Fig. 3** Emerging RD patterns from variations of *F* and *k* parameters

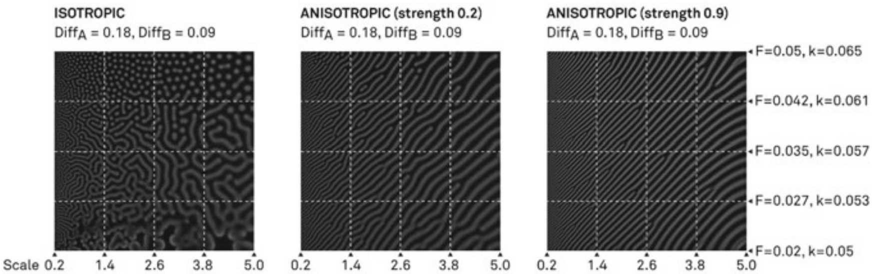


**Fig. 4** Comparison between isotropic and anisotropic growth in the employed RD

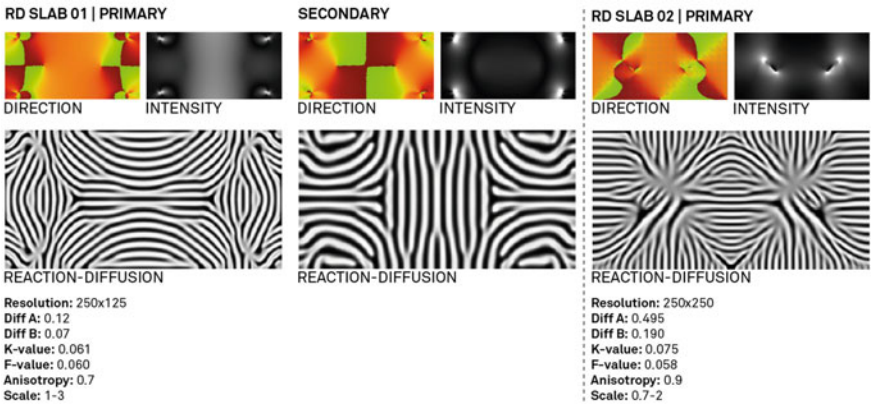


**Fig. 5** Selected ribbing patterns for RD Slab 01 (two ways) and RD Slab 02

## 6 Multi-field Design Compositing

In this phase, the three-dimensional geometry of ribbed slabs was obtained by combining the previously collected information layers. Scalar 2D maps representing design elements, structural data, and RD patterns are combined into a single height map with a compositing method for generating the slab geometry. The RD pattern was used to create a series of ribbed elements in the slab´s bottom surface to resist the tensional component induced by the bending moment. The ribs´ cross-section shape was tuned mathematically through function curves according to the size of reinforcements and needed concrete cover. The ribs´ sectional height (H) for the primary ribs was parameterised according to the moment intensity (I) to obtain a sufficient moment of inertia for any given point moment in the slab without the need for additional steel reinforcements. This is achieved with the following formulation H = RD*I*T. For the case of a two-way ribbed slab, the secondary ribs´ sectional height was parametrised on a different layer. Afterwards, the information on the cross-section height for primary and secondary ribs was combined using the maximum value at every point of the slab: $h = \max(h_1, h_2)$. The map-based compositing for the supports provided a mathematical control for the transition among the various slab parts (Fig. 6).

## 7 Structural Feedback and Simulation

Volumetric FEA was run in Abaqus to verify the outcomes of the design optimisation process and compare them to non-optimised slabs with the same boundary conditions and weight. The analysis tested the slabs at their Ultimate Limit State (ULS) for a distributed load of 6 $kN/m^2$. The two slab prototypes proved a reduction of the weight-to-displacement ratio of 33 and 37.5%, respectively.

## 8 Robotic Fabrication and Augmented Construction

### *8.1 Field-Based Robotic Milling of Complex Molding*

Robotic CNC milling was used to manufacture styrofoam moulds bypassing conventional CAD/CAM processors. Various milling strategies were developed parametrically and tested for 7-axis robotic milling to minimise the processing time. Two main strategies were investigated. In the first one, the heightmap obtained from the multi-layer compositing method was used to determine tool orientation, density/resolution of the machining steps and the nature of robot motion (e.g. continuous/punctual). On the other hand, the second strategy started from a mesh geometry generated from the compositing, which was further processed to achieve different surface finishing

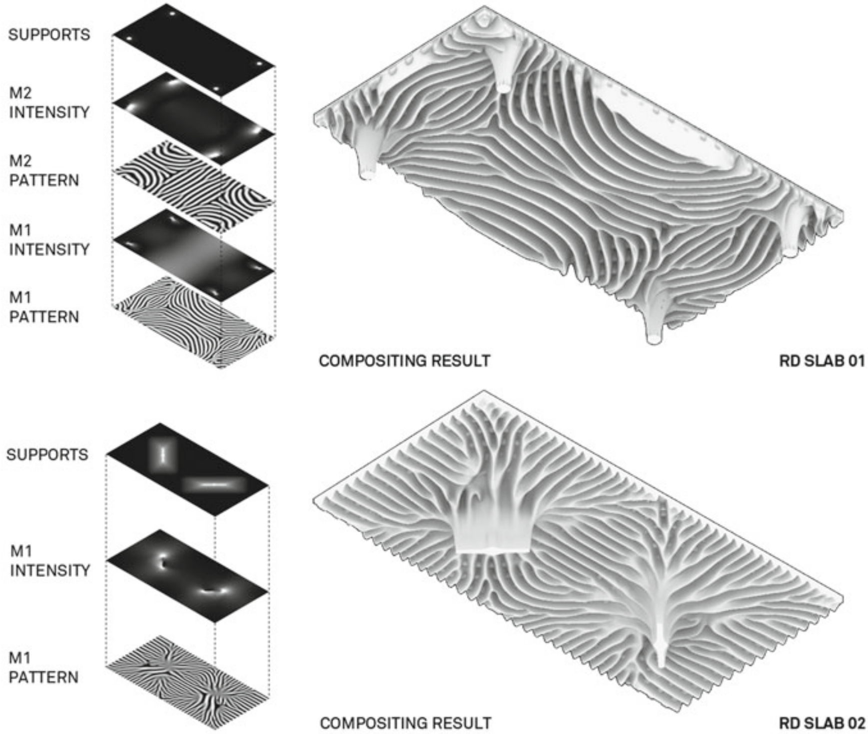


**Fig. 6** The variable geometry of the slabs is controlled by the combined values of various maps

patterns. The tool was oriented vertically, while angle and milling resolution were the focus parameters in the contouring method. Initial toolpath explorations involved small-scale experiments performed on 20 by 20 cm specimens, which were evaluated in terms of production time, kinematics, and visual features. Five methods were studied: (1) *punch-milling* with variable tool inclination and punch depth informed by the composited maps (Fig. 7a); (2) *blading* through a path informed by the composited maps (Fig. 7b), and through the same path manipulated with sinusoidal function; (3) *parallel contouring* following 45 and 90 degrees angles with different milling resolution/overstep distance (3-8 mm) (Fig. 7c) and manipulated toolpath by application of sinusoidal functions along Z and XY plane orientations; (4) *geodesic offset contouring* to optimise the milling resolution in relation to the geometry and (5) *perpendicular contouring* to the structural ribs, performed as a continuous zig-zag toolpath. After these initial tests, the *geodesic offset contouring* and *perpendicular contouring* strategies were selected to fabricate the two slabs on a scale of 1:10. They have been considered a mid-way solution between the faster toolpaths, which compromised geometric complexity and formal precision such as blading, and highly detailed but time-consuming punch-milling tool-paths.

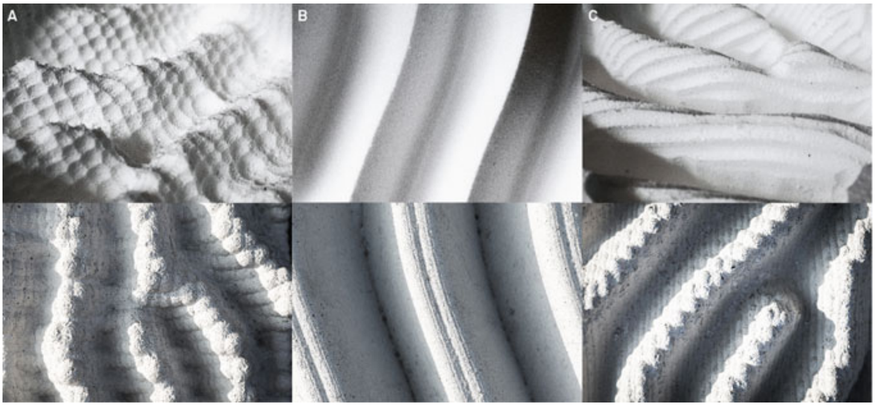


**Fig. 7** Top–Robotically fabricated styrofoam formworks with different milling strategies; Bottom–Cast concrete panels

**RD Slab 01–Geodesic offset contouring**. A shell mesh geometry was used to generate geodesic contours with a 10 mm offset, originating from the support points and propagating towards the centre of the slab. The obtained three-dimensional curves are then translated into robotic target frames with a point distance of 5 mm (Fig. 8).

**RD Slab 02–Contouring perpendicular to structural ribs**. For the second slab, the medial axis of each structural rib was extracted from the Voronoi skeleton of the RD pattern. For each region, it is then created a continuous zig-zag pattern perpendicular to the medial axis following the ribs' slopes. The distance between the perpendicular milling paths was set to 10 mm, along which robot target frames were generated at a distance of 5 mm, keeping the same resolution settings as the first slab (Fig. 9).

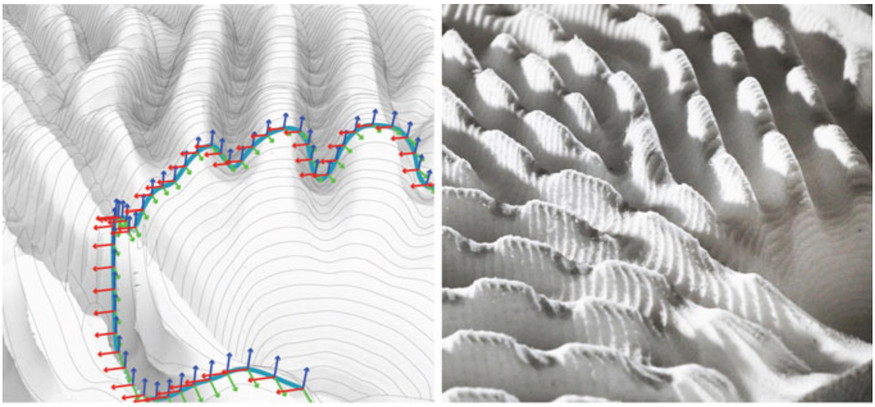

**Fig. 8** Left: Robotic toolpath for geodesic offset contouring of RD Slab 01 and mesh visualisation of the milled EPS formwork; Right: Image of the milled EPS formwork

**Fig. 9** Left: Robotic toolpath for the contouring perpendicular to structural ribs of RD Slab 02 and mesh visualisation of the milled EPS formwork; Right: Image of a milled EPS formwork

## 9 Mixed Reality Bending of Reinforcement Bars

Although the provision of reinforcement bars was not necessary according to the FEA, minimal longitudinal and transversal reinforcement was included to obtain ductile structural behaviour. This was achieved by placing (i) one 4 × 50x50mm BST-500 mesh and (ii) 6 mm B550 reinforcement bars. The reinforcement layout for the individual bars was derived from an analysis of tensional areas of the RD structural patterns. This resulted in a complex three-dimensional curve network. MR allowed the user to bend and check the individual reinforcement bars quickly, a crucial pre-assembly step to ensure that parts fit together as intended. Mixed Reality (MR) was adopted to efficiently achieve the accurate bending of 3D rebars, which was manually executed with the help of a manual rebar bending device (Fig. 10). Bending sequences were communicated to users wearing a Microsoft HoloLens 2, which was a guide for manually bending the bars into their positions.

## 10 Robotic Fabrication and Concrete Casting

The used robotic setup is a KUKA KR240 R3330 industrial robot installed on a six-metre long linear unit equipped with a 12 kW rotary spindle holding a foam rasp cutter of 20 mm diameter and 300 mm length (Fig. 11). The formwork consisted of two glued 1200 × 1200 × 275 mm EPS 150 blocks. It was laterally restrained to a steel welding table. Both formworks were fabricated with a spindle speed of 4500 RPM and a feed rate of 450 mm/s, resulting in an average fabrication time of around four hours. The milled formworks were lightly sanded to remove residual burrs and to prepare the surfaces for applying protective coatings. A single layer

**Fig. 10** Three-dimensional rebar bending in MR

of a water-based paint primer was sprayed onto the milled surface. This provided a smooth surface for applying a wax release agent and waterproofing the formwork for the casting process.

Once the surface dried, the formwork was prepared for casting by installing the bent rebars (Fig. 12), steel mesh and other 3D-printed connections for transportation. Both slabs were cast with Hi-Con UHPC having a characteristic compressive strength ($F_{ck}$) of 127 MPa. The material was prepared in 300-L batches and mixed for six minutes before being poured into the formwork. The self-compacting properties of the concrete ensured that the intricate details of mould were covered in concrete without vibration. The prototypes were left to air-cure for approximately 24 h before being de-moulded.

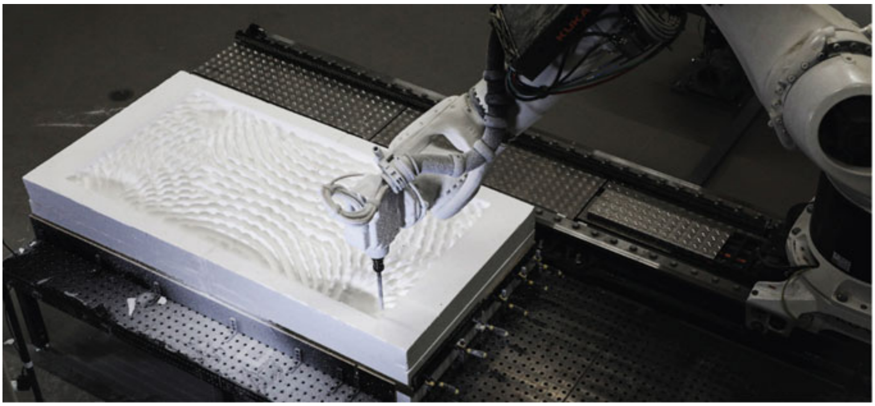

**Fig. 11** Robotic milling of the styrofoam formworks for RD Slab 01

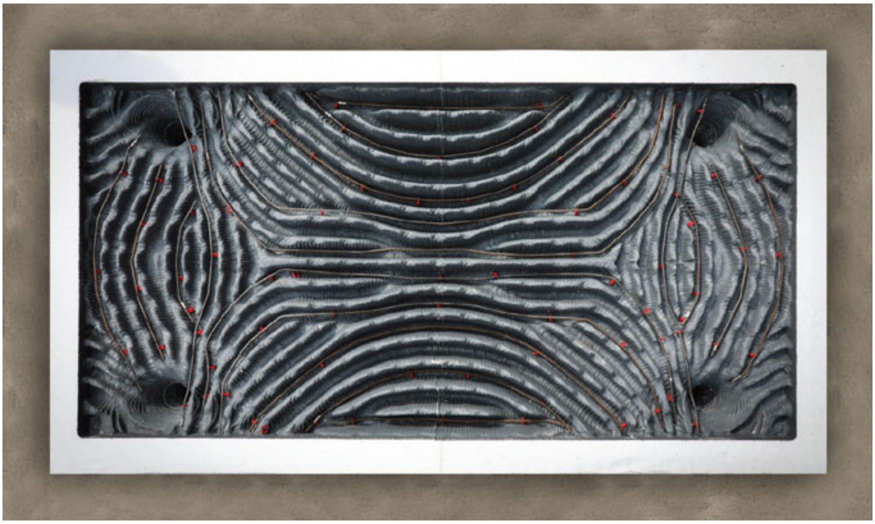

**Fig. 12** Coated formwork of RD Slab 01 with 3D bent rebars in MR

## 11 Results and Discussion

Reducing embodied carbon in reinforced concrete structures is a priority for architectural designers and engineers nowadays. Radical design approaches are required to achieve sustainable targets at a global scale. Construction 4.0 principles and technologies are supporting this paradigm shift by: (i) enabling the automation of complex design operations; (ii) promoting data-driven design with early-stage structural analysis to embed fundamental engineering notions at the concept level; (iii) introducing generative design methods to effectively explore efficient design solutions; (iiii) computational design and fabrication tools becoming more accessible to architects, structural engineers, integrated designers, construction engineers.

The chapter discusses these topics, focusing on experimental activities conducted for designing and engineering ribbed concrete slabs. Several innovative features were presented. Anisotropic RD was employed for the first time to explore structural patterns interactively. Scalar and vector fields in the form of image maps were used to exchange performance data across simulation and modelling software in a synthetic format and drive structural and milling explorations. A software pipeline that connects structural analysis, generative design, robotic fabrication, and MR construction was presented. The pipeline was developed and tested during the SDU CREATE´s summer school in Experimental Architecture (2022) with students from architecture, civil engineering, integrated design, and mechanical engineering who could easily engage with complex design/engineering and fabrication tasks. Two scaled prototypes (Fig. 13) were engineered, manufactured, and successfully tested with non-linear FEA and non-destructive structural tests. The outputs show a previously unseen ribbed slab typology, which combines material and embodied carbon

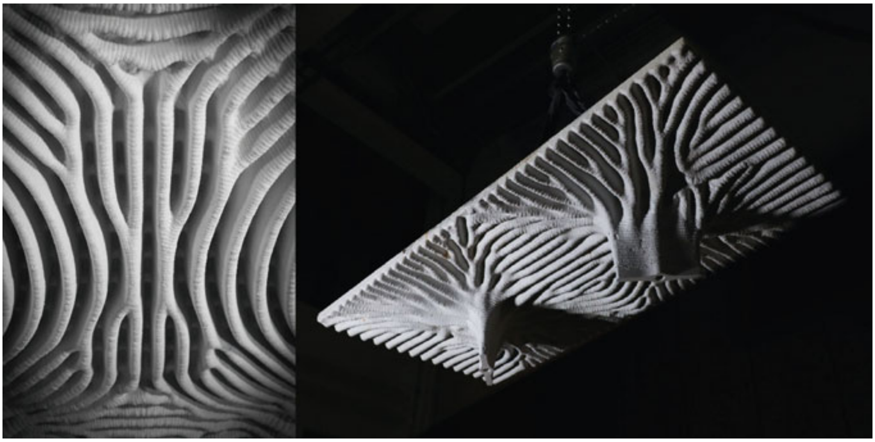

**Fig. 13** Close-up view of RD Slab 01 (left) and global view of RD Slab 02 (right)

reduction with distinct aesthetics. Future work will further investigate the opportunities this approach opened, including an evaluation of its acoustics behaviour for future construction applications.

**Acknowledgements** The work described in this chapter was developed during the Experimental Architecture X Robotic Milling Strategies−SDU CREATE Summer School 2022 (8-21 August).−Organised by CREATE − Led by Assoc. Prof. Dr. Roberto Naboni, University of Southern Denmark (SDU). Teaching team: Roberto Naboni, Alessandro Zomparelli, Luca Breseghello, Anja Kunic, Hamed Hajikarimian. Software Partner: Karamba3D (parametric engineering). Material Partners: Hi-Con (UHPFC), Teknos and Lakkgruppen (coating material). Students: Ahmed Mosallam, Boas Olesen, Cecilia Rask, Christian Jørgensen, Christina Jensen, Elma Ramic, Esben Kay, Eyjolfur Logason, Oscar Oweson, Julia Przado, Kate Heywood, Marie-Louise Merser, Mathias Nielsen, Nanna Larsen, Nicolas Ortiz, Nikolaj Rytter, Omar Rawashdeh, Paula Riehn, Rikke Ejlersen, Sara Sander, Sofie Skov-Carlsen, Steen Hansen, Viktor Hansen.

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# Digitally Designed Stone Sculpting for Robotic Fabrication

**Shayani Fernando, Jose Luis García del Castillo y López, Matt Jezyk, and Michael Stradley**

**Abstract** In this chapter, we present case studies in digitally aided marble sculpting for robotic fabrication developed at the Digital Stone Project workshop. The residency brings together artists, architects, designers, researchers and technologists engaging in state-of-the-art digital tools for the realization of innovative works of art in stone. These projects were developed during the Digital Stone Project research residency during 2013 to 2018 and showcase the potential of novel input methodologies to drive creative processes in design, architecture and the arts. The case studies demonstrate both conceptual and technological development in the design process through 3D modelling, scanning and fabrication workflows, developing toolpaths, virtual reality, haptic interaction and reversible construction techniques. The chapter examines the value of robotic technologies in the design and construction process relative to collaborative crafting of the hand and machine. Accommodating for material tolerances and interrogating the implications of computational crafting in relation to Industry 4.0 and exploring the role of the artisan in machine crafted architectural components.

**Keywords** Digital Stone · Structural Design · Robotic Crafting · Workflows · Sustainability

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_28

**United Nations' Sustainable Development Goals** 9. Industry, Innovation, and Infrastructure · 11. Sustainable Cities and Communities · 12. Responsible Consumption and Production

## 1 Introduction

Exploration in robotic fabrication has seen a remarkable development in the last decade, particularly in the field of architecture. The democratization of Computer-Aided Design (CAD) to Computer-Aided Manufacturing (CAM) tools led to novel inquiries into the affordances of industrial robotic arms in mass-customization work-flows, and their role as potential "all-purpose fabrication machines." Such renewed interest led to an explosion of research in the field, enabled by the proliferation of dedicated robotic fabrication shops in architecture schools around the globe as well as specific conferences on the topic [1].

However, it could be argued that, with exceptions, the limitations of conducting robotic fabrication in non-industrial contexts may have biased most of the current research to a particular set of outcomes. On one hand, the additional facility requirements to conduct subtractive manufacturing–ventilation, debris disposal, safety measures–may have favored explorations on additive manufacturing, such as 3D printing or assembly operations. Comparably, the costly tooling necessary to perform intense milling operations on harder materials such as stone or metal could have resulted in work focusing on softer substrates such as wood, foam or fresh clay. Consequently, certain forms of robotic fabrication, such as stone carving, have not had the opportunity to be broadly explored.

Intriguingly, the stone carving industry is itself currently undergoing its own new Renaissance, this time powered by the skill of industrial robots [2]. An increasing number of companies now rely on CAD/CAM workflows and robotic fabrication to accelerate their production and remain competitive in a market where material and labor costs are continuously on the rise [3]. Nevertheless, a large portion of their art-oriented production is geared toward the reproduction of existing physical models, typically relying on 3D scan-to-milling processes. The industrial nature of these fabrication processes, combined with the technical literacy necessary to harness the computational frameworks driving it, constitutes a large entry barrier for designers and artists hoping to explore the creative space afforded by these technologies.

### *1.1 The Digital Stone Project*

The Digital Stone Project [4] and Garfagnana Innovazione [5] are a collaborative team to bring together artists, architects, educators and students from across the globe to the historic Garfagnana region of Italy to work with high technology and ancient

Tuscan stone. Over the course of a month each participant produces a sculpture or prototype that is carved with a 7-axis robot arm and finished by hand.

This collaboration between designers, technologists and the advanced technology facility at Garfagnana Innovazione has exciting implications for the future of architecture, sculpture and digitally aided design and manufacture. The artists and architects collaborated with robotics engineer Gabriel Ferri to create the computational data that drive the robotic cutting arm. This way of working represents the pinnacle of current manufacturing capability joined with computer aided design (CAD).

Originally designed for automotive and aerospace manufacture, these robots have been coopted to re-invigorate the declining stone industry in the Garfagnana region and to reintroduce the skills associated with marble sculpture [6]. The work includes projects made with generative design, 3D scanning, and 3D programs in animation, CAD (computer aided design), and CAM (computer aided manufacture). Participants wrote algorithms to create the designs for carving or developed projects through interactive computer design programs such as Rhinoceros 3D, Grasshopper, Cinema 4D, 3D Studio Max, and ZBrush.

The work produced in the Digital Stone Project residencies reveals how the development of CAD/CAM and robotics digital manufacturing technologies has helped to reduce the disparity between the geometric forms able to be generated using modern design software, compared to the methods of materializing the outcome. This chapter aims to describe the design and manufacturing processes through 6 case studies of prototypes produced during 2013 to 2018. They explore minimal surfaces, non-standard tool paths, interlocking joinery systems and integrated scanning to milling.

During the DSP residencies one of the greatest challenges facing the engineers to fabricate the digital models is translating the artist's idea into stone through the machine. According to Gabriel Ferri, robotics engineer at Garfagnana Innovazione (2022), "since the idea itself is not linked to the material many times it must be adapted to respect the physical limits of the stone. Finding a compromise between the three parts (1) artist's idea, (2) physical limit of the stone and (3) physical limit of the machine, is the main challenge. To address these challenges the digital stone processing facilities has several resources to help enable and develop solutions. They are described in the following.

### *1.2 Digital Stone Processing*

The state-of-the-art facilities at Garfagnana Innovazione have assisted the participants of the residencies to realise their projects efficiently and in a resourceful manner. The main hardware used is described in the following [7]:

**Robotized 3D scanner** High performance instrument, suitable to scan both outdoors and indoors. Due to its laser technology, it can reconstruct 3D solid models starting from objects with every form, dimension and complexity. The extreme precision in the survey of points and surfaces assure an exact reconstruction of the scanned object. This instrument, born from 100% Italian research (CNR), can be used manually like a common 3D scanner, but also in synergy with their anthropomorphic robots gaining the skill, unique in this sector, of reconstructing clouds of points independently, without further actions needed on the digital realignment of the scanned model.

**Anthropomorphic robots** Two robotized stations with two high precision anthropomorphic robots (7 interpolated axes) are the state of the art of technology for the stone processing. The vast working area, up to 2.5 m of height, allow the creation of big and full-round works. Besides the large variety of tools for the processing of every type of marble and stone, there is also the possibility to work materials for the rapid prototyping: plastics, polystyrene, resins, etc. These machines, together with their powerful software, can perform complex operations with extreme efficiency: the results of the creation of human or abstract figures are qualitatively excellent. Progressing from the scale model (created on a PC) to the final realization is now more efficient.

**CNC work center** CNC work center (5 interpolated axes) to work with blocks, solids and marble slabs, granite, natural stone veneer and glass. It makes every kind of drilling, milling, cutting with blades, contouring, shaping, recessing, polishing, carving, engraving, chamfering, 3d writing and processing. With one of the biggest working areas available, this machine can make big lots with precision and high rapidity.

These facilities have remained for the last few years. According to Gabriel Ferri (2022), while no new tools have been developed, new finishing procedures have been created as a result of the workshop residencies. For example, in the work of Jon Isherwood, "He is very attracted to the gesture of manual finishing, so we tried to translate the human gesture into code for the robot in order to replicate the movements that leave the desired mark on the stone [8]." The workflows are directly impacted by the type of project and will be explained in detail in the case studies. As Ferri states, "Perhaps more than the machines in recent years we have witnessed an evolution of the software. And I believe that in the next few years it will evolve even more because as a user I recognize that there are still many gaps and room for improvement." The following will describe case study projects and concepts by participants of the Digital Stone Project workshops. These specific projects were chosen for their innovative design to production methodologies specifically relating to the field of construction and Industry 4.0 in the creation of bespoke architectural components. The projects will be discussed in relation to **project concepts, digital design workflows, tools and techniques**.

## 2 Minimal Surface Geometries

The first case study project concept uses Minimal Surfaces which are a class of geometric surfaces characterized as having minimal surface area for a given boundary. The classic example is the surface formed by a soap film stretched between a boundary frame [9]. In mathematics, minimal surfaces are defined as 'surfaces with zero mean curvature" [10]. Zero mean curvature can best be understood as any point on a surface where the lines of principle curvature are equal and opposite. It is possible to compute minimal surfaces like the Catenoid and Helicoid based on parametric equations.

Computational optimization and dynamic relaxation techniques can be used to find minimal energy states for these types of surfaces, instead of generating from a mathematical equation. Interestingly there is a strong correlation between the minimal energy states found computationally via optimization and physical, empirically derived forms [11]. It can be observed these minimal surfaces are operating purely in tension. This study is quite similar to catenary curves found in 'hanging chain' models. This makes minimal surfaces also very relevant in the study of tensile fabric structures. It also makes minimal surfaces relevant to the study of forms operation purely in compression, in the form of free-form grids shell structures [12].

The Costa Minimal Surface was discovered relatively recently by Celso José da Costa, a Brazilian mathematician and is used in Case Study 1. The Costa Minimal Surface is rather like a Mobius Strip or a Klein Bottle, where the delineation between the outer and inner surfaces starts to blend. "The Costa surface is a complete minimal embedded surface of finite topology (i.e., it has no boundary and does not intersect itself… Until this surface was discovered by Costa (1984), the only other known complete minimal embeddable surfaces in R^3 with no self-intersections were the plane (genus 0), catenoid (genus 0 with two punctures), and helicoid (genus 0 with two punctures), and it was conjectured that these were the only such surfaces" [13].

## *2.1 Case Study 1–Costa Minimal Surface (2014)*

This project, titled Costa Minimal Surface [14], was designed and fabricated as part of the Digital Stone Project in 2014. Previous research had been conducted in the digital fabrication of tensile structures as well as compression structures. In many of these cases, computational design, simulation and optimization techniques were used to create a digital design, and then computer numerically controlled (CNC) equipment was used to fabricate the final shape. In Case Study 1, a design was created to explore minimal surface geometry using marble instead of in tensile fabric materials. There were three main goals for the design and fabrication of this case study:

**Design**: From a design perspective, the goal was to explore the interplay between the thinness of these minimal surface 'soap bubble' geometries, contrasted with the heavy materiality of stone. It was also very important to ensure the smooth surface continuity was maintained, to help the observer understand the smooth, sensuous curves of the Costa surface geometry.

**Simulation/Computation**: Case Study 1 required the development of specialized software to support the simulation, analysis and fabrication of the piece. The goal was to create a parametric design workflow to find the desired geometric form in terms of sculptural qualities in order to achieve the design goals above, then support a seamless process of converting the geometry into CNC code able to be executed on the 7-axis industrial arms.

**Fabrication**: There was also the technical challenge of milling the stone to follow the smooth, thin surfaces of these geometries. It was unknown exactly how thinly the stone could be milled, and if these doubly curved surface topologies could be expressed in stone at all. It was desired to obtain a slightly translucent material quality in the marble, yet still retain the overall structural integrity of the piece by virtue of the fully in compression structural nature of the minimal surface. How the anisotropic nature of marble would interact with the thin shell geometry was also an unknown.

During the design process for Case Study 1, many mathematical surfaces were explored. The Costa Minimal Surface was found to be most suitable for this type of sculpture, given the constraints on the size of the piece and the available fabrication techniques. The software Mathematica [15] was used to explore the surface domain and generate the geometry (see Fig. 1). Online examples for how to compute the Costa function in Mathematica were referenced [16] (Fig. 2)

A usable geometric mesh needed to be computed from the smooth analytic surface. A grid of points was evaluated in the UV parameter space of the surface and then

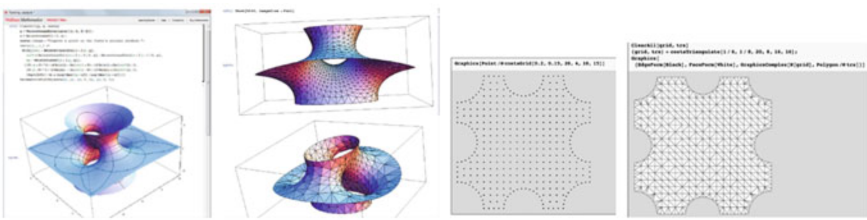

**Fig. 1** Left–Mathematica Software was used to plot the surface–Further refinement of the domain of the surface, Middle Right–Computing the UV Grid [16] Right–Triangulation of surface via the UV grid [16]

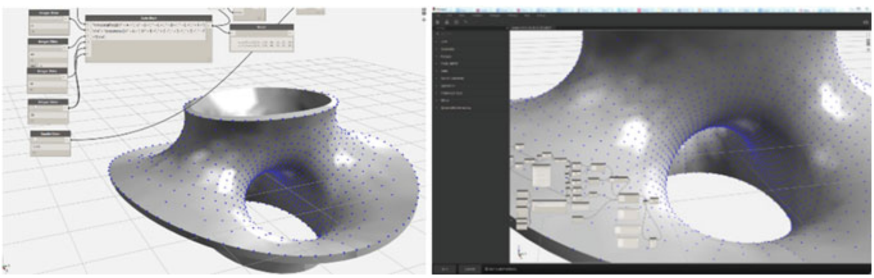

**Fig. 2** Left–Dynamo Computational Design Software was used to parametrically control the design–simulation loop with Mathematica, Right–Plotting the UV points in Dynamo, refining the edge treatments

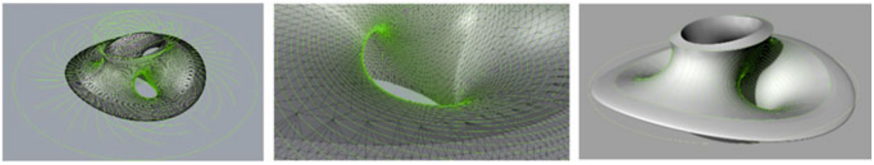

**Fig. 3** Left–NURBS curves based on the UV parameterization. Middle–Close up showing relationship between the UV parameterization and the meshed surface geometry Right–The final design geometry

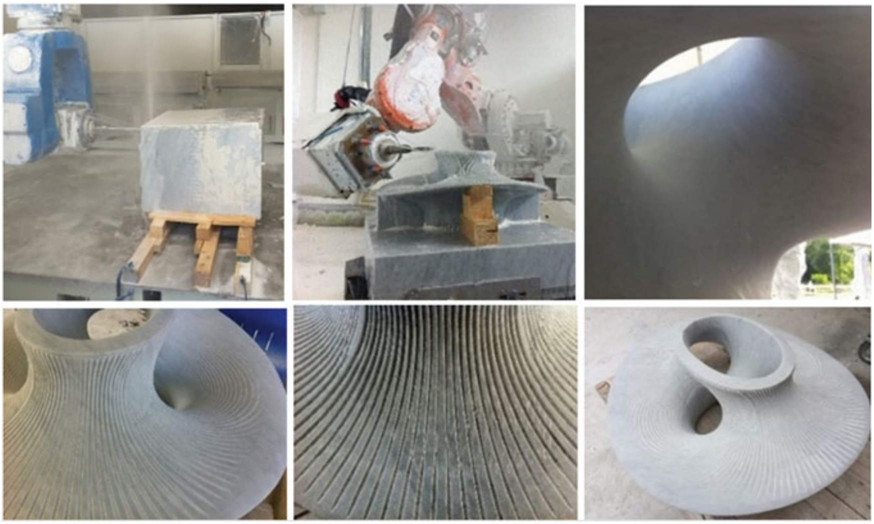

**Fig. 4** Top: left–fabrication rough block middle–fabrication detail, right–smooth surface, bottom: left: UV lines on surface, middle- UV lines close up, right: final sculpture

used to construct a mesh. Online examples were referenced and modified extensively [16]. The software Dynamo (an open-source visual programming tool) was used to create the overall parametric design, simulation and fabrication loop. An open-source Dynamo C# software plugin called DynamoMathematica [18] was developed and used to set input parameters and send data to Mathematica. Once the form was simulated, the geometric mesh was sent back to Dynamo. Special functions needed to be developed in Mathematica to compute the normals for this non-trivial surface. [17] The Dynamo script used the normal to allow thickening the meshed surface and creating NURBS curves based on the UV parameterization (green lines below, see Fig. 3).

The milling toolpaths were created and then run on a 7-axis ABB robot in the mountains of Tuscany as part of the Digital Stone Project at Garfagnana Innovazione. Custom CNC G-Code was developed by Gabriel Ferri to allow the UV lines of ruling to be carved into the surface. The piece was finished by hand using various chisels, grinders and sanding equipment. The following images (see Fig. 4) show the fabrication method and final milled sculpture.

# 3 Interlocking Joinery Systems Based on Catenary Geometry

The following will describe a joinery system exploring Catenary geometry and is inspired and developed by hanging chain models and catenoids, which are explained in the previous case study the Costa Minimal Surface. However, the design intention of this system was to utilize dry joint connections with interlocking wave geometry. While case study 2—Catenary Tales explores the potential tensile forces of the interlocking wave joinery system, Case study 3— Archi-Twist' investigates structural stability through the twisted interlocking wave joint.

The waveform prototype joint design was developed through a process of iterative drawing which was then parametrised in Rhino 3D and GRASSHOPPER. One of the most significant aspects of this geometry is that it is made from 'ruled surfaces' to accommodate fabrication methods with robotic wire cutting. As a comparison study into EPS foam blocks and natural stone blocks [19] two similar geometries were fabricated with Gosford quarries in Sydney. This prototype demonstrates both potential for column and cantilever structural conditions without the use of extra connectors or mortar, demonstrating reversible construction methods.

## *3.1 Case Study 2—Catenary Tales (2015)*

The concept for the development of 'Catenary Tales' (2015) [21] stemmed from an exploration of self-supporting structures in natural stone. The sculptural prototype is made from interlocking wave joinery in varying sizes of modules which engages with the tensile strength of stone. The production process involved the design using 3D modelling software Rhino 3D and manufactured as part of the DSP workshop.

A combination of machined and hand finishes were applied (see Fig. 5) to the sculptural prototype. The overall dimensions are 38 × 36 × 80 cm and weighing at 60 kg in total. The marble type is similar to the colours chosen for Case Study 3– 'Archi-Twist' which include Bianco Acquamarina, Venato Orto di Donna and Bardiglio Imperiale. The darker colours at the base while the lighter Carrara marble at the top which further contributed to highlight the complexity of the geometry and material.

The exhibited prototype 'Catenary Tales' was successful in that through the collaboration of the hand and the machine, the realisation of the initial 3D model was achieved. The specific factors which made it successful include the skill of the craftsman in order to remediate the machine inconsistencies and performance with the material. The skill of the fabrication team and technicians to realise the 3D model into physical reality involved many attempts especially when there were cracks and fractures in the material. The workflow of both the modelling and fabrication process could have further integrated methods of material surveying and scanning. However, the focus was on developing the skill of crafting and carving away material from

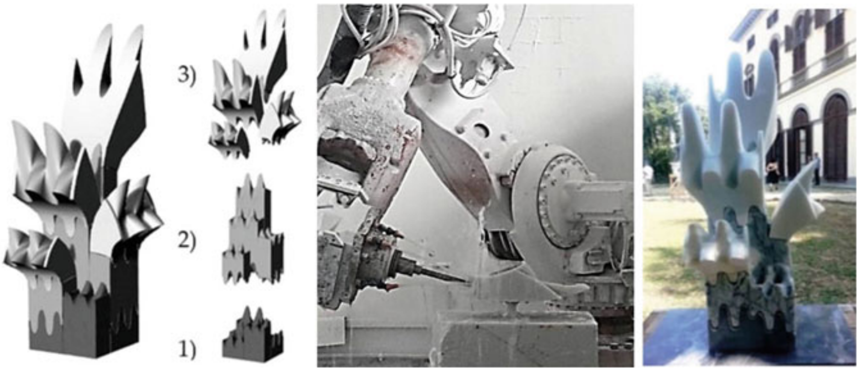


**Fig. 5** Case study 2 Left–Digital model and assembly sequence, middle–7 axis milling, Right-Final exhibited sculpture

natural stone. Constraints included a limited 25-h machine time for each prototype which affected both the final scale and number of machined parts which were in the end grouped together [20]. The sculptural prototype demonstrates bespoke construction typology with dry joint connections as a contribution towards the innovation of architectural components.

## *3.2 Case Study 3—Archi-Twist (2017)*

The concept of the 'Archi-Twist' prototype designed and manufactured as part of the Digital Stone Project 2017 [22] is a twisted catenary arch comprised of innovative modular interlocking wave joinery based on catenary curvature. The method of geometry generation was developed in an entirely parametric environment. In contrast to using sinusoidal or interpolated curvature (used in the initial wave jointed block geometry), catenary curvature for the interlocking wave amplitude has a higher contact surface area thus facilitating a better interlocking capacity. Furthermore, the 180-degree twist of the bases of the arched structure was modelled for both aesthetic and structural reasons due to the extent of the twisting capacity of ruled surface joints. It not only tested the potential capacity of the wave joint contact surfaces but also provided a stabilising mechanism for the overall macro geometry of the arch [20].

Due to limitations in machine time which were 25 h per project within the workshop setting, the scale and number of blocks to be fabricated had to be reduced from 7 parts to 5. Each part (see Fig. 6) was machined in approximately 5 h including tool changes. However, this was still not enough as a final finished module as there was usually 1−2 cm extra material left to sand by hand using the power tools, grinders and hand sanding paper processes similar to processes used by traditional marble sculptors. The overall dimensions of 'Archi-Twist' were14 × 66 × 56 cm, weighing at 38 kg in total.

**Fig. 6** Case study 3 Left- digital model, middle–fabrication, right–final exhibition sculpture

The above case studies demonstrate the use of bespoke dry joint connections using a specific geometry of the wave jointed blocks which is a developed variation of the osteomorphic block. Modular dry joints in the construction industry have gained acceptance for their versatility and reduced labor costs in comparison to traditional brick and mortar methods. The ease of assembly and disassembly make using connecting blocks for spatial assemblies.

## 4 Non-standard Tool Paths

A tool path is the direction through space that the tip of a cutting tool follows on its way to producing the desired geometry of the designed work. Nonstandard toolpaths were explored as part of the DSP workshop. The following is an example of a non-standard approach to the development of tool paths and will describe specifically a non-standard method of an engraving toolpath.

### *4.1 Case Study 4—Orbital Body (2015)*

This project, titled Orbital Body, was designed and fabricated as part of the Digital Stone Project in 2015 and exhibited at the Marble Codes exhibition [21]. Orbital Body is a seating element carved from a single block of Bardiglio Imperiale marble and finds novel geometry in the characteristic markings of several different milling passes and tool types. The piece was fabricated through four subsequent machining steps before being hand-finished. As is typical in CNC milling and other fabrication processes, each subsequent machining pass increased in detail and decreased tool size.

This 4 + 1 step procedure moved through the following machining steps: (1) fabrication of a marble block to match the approximate proportions of the piece's bounding box using a robotically controlled diamond saw, (2) a coarse, flat-end roughing pass which removed the majority of excess material located outside the positive volume of the piece, (3) a ball-end, finishing pass which removed a thin layer of material, closely approximating the curvature and geometry of the digital model, (4) a detailed engraving pass using a ball-end, pencil-neck tool, which inscribed a series of overlapping grooves into the surface of the piece, and (5) the hand-finishing and polishing of the piece to achieve the desired finish and surface texture.

Much of this machining procedure was adapted from standard workflows in CNC-fabrication, however, the detailed engraving toolpath (step 4, above) required a non-standard approach. The engraving toolpaths were produced in Rhino 3D by arraying a series of construction planes along the central mid-line of the piece, intersecting the curved volume of the piece with these planes, and exporting the resulting linework as the engraving toolpath. Originally, the design-intention of the piece was for each engraving toolpath to form a closed loop in space. While this was geometrically possible, the dimensional and rotational limitations of the robot arm made this impossible to fabricate. Working closely with the fabrication engineer, the simulated limit of the robot arm's rotational "reach" was used to adjust the engraving, surgically clipping the engraving toolpaths in order to remove any areas unreachable by the robot arm.

Despite the technical hurdles in realizing the engraving toolpaths, their contribution to the overall piece is substantial aesthetically and functionally. In terms of the work's functionality as a seating element, the overlapping engraving lines of the piece impart tooth and friction to an otherwise smooth, slippery, gloss-finished surface. The depth and spacing of the engraving is deepest/densest across the horizontal surface of the seat and is more shallow/sparse along non-seating areas. As the piece was intended for both indoor and outdoor sites, the engraving toolpaths were designed to function as micro-gutters and help to shed water from the seat surface. These engraved grooves, along with the overall slight convex curvature of the seat, allow the seating surface to shed water quickly and prevent the pooling of water in outdoor environments.

The overall form of the piece seeks to capture qualities of speed and continuity to match the smooth, continuous surface quality of the finely-honed stone. Despite this formal aspiration of continuity and fluidity, the piece had to observe two major functional constraints: balance and weight. Viewed in plan (see Fig. 7), the piece is perfectly rotationally symmetrical. Working in Rhino 3D and Grasshopper, each subtle push and pull of the form is matched symmetrically on the opposite side of the form. This allowed for the sculptural, intuitive manipulation of the overall form during design, while maintaining a consistent center-of-gravity and eventually yielding a seating object which resists overturning. The void at the center of the piece also operates functionally. The removal of material at the center of the piece greatly reduces the weight of the final work, allowing it to be moved or adjusted by two people standing at either end of the piece. In future iterations, the central void of the piece might be extracted as a monolithic block, reducing both machining time and material waste.

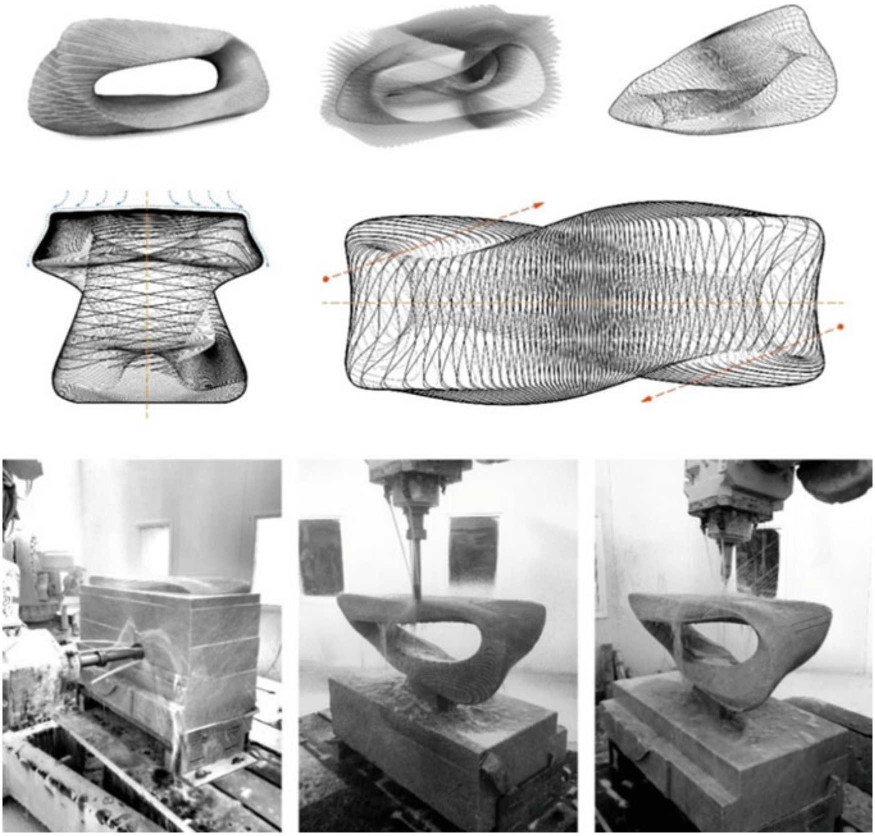

**Fig. 7** Case study 4 Top- 3D model showing the development of toolpaths for engraving, Middle–Plan and section views, Bottom–Fabrication using 7 axis milling

## 5 Interaction Methodologies and Integrated 3D Scanning to Milling

In this research, we borrow methods and logics from traditional sculpting techniques, and explore their power to be computationally augmented, and to include the agency of the designer in the design and fabrication process. The goal was to showcase the potential of novel interaction methodologies to drive creative processes in design, architecture and the arts.

### *5.1 Case Study 5—Untitled 50,069,744 (2018)*

The first sculpture produced for this research is called “Untitled 50,069,744,” and it constitutes a case study on the use of digital technologies to computationally augment the 3D sculpting process, inspired by the freedom of physical gesturing. The goal for this piece was to create a system that could capture the fluidity of human motion and freeze it in time into a delicate and graceful manifestation. Additionally, the project sought to push the tectonic capacity of the stone to its limits and investigate how thin the sculpture could be fabricated. It was determined that the form of the object would be generated by digitally tracking a human sculptor’s hand, and that these motion steps will be used to generate a self-standing vertical surface to be milled at a specific thickness.

In order to achieve this goal, a bespoke modeling environment was prototyped using Autodesk’s Dynamo (see Fig. 8). The system was able to read physical motion from a hand-held motion controller, and use it to generate a three-dimensional thin solid, with its form was inspired by the undulating shape of a piece of fabric draping over itself. The piece was set to be milled out of a 1800 × 800 × 180 mm block of Arabescatto Vagli, a local marble with gray and golden veins, and an elevated degree of translucency through its main white body. A target thickness of 8 mm was estimated by the manufacturer as an ideal compromise between material stability for fabrication and maximizing thinness for translucency.

The milling operations were programmed with commercial CNC software, and the sculpture was milled using an industrial robotic arm and an external rotary 7th axis. As the sculpture was created to be publicly exhibited at the Digital Stone Project exhibition [23] a large industrial robotic fabrication space, only one of the sides was manually polished, whereas the opposite side was left with the raw toolpath markings for the fabrication history of the object to remain more readable (see Fig. 9).

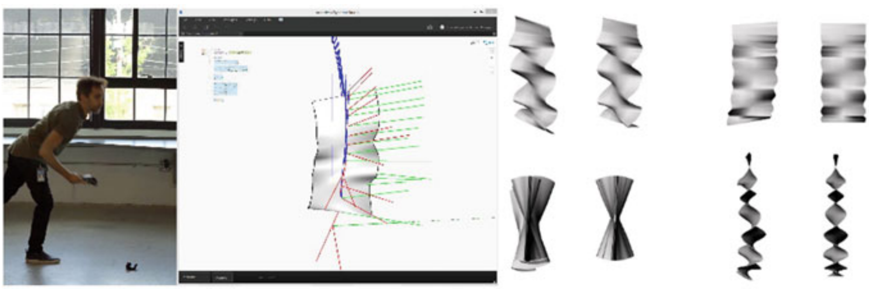

**Fig. 8** Left–The interactive, hand-based 3D sculpting environment, Right–initial tests

**Fig. 9** Left—Final sculpture model, Right—Milled sculpture in the shop and the exhibition gallery

## *5.2 Case Study 6—Dereliction (2018)*

The second sculpture produced for this research was called "Dereliction," and it is a study on the capacity of computational workflows to be adaptive to the physical world and use preexisting conditions as source input in form generation processes. Additionally, the project showcased the potential of digital technologies to mimic certain forms of craft, and the use of algorithms as creative tools. The main question addressed by this work was how digitally augmented sculpting could be harnessed to reclaim discarded materials from marble extractive processes, giving them a second life by adding value through digital craft, while improving the sustainability of the marble extraction process.

To fulfill this vision, an integrated 3D scan to robotic sculpting workflow was developed. A large-scale laser scanner was attached to the robot flange, and a 360° robot scanning procedure was developed to achieve a full three-dimensional representation of the target stone piece. The scanned point cloud was assembled and rebuilt using commercial 3D-scanning software, resulting in a high-resolution polygon mesh. A custom parametric modeling environment was developed in Dynamo, to accept input polygon meshes, representing the 3D-scanned rock, and output the full robotic procedure to groove a custom pattern on its surface (see Fig. 10). The main contribution of the model is the internal translation of the polygon mesh into a graph data structure, susceptible to be analyzed using propagation algorithms, customizable by the designer. Toolpaths were generated using the Robot Ex Machina framework [24].

For the final piece, a mossy marble boulder abandoned in a nearby creek was reclaimed. The rock was placed on the rotary axis of the robot for scanning, and its

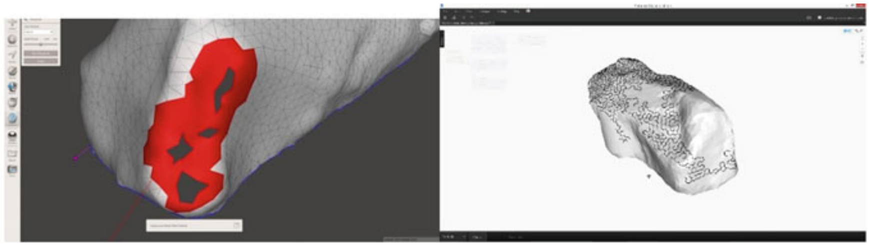

**Fig. 10** Left—Mesh reconstruction, Right—toolpath propagation

**Fig. 11** Left—Fabrication using 7 axis milling, Right—Milling details

position was fixed to avoid calibration errors. The scanned model was post-processed using the abovementioned workflow, and an error-proof robot procedure was generated. A 5 mm diameter milling bit was chosen, and the procedure was successfully run on the robot, taking approximately 2 h to complete (see Fig. 11). No latter treatment or polishing was applied to the piece.

## 6 Conclusion and Future Work

The above case studies demonstrate the value of robotic technologies in the design and construction process relative to collaborative crafting of the hand and machine. The collaborative effort accommodates for material tolerances and interrogates the implications of computational crafting in relation to Industry 4.0, while exploring the role of the artisan in machine crafted architectural components. The case studies investigated both conceptual and technological development in the design process through 3D modelling, scanning and fabrication workflows, developing toolpaths, virtual reality, haptic interaction and reversible construction techniques using bespoke geometry and customized toolsets.

However, the trend towards discrete modular construction must be acknowledged as future work specifically for the case studies with dry joint connections. The use of discrete modularity as opposed to bespoke in interlocking joinery systems in this case rationalises the choice of material and geometry. According to Tessmann, Rossi (2019), "structures are made from discrete and manageable elements that are aggregated in a defined (or rule-based) way. The aggregation becomes a structure if it redirects loads." While both discrete and bespoke modular blocks consume material, discrete geometry prevents excessive waste generation by limiting the number of variations to the block types to be fabricated and assembled. In bespoke systems each module is individually designed and manufactured, often using more material and labor for the design and production process. Discrete systems only use a limited amount of block variations usually limited to two or three hence can use existing waste material and offcuts, depending on the scale of modules. This is significant in today's construction sector in line with the Sustainable Development Goals [26] to build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.

**Acknowledgements** The authors would like to acknowledge the support of Digital Stone Project president Jon Isherwood, the DSP committee, the staff of Garfagnana Innovazione and Autodesk to support the development of the participants' projects; and the University of Sydney, Australia and Ingenium grant at TU Darmstadt, Germany.

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Towards Novel Modeling Frameworks for Robotically-Enhanced Marble Sculpting" by Jose Luis García del Castillo y López, with his permission.

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# MycoCode: Development of an Extrudable Paste for 3D Printing Mycelium-Bound Composites

**Fatima Ibrahim, Giorgio Castellano, Olga Beatrice Carcassi, and Ingrid Maria Paoletti**

**Abstract** Additive manufacturing of sustainable and biodegradable materials offers an alternative fabrication paradigm to current composites used in architecture, based on the growth of materials rather than on extraction. This research investigates the extrusion of a mycelial-hemp and clay mix without additional additives and thoroughly evaluates the steps leading to it. The analysis entails four major steps: manual material investigation to figure out the finest ratio between clay and hemp shives for smooth extrudability, understanding hardware and software determinants that impact the resultant printed form, preparation of the material for 3D printing under sterile conditions and printing the Mycelium-clay mix varying properties analyzing the emergent characteristics of the material. Therefore, the research explores the possible combination ratios of a clay substrate with the addition of hemp shives inoculated with *Pleurotus Ostreatus*, without using any additional additives to test the paste's extrudability properties. The research successfully achieved a balanced ratio between mycelium, hemp, clay, and water when the relative percentage of clay and hemp shives were kept at 85–15%, respectively. The investigation also helped deduce that 3D extrusion printing with the Delta WASP 40,100 Clay Printer, with a nozzle diameter of 9 mm, is most optimal when the layer height is one-third of the nozzle diameter and the Extrusion (E) Value and Feed rate (F) is kept constant throughout the printing, in our case at 30 mm and 1500 mm/min, respectively.

**Keywords** Additive manufacturing · Digital fabrication · Mycelium-clay · Extrudability · 3D Printing · G-codes · Emergent attributes

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_29

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss

## 1 Introduction

### *1.1 Industry 4.0*

The current paradigm shift in the Architecture, Engineering, and Construction (AEC) industry, dubbed as the Fourth Industrial Revolution, or Industry 4.0, has created numerous opportunities for innovation and invention. This has also paved the way for the emergence of a more collaborative and cross-disciplinary technological era to emerge. One such innovative research field that has spawned a plethora of sub-research studies is the use of additive manufacturing (AM). This study aims to investigate the marvels of additive manufacturing of bio-based materials that are drawn and built upon the fundamentals of bio-design while also being biodegradable. Although additive manufacturing reduces waste generation, the use of biobased materials ensures that the material is biodegradable at the end of its life cycle, minimizing any significant environmental impacts. Holistically, this research is one of many springing studies that could potentially lead to the replacement of building materials that are detrimental to the environment with more environmentally friendly ones, owing its success to the advancements of technology and digital fabrication.

### *1.2 State of the Art: Mycelium Fabrication Technologies*

In the recent decade, the shift in global perspective due to the excessive contribution to global warming and global carbon emissions encouraged the AEC to explore and use more eco-friendly methods and materials [1]. This has opened a novel avenue: the discourse on bio-based materials and their application in the AEC Industry [2]. Recent research in the burgeoning discipline of biodesign has begun to provide intriguing answers for environmental issues created by the fast population increase and the discard culture that has accompanied it [2]. As Myers [3] suggested, "Biology-inspired methods to design and manufacture" are used in biodesign, and "life creatures [are] essential components in design" [3]. To achieve increased architectural flexibility, construction is being driven towards automation by numerous factors, including a reduction in labor for safety concerns, a reduction in construction time on site, and manufacturing costs [4]. In particular, AM is an interesting process of layer-by-layer material deposition to form 3D model data. It primarily negates the need for excessive formwork while reducing the waste produced [5]. The practice of AM further becomes more environmentally conscious if using sustainable or bio-based materials that are biodegradable or compostable at their end-of-life (EoL) [2]. Engineering natural materials with the themes of sustainability and EoL concerns have become a strategical design approach. Materials made from cellulose, silk protein, eggshell membrane, bamboo, and mycelium composites [6] have recently received considerable attention [7]. In this regard, mycelium-based composites offer renewable and biodegradable options for various design and production processes, including architectural applications [2]. Mycelium is the vegetative portion of fungus, made up of a mass of hyphae [2]. In fungus, hyphae are a long, branching filamentous structure that acts as a growth agent [2]. Each hypha contains one or more cells that divide to accelerate the growth process and has a diameter of 4–6 μm [2]. Mycelium breaks down biopolymers into simpler entities via enzymes released by hyphae, which are subsequently absorbed through active transport. This cellular process allows living creatures to consume carbon-based nutrition [2]. The hyphae emerge from the substrate and into the air, forming a "fluffy or compact coating covering the substrate, known as fungal skin" [8].

Mycelium-based composites have been widely studied and investigated in the previous years [9], which have led to the production of products like Mycelium-based leather by Mycoworks [10], acoustic and flooring panels by MOGU [11], daily use items such as vessels and bowls by Officina Corpuscoli [12], packaging items initially started by Ecovative [13] and furniture pieces by Phil Ross [14] and Eric Klarenbeek [15]. The application of mycelium-based composites is not only limited to products; it has also been explored in the realm of architecture at a pavilion scale by studios and architects that made use of molding techniques such as, the Hy-fi project by The Living Studio [16], Mycotree by ETH Zurich [17], the Growing Pavilion by Company New Heroes E. Klarenbeek [18] and MY-CO space by MY-CO-X Collective [19]. In contrast, Blast Studio's Tree Column [20] and Lund University's Protomycokion [21] are mycelium-based projects that are additively manufactured through a direct ink writing (DIW) 3D printing technique. The application of mycelium-based composites in AEC is a novelty in the last decade, whereas, clay has been used for millennia [22]. This is due to clay's insulating characteristics, heat storage capacity, ability to minimize construction energy use, and high local availability [22]. However, this material is usually associated with traditional and vernacular architecture in undeveloped places [22]. In recent years, the 3D printing of clay and the related parameters have been explored by Benay Gürsoy [23] to analyze the impact of the printer and variables in the G-code on the resultant clay print. Interesting 3D printing projects are present in the literature, such as the Tree Column by the Blast Studio [20] and Protomycokion at the Lund University [21], which uses biopolymers to feed mycelium and create 3D printed objects. Moreover, the conceptual exploration of clay and mycelium with varying substrates such as sawdust and coffee grounds for potential 3D printing in the project Claycelium by IAAC, Barcelona [22] paves the way to combine the clay and mycelium-based potentials in the AM sector. Benay Gürsoy tests the 3D printing of clay and the digital parameters involved in the additive manufacturing process that affects the printed form [23]. However, these projects embed in the extrudable paste the use of additives. Hence, what is missing is a clear guideline on how to develop and prepare an extrudable paste and the 3D printing parameters when a clay, hemp shives, and mycelium composite are combined without additive materials. Therefore, this research offers guidance for embarking upon similar research, by investigating the digital additive fabrication of mycelium clay and by providing a step-by-step explanation of the extrudable mix and printing parameters that influence the printed element.

### *1.3 Research Gap and Aims of the Research*

In this paper, the subject of focus is the additive extrusion of a mixture composed of mycelium, hemp shives, and clay without any extra additives, along with factors that affect the final form during the different steps of 3D printing of the material.

We can discern a symbiotic link between the qualities of clay, a common building material, and mycelium, the living fiber network that connects our plant life across the earth [22]. Mycelium is a living organism that requires nutrients to grow, which are not sufficiently found in clay. However, hemp shives provide ample nutrients to mycelium for its growth, which is why hemp qualifies as an apt substrate for mycelium. A mix of mycelium and hemp cannot be extruded via an extruder or printer due to hemp's water retention characteristic, which results in the poor self-adhesion nature of the mixture and eventually the inability to maintain form [24]. Therefore, owing to clay's viscous, elastic properties, it is incorporated into the mycelium-hemp mix [25]; simultaneously, as mycelium grows through the mix, feeding on hemp shives and piercing through the clay here it acts as a 'natural binder' [7], consequentially holding the entire form together. The fungi-based compound can store biogenic carbon in its biomass and lower the process's environmental impacts [9]. Moreover, the fibers enhance the mechanical properties of the clay [26].

"Tools are never neutral,"–Pérez Gómez, because they "underpin conceptual elaboration" and "the entire process of form production" [27]. In digital manufacturing processes, there exist indeterminacies that may be examined as possible design drivers. Digital fabrication methods demand precise control over the process since specified instructions must be followed before materialization, the shift from a computer model to its physical manifestation is seldom smooth. These technologies control and precision make the transfer from digital to physical easier: intricate and complex digital models may be realized without the need for established hands-on abilities. Despite these benefits, digital fabrication technology does not always encourage innovative design discoveries, or a design approach guided by production [23]. According to Gürsoy [23], beyond the seamless materialization of the digital model, digital manufacturing techniques may continually influence design ideation through emerging tectonic features [23], investigating the ramifications of a digital fabrication method that is not based on imposed and strict formalisms but unique and contextual ones.

Based on the available literature review and room for research, this research explores the possibility of growing mycelium in a clay and hemp mixture, preparing this material for a 3D printer, and exploring its emergent properties as it goes through several facets; such as material preparations manually, digital algorithms, geometries, and generated G-codes, printing limitations such as nozzle sizes, print settings (print speed, extrusion speed, layer height, and nozzle width), printing base (dynamic or static), the material of the print base whether it adheres to the material or not, etc. [2]. Pondering upon the determinants mentioned above, this research investigates the emergent properties of the novel material for 3D printing and the impact it has on the resultant object's form and finishes.

## 2 Methodology

For a fair investigation, the material preparation step remains of utmost significance as it helps determine the properties of the extrudable paste. *Pleurotus Ostreatus* is a specific mycelium species used in this research [9]. Mycelium requires nutrients to grow, which it usually extracts from lignocellulosic biomass; for this investigation, hemp shives are used as the substrate for the experiments with mycelium. This research method was conducted through material experiments, algorithmic iterations, and a series of 3D printed experiments. A variety of material mixes and samples with different G-codes with varying determinants were extruded with the help of a 3D clay extruder to elaborate various attributes dependent on the material and manufacturing procedure. The study was divided into four stages: (i) manual material testing–determining the optimal ratio for mycelium, hemp shives, and clay for extrudability, (ii) hardware and software configuration- preparation of G-codes, (iii) preparation of material for the 3D printer in sterile conditions and adding mycelium to it, (iv) 3D printing a series of forms with differing G-code attributes, as well as samples with different curve toolpath geometries that have the aim of elaborating printing strategies of the material based on the digital fabrication process.

### *2.1 Material Investigation*

The additive manufacturing of mycelium, hemp shives, and clay allows for more precision of the desired form. The biomass mix is printed, and mycelium is harvested throughout the form to bind the clay and hemp together. As the aim was to have an extrudable mix, an array of physical experiments was carried out experimenting with different ratios of clay and hemp to evaluate the most optimal extrudability with the varying ratios of hemp shives. Clay is especially well suited for 3D printing studies because it allows for extensive modification before, during, and after the printing process. Unlike other materials that can be 3D printed, clay has specific qualities such as viscosity, elasticity, and texture that determine the final printed shape [28]. Apart from those mentioned above, the 3D printer and its extrusion nozzle, the 3D printing parameters, curve toolpaths, and the varying Extrusion value € will also influence the final form as additional parameters. The layer-by-layer deposition of clay is evident in the final form as the layers remain visible despite not being anticipated in the digital 3D model, making it a characteristic of 3D printed clay objects and giving it a tectonic aspect. Moreover, since clay is printed while it is still wet, it can contribute to the sagging of overhangs under gravity as the clay does not harden immediately, making it another emergent property. 3D printing with clay retains the traits of unpredictability in this way [23]. The procedure becomes as crucial as the final product when unanticipated variables must be identified during the process. The accuracy, efficiency, and consistency of 3D printing may no longer be the most enticing features in this new setting. Moreover, the extruded form requires time to dry. As a result, the printed items are exposed to the surrounding conditions and are still susceptible to modification after printing. This brings up new possibilities for a design and manufacturing process incorporating digital and analog techniques [23]. In the current research, no extra additives are used in the mix to singularly explore the properties of viscosity and extrudability of the paste and the growth rate of mycelium with a set ratio of mycelium and hemp. In order to investigate the physical characteristics of the paste to make it suitable for extrusion, the experiments are carried out in two stages. The first one is manual extrusion via a manual syringe to assess whether the mix is extrudable or not. The second stage is the 3D printing of the paste through the Delta WASP 40,100 Clay 3D printer with a 9 mm nozzle diameter [29] with an optimal ratio of clay-hemp mixes and additional computational parameters to evaluate the final form with overhangs. The mixture of mycelium, hemp shives, and water is not extrudable since hemp retains high quantities of water and does not form a cohesive mixture as hemp clumps and does not adhere to each other. Despite hemp's inability to form viscous mixtures, it remains relatively significant to the overall process as it reinforces the clay through the drying process while providing nutrients for the mycelium to grow through the form. For this exercise, hemp shives were ground and sieved by a number 35 laboratory mesh strainer with resulting fibers of length 0.5 mm. The fibers were mixed with varying percentages of clay relative to the weight of hemp to analyze its extrudability. The percentage of clay initially used was 70% clay and 30% of hemp, and the ratios were then altered to achieve the best viscosity for the mixture to make it optimal for printing. The later experiments made use of 75% clay and 25% hemp, followed by 80% clay and 20% hemp, and eventually used 85% of clay and 15% of hemp. Increasing the percentage of clay allowed for more viscosity of the mixture but simultaneously reduced the available substrate (hemp) for the mycelium to feed on.

## 2.2 Experimental Procedure for Manual Extrusion

Manual extrusions of the clay and hemp mixture were conducted to analyse the viscosity, extrudability, and adherence between layers of the mixture [30]. For this purpose, a standard lab syringe with a 50 ml capacity was used; the tip of the syringe was cut to approximately 9 mm in diameter to simulate the extrusion of a clay printer with a nozzle size of 9 mm. Another significant observation made during the research was the removal of the rubber on the plunger, known as the seal or plunger tip of the syringe, to prevent it from creating an air-tight space within the syringe shaft, as it made it impossible to extrude the paste due to the pressure build-up inside the syringe.

As previously mentioned, a hemp and water mixture are hard to extrude; therefore, it was mixed with clay to achieve the desired consistency. Experiments began by mixing a ratio of 70% clay and 30% of hemp, whereby 10 g of hemp were mixed with 23 g of clay by adding 45 g of water, as shown in Table 1. The percentage of water was proportional to the weight of hemp by keeping it constant at 4.5 times the weight of hemp. It was hard to achieve a printable extrusion due to the clumping of hemp and water as the mixture remained non-adherent, non-viscous, and non-continuous. Moreover, despite applying much manual pressure to extrude the paste, the results were undesirable, and only water came out of the syringe as it was squeezed out of the moist hemp that retained water.

Based on the results from the first round of manual tests, the second round of tests was conducted by increasing the percentage of clay in the mixture from 23 to 30 g (from 70 to 75% of clay), as shown in Table 1. Since there was no more addition of hemp to the mixture, the water content was also kept constant as there was still water retained in the fibers. The ratio between clay and hemp was 75 and 25%, respectively. However, despite increasing the weight of clay, the mixture remained non-extrudable as the water kept separating from the mixture and dripping out through the syringe.

Further experiments were conducted on varying the ratios of clay and hemp as the following set of investigations made use of 80% clay (40 g) and 20% hemp (10 g) with no additional water added (Table 1). This mixture despite being semi-viscous and highly self-adherent was not extrudable as the mixture stuck in the syringe due to the adherence of the mixture within the syringe. Finally, using a mixture of 85% clay (57 g) and 15% hemp (10 g) with water was kept constant at 45 g (Table 1) was optimal as the water was not separating from the mixture, with fine extrudability,

**Table 1** Experiments: different Clay-hemp ratio

| | Clay 70% Hemp 30% | Clay 75% Hemp 25% | Clay 80% Hemp 20% | Clay 85% Hemp 15% |
|---|---|---|---|---|
| Material | Weight (g) | Weight (g) | Weight (g) | Weight (g) |
| Clay | 23 | 30 | 40 | 57 |
| Hemp shives | 10 | 10 | 10 | 10 |
| Water | 45 | 45 | 45 | 45 |


**Fig. 1** Left: first trial—manual extrusion. Experiment: Clay 85% and Hemp 15%. Right: second trial—manual extrusion. Experiment Clay 85% and Hemp 15%

viscosity, adherence, and maintaining its form as shown in Fig. 1. Based on the manual trials conducted, it was deduced that the most optimal ratio for clay and hemp for smooth extrusion and the best layer adhesion was 85% of clay and 15% of hemp with water as 4.5 times the weight of the hemp.

## *2.3 Material Preparation for 3D Printer*

After having evaluated different ratios of clay and hemp shives to achieve the ideal mixture manually, experiments were further conducted with a Clay 3D Printer Extruder- the Delta WASP 40,100 Clay 3D printer, to investigate further the aforementioned hypothesis regarding the attributes of the clay-hemp mixture. The printer had a nozzle of 9 mm used for these experiments and pressure was kept constant at 0.4 MPa, throughout the printing.

In order to conduct the experiments through the 3D printer approximately 3.8 kg of material was prepared, manually to be loaded into the printer. Initially, hemp was ground in a 500 W blending machine to extract 300 g of 0.5 mm hemp shives, the hemp was divided into three portions, 100 g each to make separate batches. To each 100 g of hemp, 567 g (85%) of clay was added, along with periodically adding 450 g of water (Table 2). The mixture was kneaded by hand to achieve a soft and homogeneous consistency.

After creating three separate batches of the clay-hemp mixture, each weighing 1117 g, they were added into three separate autoclavable bags after which the mixtures were sterilized in an autoclave [9] at 120 °C for 1 h [9]. The clay-hemp mixtures after being sterilized were left to cool down for 24 h before adding mycelium to the mix. For each bag, 20% of the weight of the mix without water was taken as the amount of mycelium to be added, therefore, to each bag 133 g of mycelium was added,

**Table 2** 3D printer material preparation: Clay-Hemp ratio 85%:15%

| 3D printer ,material preparation: Clay 85% Hemp 15% and Water only | |
|---|---|
| Material | Weight (g) |
| Clay | 1700 |
| Hemp shives | 300 |
| Water | 1350 |
| | Total weight (without mycelium) 3350 g |
| | Total weight (without mycelium per bag) 1117 g |

**Table 3** 3D printer material preparation: Clay-hemp ratio 85%:15% with Mycelium

| 3D printer material preparation: Clay 85% Hemp 15% and Water only | |
|---|---|
| Material | Weight (g) |
| Clay | 1700 |
| Hemp shives | 300 |
| WaterK | 1350 |
| Mycelium (20% of the weight of Clay + Hemp) | 400 |
| Total weight (without mycelium) 3350 g | |
| Total weight (without mycelium per bag) 1117 g | |

which was 20% of 667 g of the mix without water (100 g of hemp, 5667 g of clay), as stated in Table 3. Mycelium was mixed well into the clay-hemp mixture under sterile conditions to avoid any contamination. For the printing process the space around the 3D extruder, the filament cartridge of the 3D printer, and the extruder were all disinfected with alcohol both before and after loading the material to ensure maximum sterilization to prevent and reduce the risk of any possible contamination.

# 3 Geometry Investigation Related to Computational Design

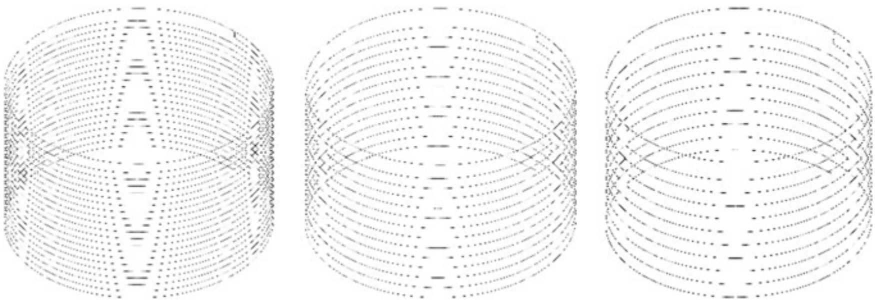
## *3.1 Computational Design and Its Connection with the Extrudable Paste*

To examine the extrudability, layer adhesion, and the deviation from the basic form-different algorithms were generated to examine these properties. The G-codes for the printer were generated via Grasshopper for Rhinoceros 7 [31].

## 3.2 Computational Design Aims to Exaggerate the Properties of the Paste

All investigations were conducted beginning at a similar point with a cylinder with a radius of 5 cm and a height of 6 cm. Firstly, the layer heights were examined considering the relationship of layer height with nozzle size and the resultant resolution of the form and layer adhesion properties. Three different G-codes with layer heights of 3, 4.5, and 6 mm (Fig. 2) were generated, respectively for the cylinder at a constant Feed rate (F) of 1500 mm/min and an Extrusion value (E) of 30 mm, with the air pressure, was fixed at 0.4 MPa. Researchers suggest, keeping the slice height to be one-third of the nozzle width as a general rule [32]. Jonathan Keep [32] in his publication—'A guide to Clay printing', suggests that the flatter your layer height is in relation to the width of the wall, the more stable your print will be, especially when the wall begins to build out or in [32]. You may prefer a more rounded look to your printed layers, but make sure they are properly packed together, or you will experience delayering during the drying process [32].

For varying other determinants in the experiments, the Feed rate (F) was kept constant, and the Extrusion (E) was altered for the cylinder with the layer height of 3 mm (one-third of the nozzle size-9 mm). Following Benay Gürsoy's investigation [23], for the first G-code, the E value was increased by 10% after thirty percent of the print was completed and in the second G-code the E value was decreased by 20% after thirty percent of the print was completed to understand the impact of the E value with respect to the material's layer adhesion, extrudability and the resultant properties of the form. For the next set of tests, the basic form of the cylinder was sliced at 3 mm, each alternate contour curve was selected, divided into 500 points each, and then each alternate point deviated on the XY-plane outwardly within the parameters of 0 to 15 mm bounds. The resultant points were then interpolated through a third-degree curve and eventually, all the contours were joined together to create a



**(a)** **(b)** **(c)**

**Fig. 2** Cylinder radius 5 cm, height 6 cm. 3(**a**) Contoured Layer Height 3 mm. 3(**b**) Contoured Layer Height 4.5 mm. 3(**c**) Contoured Layer Height 6 mm curve toolpath (Fig. 3) to be printed at an F value of 1500 mm/min and an E value of 30 mm.

For the final experiment, the Grasshopper script was altered to generate an isocurve toolpath (as shown in Fig. 4) for the cylinder, to deviate from the regular curvilinear toolpath where the Z value gradually changes throughout the print. However, the isocurves were examined keeping the F 1500 mm/min and E value 30 mm.

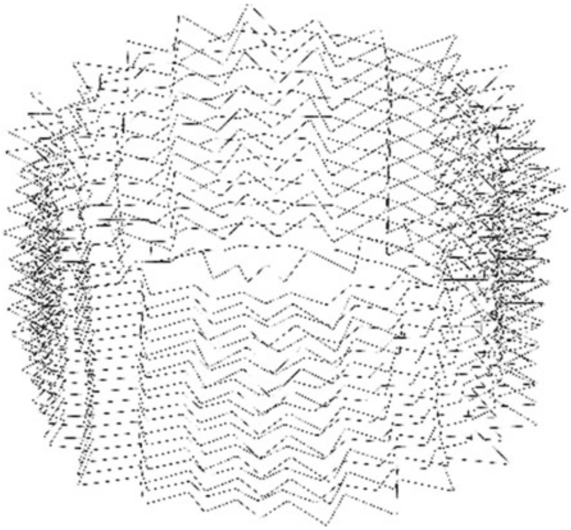


**Fig. 3** Curve toolpath generated for uncertain overhangs

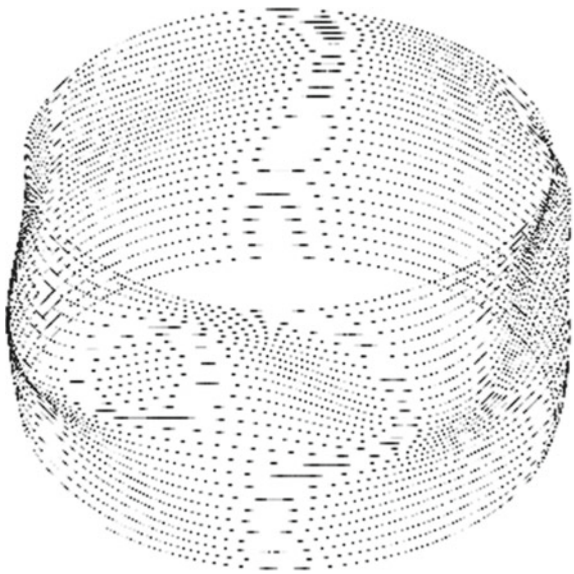


**Fig. 4** Isocurve toolpath generated

# 4 Geometry Investigation Related to Computational Design

The mycelium, hemp shives, and clay paste were successfully printed for all the five G-codes mentioned above, their properties were analyzed, and emergent behaviors of the material were recorded to help further us reach conclusions regarding the properties of the Mycelial-Hemp and Clay mix. A cylinder of radius 5 cm and height of 6 cm was used as a basis to be exploited throughout each experiment. It was also initially recorded that printing on a glass surface resulted in no adhesion between the glass and the first layer of the material, so the material dragged along with the nozzle. However, replacing the glass with a wooden surface allowed the material to be fairly deposited and not drawn along with the nozzle.

## *4.1 Layer Heights*

As displayed in Table 4, different Layer heights for the cylinder were 3D printed; 3, 4.5, and 6 mm, respectively. The toolpath with a layer height of 3 mm remained continuous as opposed to layer heights of 4.5 mm and 6 mm which started showing signs of a non-continuous layer, resulting in loss of form and layer adhesion as the layers kept breaking.

## *4.2 Varying the Extrusion Value*

For the previous set of experiments, the Extrusion value (E) was kept at a constant value of 30 mm; however, for the following two experiments, the E values were increased and decreased to understand the impact of a non-constant E value on the resultant form. As presented in Table 5, Increasing the E value increased the width of the cylinder wall and more amount of material being extruded, which caused the cylinder walls to start caving inwards under self-load. On the contrary, decreasing the E value through the course of the extrusion resulted in non-continuous material deposition and tearing of layers.

## *4.3 Evaluating Overhangs in the Toolpath*

In the last experiments the aim was to understand the properties of the paste by deviating specific points on the XY-plane and interpolated through a third-degree curve to create a curve toolpath. This experiment was carried out to assess the material's behaviour in maintaining the form and layer deposition where the extruder did

**Table 4** Extrusion of Mycelial-hemp, Clay mix with variable layer heights

| Layer heights | Side view | Top view |
|---|---|---|
| 3 mm |  |  |
| 4.5 mm |  |  |
| 6 mm |  |  |

not deposit layer upon layer on the Z-axis. As shown in Table 6, the material was deposited smoothly, and the lower layers could withhold the shape of the upper layers with overhangs without any significant sagging or breakage of the form.

## *4.4 3D Printing of Isocurves*

Lastly, a curve toolpath was modified from planar curves to periodic planar curves with the Z values changing throughout to understand whether the extrusion paste could withhold the shape or not. This was a step further from the previous experiment

**Table 5** Extrusion of mycelial-hemp, Clay mix with increasing and decreasing E values

| E value | Side view | Top view |
|---|---|---|
| Increasing E value |  |  |
| Decreasing E value |  |  |

**Table 6** Extrusion of mycelial-hemp, Clay mix evaluating overhangs

| Curve toolpath | Side view | Top view |
|---|---|---|
| Overhang bounds (0–15 mm)<br>F = 1500 mm/min<br>E value = 30 mm |  |  |

to critically analyze whether the material was suitable for more complex extrusion or not. The material maintained its shape, and the isocurves were visible in the resultant form, with the considerable resolution, as seen in Table 7. The F and E values remained constant at 1500 mm/min and 30 mm, respectively.

**Table 7** Extrusion of mycelial-hemp, Clay mix with Isocurves

| Curve property | Side view | Top view |
|---|---|---|
| Isocurves<br>F = 1500 mm/min<br>E value = 30 mm |  |  |

## 5 Conclusions and Further Studies

The research successfully achieved a balanced ratio between mycelium, hemp shives, clay, and water without adding additives. Where clay and hemp are 85 and 15%, respectively, the amount of water added to the mix is best kept at 4.5 times the weight of hemp, and lastly, the mass of mycelium added should constitute 20% of the weight of the dry mix. After the above experiments were carried out, it was deduced that to keep the highest resolution of the form; it is best to keep the layer height one-third of the nozzle width. In this case, 3 mm layer height remained most suitable.

Altering the Extrusion value (E) during the printing helped us understand that in order to print with a clay 3D extruder like the Delta WASP 40,100 Clay 3D printer, it is best to explore the values of Feed rate (F) and Extrusion Value (E) in proportion to each other and that both values should be kept constant throughout the print to ensure smooth extrusion. From the above experiments, the most suitable Extrusion Value (E) was 30 mm with a constant Feed rate of (F) of 1500 mm/min. Moreover, the material could withhold its form as overhangs were introduced from a range of 0-15 mm without any deformation during and after the 3D printing as the material was able to maintain its shape. The isocurves were visible in the final form, with an acceptable resolution, as seen in Table 10, proving that the material was able to not only maintain the form with deviating points on the curve toolpath in the XY plane but also do the same as points were exaggerated along the Z axis.

The above-discussed ratios of clay, hemp shives, water, and mycelium allow an elastic paste to be extruded without breaking and simultaneously maintaining overhangs without significant changes to the final shape. This research paves the way for further research by questioning which digital parameters (in the G-code) and technical aspects of the 3D printer could be altered to thoroughly study the impacts of 'tools' in the process of 3D printing. Furthermore, exploring and controlling the conditions of the surroundings and the environment of the space the printed form is placed in for the conducive growth of mycelium by establishing measures and conditions that prevent contamination, maintain a sterile environment, and enhance the mycelial growth. Lastly, further studies are needed to understand the deactivation of the digitally fabricated mycelium composite form and investigate the mechanical, acoustic, and thermal properties of the novel extrusion material to reach the most suited architectural scale.

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# 3D-Printing of Viscous Materials in Construction: New Design Paradigm, from Small Components to Entire Structures

**Valentino Sangiorgio, Fabio Parisi, Angelo Vito Graziano, Giosmary Tina, and Nicola Parisi**

**Abstract** The advent of industry 4.0 in the construction sector is profoundly changing paradigms that enhance the building construction sector. During the last decade, the experimentation of 3D-printing exploiting *viscous materials* has undergone unprecedented increases by construction companies. Even if reinforced concrete 3D-printing to construct buildings is growing fast, the use of other materials such as *clay* and *raw earth* is not yet affirmed both for the building *components* prefabrication or monolithic constructions. Currently, few 3D-printing applications with clay and raw earth have been experienced by research institutes and companies (e.g. Fablab-Poliba, Italy; Instituto de Arquitectura Avanzada de Cataluña, Spain; WASP company, Italy) for bricks, walls and entire buildings respectively. Beyond practical applications, the academic investigations focused on specific issues only (e.g. structural performances, new design for prefabrication or complex geometry printability). On the other hand, these examples are isolated, and a systematized design paradigm is still missing in the related literature. This chapter aims to define a new design paradigm for 3D-printing with viscous materials. A five-step procedure is proposed to achieve an effective design for both "*small components*" (to be assembled on site) and "*entire structures*" (to be printed in situ). The five steps will guide the reader towards the exploitation of the potential of the technology by experimenting complex shapes and by also respecting the actual limits of the machines. The

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_30

steps include: (i) Definition of the conceptual design; (ii) Parametric modelling, (iii) Slicing software; (iv) Performance and Printability simulation; and (v) 3D-printing.

**Keywords** 3D construction printing · Building design · Construction technology · Parametric modelling · Printability simulation · Slicing software

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns

## 1 Introduction

Additive Manufacturing (AM) is a rapidly increasing technique that allows the production of three-dimensional objects from a Computer-Aided Design (3D CAD) model through the deposition of layers of material. In contrast with subtractive technologies, the additive process does not involve large quantities of waste materials and gives the opportunity to 3D print complex geometries and shapes [1]. Innovative opportunities in the design and architecture field have been recently created by AM development and the peculiar capabilities of this technology. Plenty of research has been carried out on design for AM and particularly on small-scale applications [2]. In this context, the challenge for designers is to create high-quality products meeting functional design requirements by using AM and considering technological limitations, advantages and capabilities for each process. Indeed, by exploiting such novel technology, designers can generate customized solutions with added value compared to industrial ones [3]. On the other hand, currently, well-defined procedures to exploit the advantages of AM are based on the technician's experience and general design guidelines are missing in the related literature.

*This chapter* is aimed at defining a new paradigm for the design of 3D-printing *components* (to be assembled on site) and *entire structures* (to be printed in situ). In particular, the chapter proposes five iterative steps to achieve an effective component or building design to be achieved with 3D-printing of viscous materials: (i) Definition of the conceptual design; (ii) Parametric modelling; (iii) Slicing software; (iv) Printability simulation; (v) 3D-printing (Fig. 1). The proposed approach is explained from both a theoretical and practical point of view in three subsections. *Firstly*, a specific paragraph explains in detail the five steps to achieve 3D construction printing from the novel conceptual design to the operational use of machinery. *Secondly*, the five steps are explained from a practical point of view by proposing the design and production of *small building components*. In particular, the generation of 3D-printed clay bricks with complex shapes is presented (Fig. 2, left). *Thirdly*, the proposed method is applied to build a *whole structure* to be printed directly in situ. In this case, the five steps are applied to redefine the conceptual design of the Nubian Vaults to be compatible with a full-scale and support-free 3D-printing production with raw earth (Fig. 2, right).

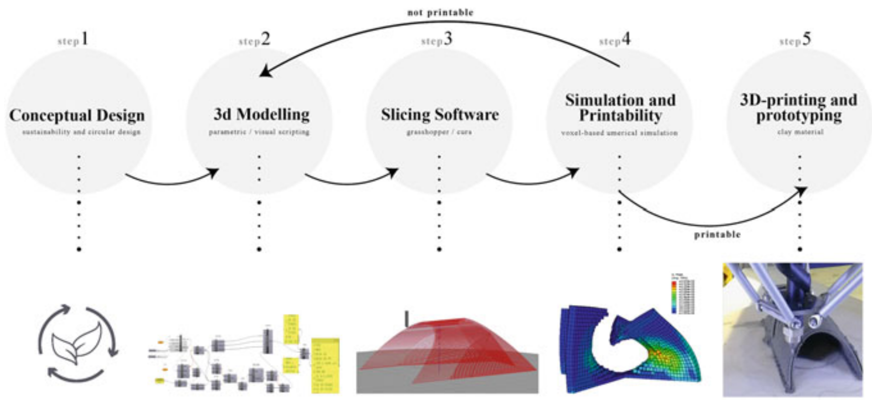


**Fig. 1** The five steps to perform an effective design and 3D-printing with viscous materials

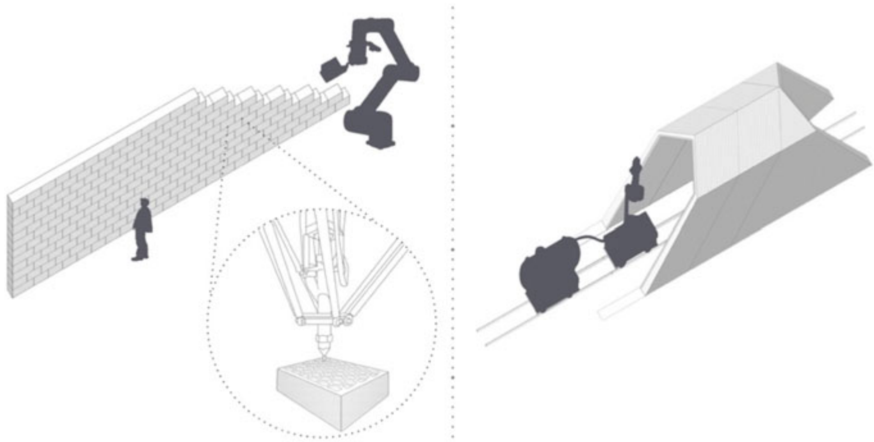

**Fig. 2** 3D printing of small components (clay bricks, left) and entire structures (Nubian vaults, right)

## 2 The Five-Step Procedure to Achieve an Effective Design and Prototyping in 3D-Printing

The proposed design paradigm is based on five steps to guide the reader to reach effective design and prototyping in 3D-printing of viscous materials (each step is described in a subsection below). In particular, the *first* step consists of the definition of the conceptual design by identifying the advantages and limitations of a 3D-printing-based production with viscous materials. The *second* step exploits the parametric modelling in order to ensure flexibility of production, customization, parametric analysis and optimization. The *third* step regards the slicing of the 3D model by setting all the 3D printing parameters (including both technology and materials). The *fourth* step is performed in order to analyze the performance of the component and simulate the 3D printing process to verify the effective printability of the designed model. If the printability simulation gives negative results, it is necessary to repeat steps 2, 3 and 4 until the combination of the design, modelling, technology and materials can produce a perfectly printable prototype. The *fifth* and last step consists of the effective 3D printing of the designed object.

### *2.1 Definition of the Conceptual Design*

The definition of conceptual design for additive manufacturing with viscous materials is based on 3 fundamental points: (a) Review of available AM technologies with a focus on capabilities and limitations; (b) Definition of the aim of the project and selection of the most suitable technology for viscous materials for entire structures or components to be assembled; (c) awareness of general limitations of 3D-printable geometries.

(a) In the first stage of conceptual design, an accurate analysis of the current AM processes is required. Seven AM processes are identified in the framework of additive manufacturing standards development by the international standard ISO/ASTM [3]: Directed Energy Deposition, Powder Bed Fusion, Sheet Lamination, Binder Jetting, Material Extrusion, Vat. Photopolymerization and Material Jetting. In the field of architecture and construction, the most relevant and widespread technique is the material jetting processes with viscous materials (e.g. Contour Crafting [4], Xtree [5] and Cybe [6]). Cementitious materials have been the most explored in AM for being cheaper than other materials and characterized by suitable mechanical properties. Nevertheless, there are AM technologies aimed at raw earth and clay deposition [7]. Consequently, the guideline for designers is to select a set of available technologies by considering the following advantages of applying an AM in construction: (i) the possibility to build more complex, functional and customized geometries, composed by parts well integrated and more easily assembled; (ii) use of innovative mixtures as a combination of materials with different properties; (iii) automation of production with reduction of manual work (specifically for entire structures), (iv) possibility to optimize of the used material by enhancing the life cycle sustainability and reducing resource consumption, waste production and pollution [8].

(b) In the second stage, a specific AM system can be selected and applied, according to design objectives and required performances. Anyhow, the first selection of the specific AM system depends on the size of the element to be produced. Currently, two different functional approaches can be identified: (i) application of large-scale systems for the fabrication of entire structures on-site; (ii) application of small/medium-scale systems to produce small building components to be assembled. Secondly, the best AM technology can be selected on the basis of the availability, costs and geometric limitations of 3D printing.

(c) In the third stage of the conceptual design process, all the geometric limitations of 3D printing must be known and taken into consideration. The construction of angled or standard overhangs, bridges, bores and channels, excessively thin wall thickness and too small elements might not be correctly printable, strictly depending on the specific AM system and its characteristics. The thickness of the nozzle, the extrusion method and the material employed highly affect the geometry of overlapping layers. Once all the geometrical limitations are known, the designer can effectively realise the concept of the component or construction. In the end of the conceptual design, the draft of the component is defined together with the target performance to be reached (e.g. functional, structural, and thermal characteristics in order to satisfy minimum regulatory standards and user comfort).

> Note that the designer generally has fewer geometric limitations in conceiving various small components to assemble at forming large-scale structures.

## *2.2 Parametric Modelling*

Parametric modelling belongs to the family of computer-aided design (CAD) concerning the use of computer-based software to aid in design processes. On the other hand, if compared with other tools, parametric modelling is able to build geometry by exploiting mathematical equations operated with visual scripting. This process provides the ability to change the shape of the model's geometry immediately when specific dimension values are modified. Consequently, once the conceptual design of the model is ready, it is necessary to identify all the dimension values that need to be parameterized (e.g. thicknesses, lengths, heights, curvatures, and parameters that define any internal fillings). The aim of parametric modelling is of basic importance since it establishes the flexibility and adaptability of the ideated component and allows fast customization, analysis and optimization of the final product. In addition, the achieved parametric 3D model can operate in synergy with specific performance analysis software. For this purpose, an iterative process can be set up to adjust the dimension values and improve the performance until the printability is reached and the target performances are satisfied (Sect. 2.4). A correct execution

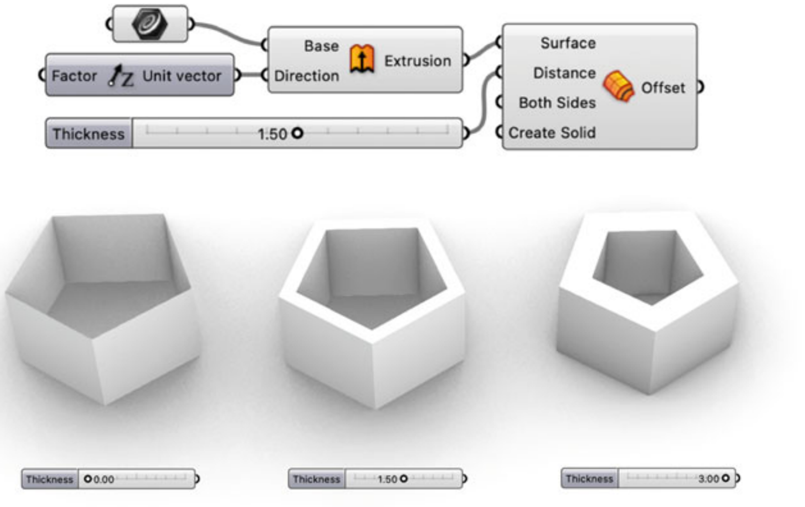


**Fig. 3** Example of a parametric model with a parameterized thickness (Grasshopper software)

of the parametric model makes the subsequent phase of the iterative adjustment of dimension values simpler and more effective.

Operatively, the parametric modelling is carried out by using specific software (e.g. Rhinoceros and Grasshopper). In these tools, 3D modelling is achieved by using specific *components* (hereafter written in *italics*) to be dragged onto a canvas and adequately connected between them. Figure 3 shows how an example of a parametric model is generated starting from a pentagonal shape. The pentagon is firstly extruded (with *Extrude* component) in the Z cartesian direction and secondly, an *offset surface* is applied by parameterizing the thickness (one-dimension values only can be varied in this example). In the end of the process, the parametric model allows to easily change the thickness dimension values. In particular, the figure shows three configurations obtained by setting different thicknesses of 0, 1.5 and 3 respectively.

## 2.3 Slicing

For the 3D printing process, analogously for other digital fabrication technologies, a connection between the digital environment and the real physical one is necessary. This connection can be achieved through computer-aided manufacturing software (CAM) that generates a toolpath (in an alphanumeric language) to provide the machine with the processing instruction. For additive technologies, the CAM procedure to convert a 3D model into specific instructions for the printer is called "slicing". Indeed, the process operates a "slicing" of the three-dimensional model to obtain a set of layers re-creating the geometry. The output of the *slicing* is called G-Code and

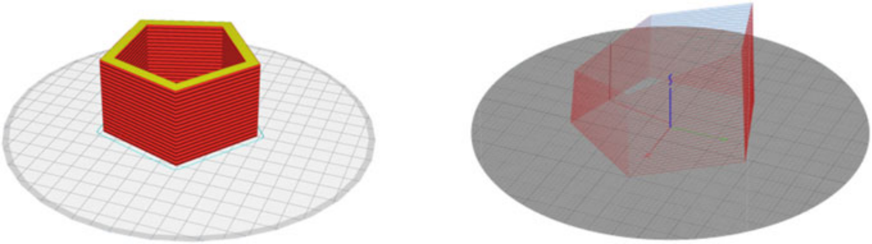

**Fig. 4** Automatic (left) and parametric (right) slicing of a simple 3D model

consists of instructions for the 3D printer that can create the object in the physical environment by producing successive layers of material. During the slicing process, numerous printing parameters can be defined such as the layer height (related to final component resolution), the pattern of the internal fill or the parameters related to the printing supports.

In this section, two possible approaches are specified to set the slicing: (i) the automatic slicing by using specific software (e.g. Cura, Simplify3D or Slicer3D) and (ii) the parametric slicing to directly draw the printer toolpath.

The software to achieve automatic slicing are very fast and user-friendly but are also limited to specific algorithms. In fact, even if this software allows to change of numerous printing settings, the tool path is automatically generated by the program and cannot be entirely decided by the user. On the other hand, "parametric" slicing overcomes the drawback of automatic slicing and gives the user full control of the procedure. In this way, the creation of the G-Code is entirely controlled by the user without randomly generating infill or tool path as in the case of the more traditional slicing software. To provide an example, by using this tool it is possible to create toolpaths that are not planar to the printing plane (an option not yet available in slicing software). Figure 4 shows the slicing process obtained for an example geometry (the same of Fig. 3) obtained both with an "automatic" (left) or "parametric" (right) slicing that allows not planar layers.

## *2.4 Performance and Printability Simulation*

The performance analysis is fundamental to achieve functional, structural, and thermal characteristics in order to satisfy minimum regulatory standards and user comfort. For this purpose, another benefit of parametric modelling is the ability to create ready-to-use input files for powerful performance simulation software (e.g. Abaqus). Typically, such software are based on finite element method (FEM) analysis that can be used to obtain solutions on a broad spectrum of engineering problems including thermal, structural and acoustic investigations. In the proposed five-step approach, the FEM is used in synergy with parametric modelling by setting an iterative procedure. The objective is to adjust the parameter of the model until the

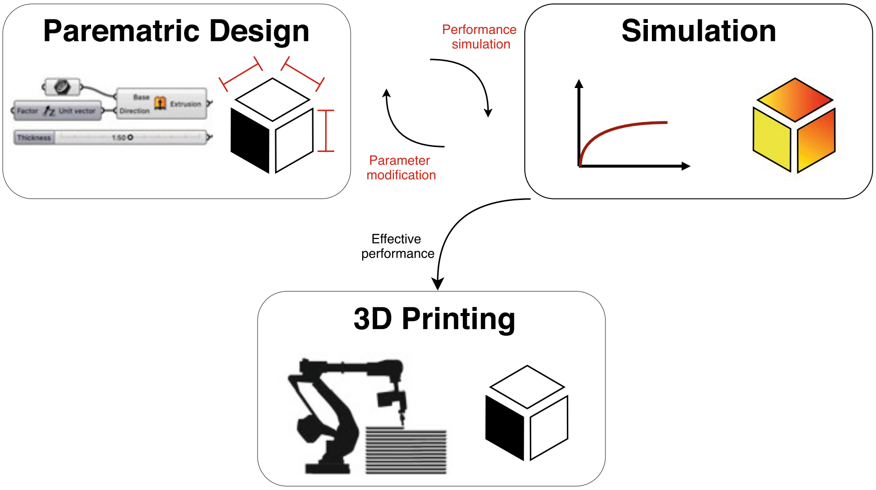


**Fig. 5** Iterative process for performance simulation and parameter adjustment

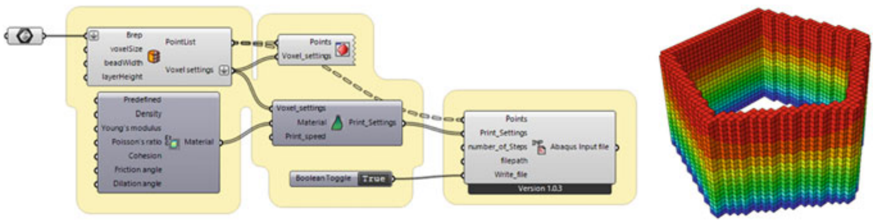


**Fig. 6** The connection between Grasshopper and Abaqus software for FEM analysis

minimum performances defined in the conceptual design are satisfied. Such operation is simpler and faster if the parametric model allows changing all the key parameters influencing the performance of the component. Figure 5 schematizes the iterative process for performance simulation and parameter adjustment.

In addition, Fig. 6 shows the components used in Grasshopper to connect the model with Abaqus software and run a printability simulation (a ready-to-use file for Abaqus is generated in Grasshopper). The resulting FEM analysis concern a printability simulation of two different configurations of the thickness (same example of a pentagon extruded shown in the previous sections).

## *2.5 3D-Printing and Prototyping*

The last step of the proposed procedure concerns the effective 3D-printing of the designed object. Even if the previous phases are carried out in a workmanlike manner, negligence in the final phase can compromise the quality of the result. Indeed, the products derived from 3D printing of viscous materials can be classified in three categories: (i) High-quality products meeting aesthetic, functional and structural requirements; (ii) Medium quality products not meeting aesthetic requirements with details not appreciable; (iii) Insufficient quality products not meeting aesthetic, functional and structural requirements, totally or partially collapsed.

To this aim, the current subsection provides a useful overview of the critical issues that can arise throughout the modelling and printing process. In particular, Fig. 7 shows 4 main fields that can generate criticalities: (I) Printing material, (II) Printer settings, (III) Design or (IV) Slicing. Every field is divided into more specific features affecting the results of a 3D printing process. In turn, each feature is associated with a specific effect derived. In the last part of the figure (on the far-right side), possible solutions to correct the wrong features are proposed. In the following discussion, a letter (**bold in brackets**) associates every specific feature (in **bold**) of the figure with the connected description.

**Material features**: The most important feature of the material employed is its viscosity (**a**). This feature leads to formal three-dimensional variations of the product and to its natural sagging as soon as the layers are deposited on top of each other. In this case, to solve a problem of a "too fluid" material it is possible to induce heat during the printing process or including additives in the mixture can be necessary to accelerate

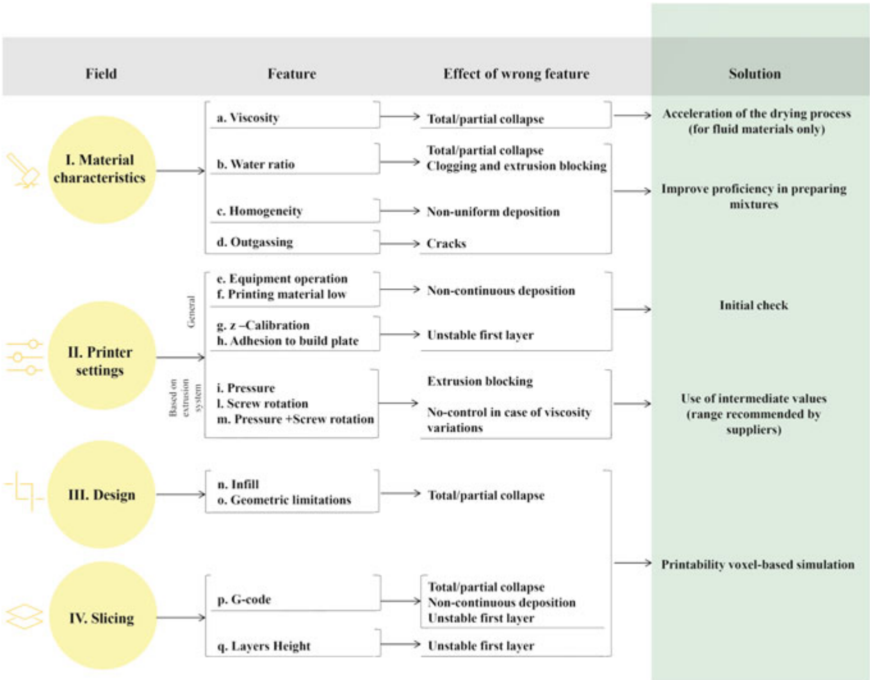


**Fig. 7** Overview of possible criticalities during 3D printing

the hardening process. In preparing mixtures, the water ratio is also crucial (**b**). Indeed, the material can result too solid or liquid according to the quantity of water introduced and respectively being less extrudable or tending to collapse immediately after extrusion. The mixture needs to be homogeneous and outgassed as well (**c**, **d**). Different consistencies and the presence of trapped air in the mixture may result in the printing of a product characterized by superficial defects such as cracks or that tends to collapse. Wrong features, in this case, can be avoided by preparing a mixture in a workmanlike manner with a suitable quantity of water, well-pressed and mixed.

**3D printer settings**: during the printing process, equipment failures (**e**) or material depletion (**f**) can occur. If the operations stop for some reason, the parts already printed get wasted or recycled and the 3D-printing process has to restart from the beginning in order to be continuous. Moreover, the origin on the z-axis needs to be well calibrated (**g**) and the extruded material must adhere to the build plate (**h**). Difficult adhesion is due to the different nature of viscous materials compared with the materials of which the plate is made. Wrong settings cause unstable deposition of the first layer with the consequent collapse of the entire extruded structure. Equipment full checks before launching a 3D printing process are considered to be indispensable. For what concerns the specific extrusion system employed, it is necessary to set proper values for piston pressure (**i**), screw rotations number (**l**) or both (**m**) in hybrid systems technologies. In case of viscosity variations and to prevent extrusion blocking, the use of intermediate values among ranges typically recommended by suppliers is suggested to be able to intervene on these settings during printing. To give an example, if the maximum pressure allowed by the machinery is being used and it is necessary to have a greater quantity of extruded material (e.g. the material is too dense) it is not possible to make this correction during the printing process by further increasing the pressure.

**Design**: the project of the infill structure determines the quality of the product. Inadequate infill regions (**n**) as well as the extrusion of "not printable" geometries (**o**) can lead to the total or partial collapse of the structure.

**Slicing**: errors in G-code (**p**) can produce an unstable deposition of the first layer and non-continuous deposition or total/partial collapse of the structure. Furthermore, layer height (**q**) needs to be well configured in order to avoid the fabrication of low-quality products in which the details are not appreciable.

In general, an effective FEM printability simulation (proposed in Sect. 2.3) should detect errors and prevent total or partial collapse during the 3D-printing processes.

## 3 The Five Steps Applied to Clay Bricks with Complex Infill

In the building sector, the possibility of creating **small components** to be assembled on-site can be very effective both for achieving customised design and high performances. The flexibility of the 3D printing can be useful to get complex geometries as in the case of the hi-performance clay bricks of Sangiorgio et al. [9]. In particular, this section shows how the proposed five iterative steps have been applied to obtain clay bricks with complex internal filling geometries [9].

## *3.1 The Conceptual Design of Complex Bricks*

The first stage of the conceptual design concerns the review of available AM technologies. Among the available technologies, in the case of 3D printed brick, the preliminary review focuses on Material Jetting exploiting clay material. During the first screening, the range of 3D printers of the Wasp company (Italy) is selected for the closeness of the supplier to the used laboratory (FabLab Poliba, Bari, Italy) and for economic convenience. In the second stage, since the proposed application concern the production of small/medium-scale building components, the machine Delta Wasp 40,100 for clay is selected. Indeed, such a machine represents a good compromise among availability, costs and geometric limitations of 3D printing (typical of a delta printer) [10]. In the third stage, the conception of the new printable bricks is defined by considering the limits of the selected machine. Beyond the limits of the selected 3D printer, two ideas guided the design: (i) The observation of the traditional and widespread external shapes and internal wall thickness of the brick; (ii) The use of periodic minimal surfaces to generate the complex internal configuration of the bricks.

Note that the periodic minimal surfaces are geometries well known for the high mechanical performances also used in ceramic 3D printing. To this aim, such geometries are selected to be integrated into clay bricks [11].

## *3.2 Bricks Parametric Modelling*

The purpose of the parametric modelling in the case of 3D printed bricks is twofold: (i) reach flexibility and adaptability of the elements allowing for a quick change of different periodic minimal surfaces as filling geometries; (ii) connect the parametric modelling with an accurate FEM analysis software in order to simulate the brick printability.

For the first purpose, the obtained visual script allows for quick modify the dimension of the brick (length, width and height), the number of minimum surfaces that can be inserted in the brick, and the thicknesses of the infill and of the external walls. In particular, the script is divided into four clusters of components in order to achieve *external shell generation* and thickness, *infill generation* exploiting the minimal surfaces, *infill thickness* and *finalization* of the brick respectively (Fig. 8). For the second purpose, the connection of the parametric modelling to the simulation software is achieved with Abaqus (FEM analysis software) through a plug-in named *VoxelPrint* for Grasshopper [12]. The components of *VoxelPrint* allow to create a voxelization of the designed geometries (convert the geometry to a set of identical

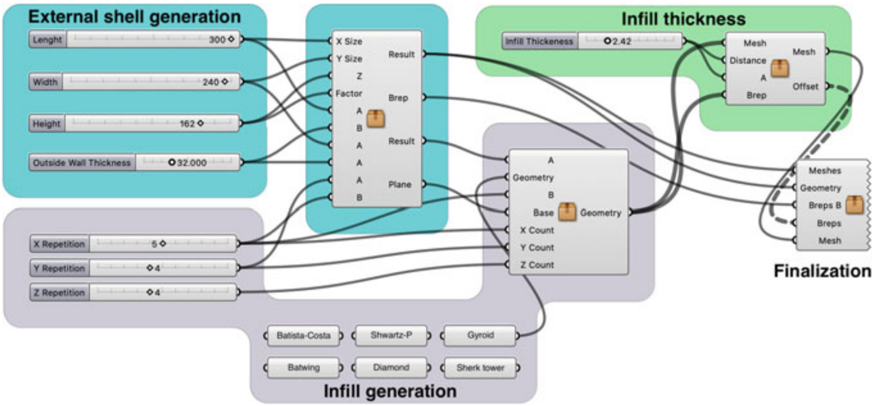


**Fig. 8** Visual scripting (with clustered components) to generate complex bricks

finite elements) and consequently achieve a ready-to-use input files for simulation in Abaqus [9].

## 3.3 Slicing Software

In the 3D printing of the proposed clay bricks, a specific path of the extruder is not necessary. Consequently, among the two slicing processes described in Sect. 2.3 the simplest approach, based on common slicing software such as Cura, is chosen.

The key parameters selected for the slicing include a layer thickness of 1 mm printed by a nozzle of 2 mm diameter and a printing speed of 30 mm/s.

## 3.4 Simulation to Verify Infill Printability

With the aim of achieving a printable brick with a complex infill exploiting minimal surfaces, an iterative process is set to adjust the dimension of the parametric model until the cells of the brick result printable from simulation. The parameters are varied by respecting the limitation of the Italian regulatory [9]: the minimum thickness of the external walls (external shell) is 1 cm while the thickness of the internal walls is considered to be at a minimum 0.8 cm. In addition, the external shell of this first prototyping is $15 \times 12.5 \times 9$ cm.

Starting from the lowest values of internal fill thickness (0.8 cm) and the number of cells (which cause the total collapse of the bricks) the iterative process led to an increase in the number of cells up to $4 \times 5 \times 5$ and an internal thickness of 3 mm. Indeed, to provide an example, Fig. 9 shows the analysis of the internal geometry

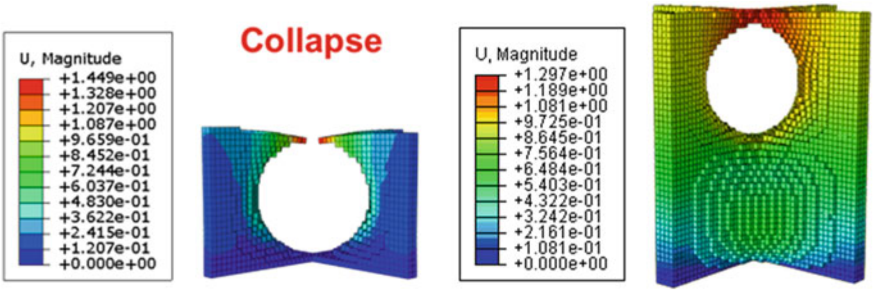


**Fig. 9** Brick cell collapse or cell perfectly printable

of "Sherk Tower" that collapses with a thickness of 1.5 mm and became perfectly printable with a thickness of 3 mm.

## *3.5 3D-Printing and Prototyping*

In conclusion, the prototypes of the bricks are printed by using a Delta Wasp 40,100 for clay by respecting all the suggestions proposed in subsection 2.5, specifically for obtaining a suitable viscosity of the printing material. To sum up, Fig. 10 shows the Slicing in the software Cura, the 3D printing and the final brick.

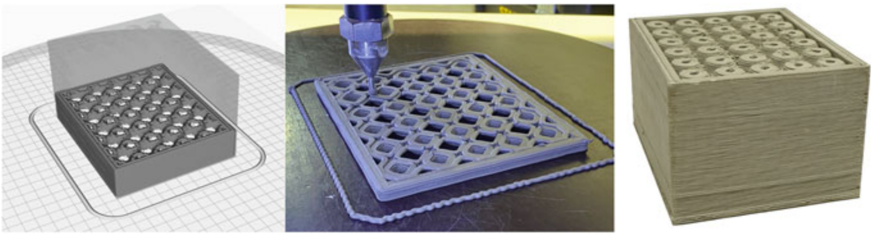

**Fig. 10** Slicing in the software Cura, 3D printing and final brick

# 4 Design of a Support-Free 3D Printed Nubian Vaults

Large-scale 3D-printing of viscous materials is becoming relevant in the research sectors of space and post-disaster architecture for giving the opportunity to extrude local earthen resources. The aim of this section is to propose a preliminary approach for 3D printing structures entirely made of raw earth. Due to technological limits in 3D-printing overhangs [13], structures are typically combined with traditional flat roofs in which just vertical walls or columns are additive manufactured. 3D-printing of roofs is a challenging process, and temporary or permanent supports may be necessary. However, the use of supports made of materials different from the locals should be avoided in extreme environments. In fact, the design and transport of formworks could be expensive and the realization hard or dangerous for workers. In the course of history, several techniques of masonry have been developed for building massive structures without the use of supports, such as Nubian vaults, Catalan vaults, and Persian vaults [14]. Considering the similarities between additive manufacturing and masonry, especially in compositional and structural fields [13], a further goal of this section is to determine a suitable strategy for closing 3D-printed structures by applying masonry constructive principles with a focus on the Nubian vault.

## *4.1 The Conceptual Design of Nubian Vaults*

The Nubian vault is a characteristic structure of the ancient region of Nubia composed by raw-earthen bricks held together by mortar. The bricks were assembled to form arches inclined at an angle of 45 degrees in relation to the level of ground. In this structure, formworks are not needed since each added layer is supported by that previously printed and already stable. Such construction principle has been reworked to be used in 3D printing with raw earth. In particular, the prototype has been conceived for being realized in the rural area of "Malandra Vecchia" (Abruzzo, Italy) and is inspired by the traditional earthen architecture present in its surroundings. In the forms, the project reminds of the "hut archetype" (Fig. 11, left). The innovative technological "hut" is thought to be made of inclined layers. Two components can be observed: (1) the part 1 is characterized by hut-shaped layers tilted at 45°, (2) the part 2 works as support for the tilted part and is composed by layers extruded horizontally.

## *4.2 Vault Parametric Modelling*

Also in this case, the aim of the parametric modelling is allowing quick changes in the model in order to optimize it and conduct a FEM analysis for the printability simulation.


**Fig. 11** Components of the nubian vault prototype and FEM printability simulation

Parameters consistently affecting the performances of the prototype are: (i) width of the span, (ii) height of the ridge line, (iii) height of the eaves line, (iv) angle of inclination of the hut-shaped layers, (v) angle of inclination of the sidewalls, (vi) thickness of infill, external walls and roof.

### *4.3 Parametric Slicing Process*

The printing process is of basic importance in this case, consequently, a parametric slicing process is set in order to draw an effective toolpath. Indeed, this method allows the creation of 45° inclined toolpath and enables different printing settings such as layers height and infill regions for each part of the prototype.

### *4.4 Performance Simulation*

In order to verify the performance of the inclined toolpath, a suitable FEM simulation (Abaqus software) is applied by investigating the deformation trends of the layers (according to the executed slicing). The right part of Fig. 11 shows the deformation of the upper layer (heavier in the central part of the arch) that remains acceptable to ensure printability.

### *4.5 3D-Printing and Prototyping of the Vault*

In the last phase, the effects of the correct slicing method can be noticed by printing a prototype and verifying the application of Nubian vault principles during production. Figure 12 shows the small-scale tests to simulate both the 3D printing with horizontal and inclined layers performed at "Fablab Poliba" Digital Fabrication Laboratory and by using a WASP Delta 40,100. The prototype realized with horizontal layers shows several printing criticalities (it collapses on the top and does not allow for

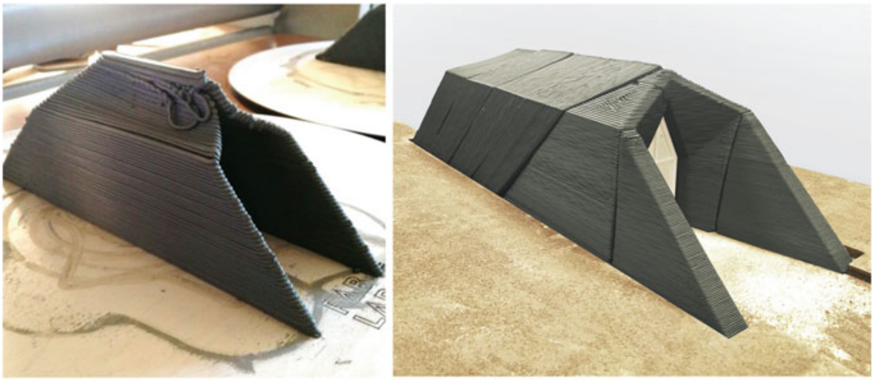

**Fig. 12** The prototypes with different slicing methods: horizontal and 45° layering

**Fig. 13** Render of the application of the 3D printed Nubian Vault in Malandra Vecchia (Italy)

the full closure of the structure) while the inclined layers are perfectly printable. In conclusion, Fig. 13 shows a rendering of the application of the Nubian vault in Malandra Vecchia, a fraction of the municipality of Casalincontrada, (Abruzzo, Italy).

**Acknowledgements** This research was funded by the European Union—European Social Fund—PON Research and Innovation 2014-2020, FSE REACT-EU.

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# A Study on Biochar-Cementitious Composites Toward Carbon–Neutral Architecture

**Nikol Kirova and Areti Markopoulou**

**Abstract** Concrete is currently the second most consumed material in the world, with it's core ingredient–cement, emitting 900 kg of $CO_2$ into the atmosphere with each ton produced. Carbon sequestering amendments can help tackle the negative impacts of the concrete construction sector. As the concrete construction industry along with the computational design tools and manufacturers evolve, they move towards new materially and structurally informed construction methods aiming at carbon neutral solutions. The research investigates the use of biochar (carbonised bio-waste) as an aggregate for sustainable cementitious composites. The literature on the topic suggests that the main limitation of biochar as a concrete amendment is the reduction in mechanical properties associated with an increase in biochar content. This chapter, however, approaches this as a design challenge for maximising carbon sequestration while reaching optimal structural performance. Based on the novel biochar-cementitious composites developed in IAAC (the Institute for Advanced Architecture of Catalonia), the work further investigates and defines new design principles for traditional building elements so that they can obtain a carbon–neutral or negative footprint. The programmability of the material mix, for instance, combined with additive manufacturing and computational design tools makes it possible to design and manufacture functionally graded architectural elements whose properties vary based on the mechanical or qualitative performance, among others. The research chapter uses three case studies and examines fabrication strategies as well as new techniques for material allocation and performance-driven design toward carbon-negative materially informed building elements. Following the properties and origins of biochar, a novel approach for building structures acting as "carbon sinks" is proposed.

**Keywords** Biochar · Cementitious composites · Carbon–neutral · Carbon sinks · Material-driven design

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_31

**United Nations' Sustainable Development Goals** 9. Industry, innovation and infrastructure · 11. Sustainable cities and communities · 12. Responsible consumption and production

## 1 Introduction

The increase in carbon dioxide ($CO_2$) emissions has been linked to rising global temperatures for nearly a century [52]. In 1938, Guy Callendar connected carbon dioxide increases in Earth's atmosphere to global warming which led to the formulation of the "Carbon Dioxide Theory of Climate Change" by Gilbert Plass in 1956 [34]. In the 1950s, a dramatic increase in the burning of fossil fuels to make electricity, oil for vehicles, produce steel and manufacturing overall vastly accelerated the rate of $CO_2$ being pumped into the atmosphere. Since then, atmospheric $CO_2$ has been increasing at an exponential rate [41]. The construction sector may not be the only contributor to this phenomenon, however, it is among the biggest.

The buildings and construction sector accounted for 36% of final energy use and 39% of energy and process-related $CO_2$ emissions in 2018, 11% of which resulted from manufacturing building materials and products such as steel, cement and glass [52]. Among those construction materials concrete stands out with its high production rate, being the second most used material in the world, which greatly increases its associated environmental costs. Compared to other conventionally used construction materials, concrete has a rather low embodied energy and embodied carbon but due to its excessive use, it is now considered to have a detrimental impact on the environment [14].

According to sustainability research, the world has exceeded four out of seven planetary boundaries. The areas of climate change, biodiversity loss, nitrogen cycle and land use have left the so-called safe operating space for humanity [47]. The built environment is a major contributor not only to $CO_2$ emissions but also to resource depletion. Regardless of the urgency to act and reduce the carbon footprint of the construction sector, concrete is still the second most consumed material, with three tonnes per year used by every person in the world [51].

The main ingredient of concrete is cement. Cement requires limestone and gypsum to be heated to about 900 degrees Celsius so that water molecules can be removed, making a powdery material that when needed can be chemically activated with the addition of water to form a durable solid, binding aggregated to produce what we now call concrete. For each ton of cement produced, 900 kg of $CO_2$ is emitted into the atmosphere making the cement industry alone responsible for approximately 5% of global anthropogenic $CO_2$ emissions [12].

Due to the global urbanisation trend, the housing demand in cities is rising. It is estimated that 60% of the new urban areas needed in 2030 have not yet been built [22]. It is also suggested that the built environment will nearly double by 2050. Aside from the fact that the concrete industry suffered a decline in 2020, the demand for concrete is projected to continue rising in the near future.

As previously discussed, the increase in $CO_2$ emissions has been directly linked to climate change and temperature rise. A point is reached where climate change cannot be mitigated solely by the reduction of the production and use of materials such as cement. There is an urgency to develop novel methods and approaches in the field of architecture and design.

Various frameworks, policies and international agreements have been put in place as acting measures to prevent further temperature rise and resource depletion as well as provide a better and healthier living environment. In 2015, the Paris Agreement, a legally binding international treaty on climate change, was adopted by 196 parties. Its goal is to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. To achieve this long-term temperature goal, countries aim to reduce the emissions of greenhouse gases such as $CO_2$ [10]. In the same year, the United Nations adopted the Sustainable Development Goals (SDGs), a universal development agenda, which goals need to be fulfilled by the year 2030 and by all UN countries worldwide [22]. Among the 17 goals depicted in the SDGs agenda, this chapter is going to address the following: Goal 9: Industry, innovation and infrastructure; Goal 11: Sustainable cities and communities; Goal 12: Responsible consumption and production.

Furthermore, in December 2019, the European Commission presented for the first time the Green Deal, which sets out how to make Europe the first climate-neutral continent by 2050 [16]. On the 14th of July 2021, the European Commission adopted a set of proposals to make the EU's climate, energy, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. Achieving these emission reductions in the next decade is crucial to Europe becoming the world's first climate-neutral continent by 2050 and making the European Green Deal a reality [16].

Various other reports by the European Commission suggest how to move towards a more sustainable future. For instance, adopting Advanced Manufacturing Technologies was proposed as a particularly beneficial research area, especially with regard to the construction sector where additive manufacturing or 3D printing has been suggested as an interesting field of research [15]. Another potential indicated innovation area is Advanced Materials. It has been indicated that lightweight materials can play a crucial role in Europe as new materials replace the old ones with more optimised and environmentally friendly alternatives [53]. Furthermore, with regard to the construction industry, it has been suggested that agricultural waste can be used to mitigate the large environmental impact of the industry and potentially link the industries. It is proposed that waste material from the end of the life cycle from the agricultural field can become useful material at the beginning of the life-cycle construction materials.

The "Advancing Net Zero" (ANZ) campaign conducted by the World Green Building Councils is a global programme working towards total sector decarbonisation by 2050. There are various ideas pushed forward within the programme such as energy efficiency and carbon offsetting. A net-zero carbon vision acknowledges the time value of carbon emissions from materials and construction. One of the proposed ways to achieve the Net-Zero vision is through radical cross-sector collaboration similar to the one proposed by the European Commission [56]. Collaboration between industries can aid circularity in design and economy.

Building on the idea of cross-industry collaboration, the "From Farm to Facade" EU initiative proposes exactly that by combining end-of-life products with new materials, the agricultural and construction sectors can mutually benefit [37]. For example, if waste produced by the agricultural sector is used as a product in the construction sector not only does waste obtain a newfound value and is therefore upcycled but raw materials are not extracted and therefore depleted in the same manner. This scenario aids both sectors to become more sustainable, producing less waste and decreasing their energy consumption and loss.

In 2016 a report by the European Environmental Citizen's Organisation for Standardisation (ECOS), included biochar among other waste materials that can be used as a fertiliser in the agricultural industry. Up until recently, there were no links between biochar and the construction sector, but this has changed. Research publications on the non-agricultural uses of biochar have increased exponentially since 2017.

## 2 Background

### *2.1 Cementitious Materials with Reduced Environmental Impact*

As previously stated, there is evidence that the concrete construction sector has a large negative impact on the environment. To mitigate and reduce this impact, various solutions are investigated and developed both from the material engineering side and from the construction technology side. Research is being carried out to develop mitigation strategies to control $CO_2$ emissions from the cement manufacturing sectors while retaining concrete's performance. These strategies include changes in the raw materials, the introduction of carbon-negative amendments, novel fabrication techniques, and material reduction, among others.

In this context, life cycle assessment and the effectiveness of alternative bio-based ingredients in cement manufacturing are also investigated. Additionally, notable studies on the efficacy of waste and ash-based amendments in cement have been reported. Although the addition of biobased amendments such as fly ash or biochar are cost-effective, they may reduce concrete's performance. Studies have found that the addition of biomass to cement causes its degradation due to the alkaline nature of the cementitious material which results in a decrease in durability [55]. In ash-based amendments, the presence of organic and inorganic impurities can be linked to the further depletion of cement's properties [28, 40].

There are several types of industrial waste or by-products that have pozzolanic properties and therefore can substitute cement or be added to concrete to reduce the amount of cement needed. Some of the most used by-products are: blast furnace slag which derives from the production of iron and steel (in blast furnaces); silica fume—a by-product of the manufacturing of silicone; and fly ash—a by-product of the coal industry.

Regarding blast furnace slag, research shows that partial substitution of cement with slag can improve durability and reduce the carbon footprint creating a more sustainable alternative to traditional concrete. However, both blast furnace slag and silica fume are not commonly used in concrete buildings but rather in infrastructure in harsh environmental conditions. Furthermore, comparing the costs associated with the use of slag and silica film to the costs of Portland cement it is still more economically favourable to use Portland cement.

Fly ash is one of the most adopted industry amendments for concrete. It has significant environmental benefits. With the right quantity of fly ash, the structural performance of concrete is improved but with the wrong balance, the decrease in strength is significant. Fly ash is mostly used in infrastructural elements rather than buildings mostly because it is better suited for precast rather than on-site construction but also because it has a degree of unpredictability. The main limitation of fly ash is that it does not allow air to penetrate through the material which makes it not suitable for cold climates and winter construction. It is also linked to the industry that produces it which is the coal industry. The coal industry is very harmful in terms of air pollution. Fly ash is abundant in developing countries that are still relying on coal for heating and energy production but in places such as Europe sufficient amounts of fly ash are not available. Making it harder to integrate into the construction sector.

Cement replacement and sustainable concrete amendments are slowly penetrating the concrete market. One of the main limitations of the slow adoption of these material systems is the associated economical costs and dependability on external, often highly polluting, industries. The research proposes an alternative solution for a sustainable concrete amendment that derives from the agricultural industry. It is proposed that biochar can be used within cementitious materials in order to decrease the carbon footprint of concrete and cementitious mortars. Biochars are produced throughout the globe by the local agricultural industries making them an abundant product in comparison to some of the previously discussed industrial by-products.

## 2.2 Biochar in Architecture

Organic waste or by-products from plants and/or animals, in particular waste from the agricultural industry or forestry management, have been underutilised for decades. Their primary use is for fuel production by direct combustion [3, 25]. Biochar is the solid residue obtained from the controlled thermal decomposition (pyrolysis) and gasification of biomass under limited oxygen [5, 54]. Notable control parameters are heating rate, temperature, and feedstock type (Tomczyk et al. 2020). The quality and type of feedstock affect the structure, chemical composition, and yield of the produced biochar. Biochar is black in colour, rich in carbon, has a large specific surface area, and has a porous structure. Aside from carbon, compounds such as ash, nitrogen, oxygen, and sulphur have been identified in biochar [27].

Biochar production has increased significantly in the last decade. Companies such as Carbofex, a Finish biochar producer, are developing new technologies for biochar production with minimal environmental impact. Biochar has been produced mainly as a by-product from agricultural waste and feedstock management, as well as forestry management. Biochar is commonly used for soil remediation [29, 46], carbon sequestration [49], energy storage and conversion purposes [26], etc. The most common use of biochar, currently, is as a fertiliser. The architectural and construction applications of biochar are underdeveloped and have been explored more rigorously only in the past several years.

The properties of biochar have been explored for the first time in an architectural context by the Ithaka Institute. As demonstrated by previous research the addition of biochar can lower the thermal transfer and enhance the water absorption of cementitious mortars and other materials. These qualities create an ideal condition for isolating buildings and regulating excess humidity. A study from the Ithaka institute has demonstrated, on a building scale, how the use of biochar plaster can regulate humidity, provide carbon negative finishing, and enhance thermal insulation while maintaining breathability [44]. It is also suggested that when biochar is applied in brick form with a thickness of up to 20 cm it can be used as a substitute for Styrofoam as an insulative material. Furthermore, if biochar is to be mixed with clay and lime instead of cement at the end of life, the material can be directly used as a compost closing the cycle of the construction material.

"Made of Air" was founded in 2016 by architects Allison Dring and Daniel Schwaag, who have developed a type of thermoplastic that can be easily moulded and holds large quantities of biochar-derived organic waste mixed with sugar cane. In April 2021, thermoplastic was installed on a building for the first time. An Audi dealership in Munich was clad in seven tonnes of hexagonal panels. It was assessed that the entire facade cladding accounts for 14 tonnes of carbon that would be sequestered until the recycling of the cladding tiles [23].

Another example of a biochar-derived product that has application in architecture comes from a U.S.-based company called "Interface". They produced their first carbon-negative carpet tile in 2021. The company specialises in carpet backings made of biochar and other composites. Because the company's product is on the market there was little information found on the material composition and carbon footprint.

The state-of-the-art analysis shows that currently there are no biochar-derived building elements or structural elements for the architectural sector. All the products mentioned above are related to either interior use or exterior cladding systems. However, it is interesting to note that all of the products reached the market after 2020. The interest in biochar and its ability to sequester carbon is rising and more and more companies, industries and researchers are looking into the properties of the material.

The research proposes that there are further applications of biochar cementitious composites that can be used within the architectural and construction sectors to reduce the carbon footprint of structural building elements.

## *2.3 Biochar Cementitious Composites: Performance*

The following section discusses several categories of biochar research. An extensive literature review on biochar in architecture from a material science and engineering perspective is used to set the ground for the research. The main categorisation is done in three categories based on material performance: Environmental Performance; Mechanical Performance; Qualitative Performance. Following, several case studies of existing architectural applications of biochar are presented and analysed. Furthermore, three applied research projects where the author has contributed to the state of biochar-cementitious materials research are described and analysed in detail.

### 2.3.1 Environmental Performances

Carbon Sequestration

Carbon sequestration, including geological, oceanic, and terrestrial ecosystem sequestrations, plays an important role in mitigating global warming. Embedding carbon sequestering techniques and materials in industries such as the construction industry can aid in meeting environmental goals with minimal cost. Among many construction materials that are associated with carbon sequestration, indubitably timber stands out. Wood is one of the most environmentally friendly construction materials. Recently, it has gained a lot of research interest in reaching higher design freedom with the aid of digital fabrication methods. Even so, concrete is still the number one globally used construction material due to the associated design freedom, cost efficiency and ubiquity. Making it important to investigate carbon sequestration possibilities of concrete and cementitious mortars. Biochar can help the concrete construction industry meet the current environmental demands due to its long-term carbon sequestration potential. Furthermore, as cement or a fine aggregate replacement in concrete or mortars it does not only sequester carbon but additionally decreases the consumption of cement; hence, saving energy and reducing the discharge of $CO_2$ in cement production (Li et al. n.d). Several studies on cement mortars demonstrate the carbon sequestering potential of biochar when investigated as an amendment to the composite [16, 17, 20, 21, 33, 42, 48].

Most studies focused on carbon sequestration propose treatments to improve the performance of the material. One of the discussed options is pre-treating biochar with a 0.1N HCl solution. It is suggested that this technique can improve the carbon sequestration ability of biochar-cement mortars [56]. The research shows that this treatment provides additional benefits to the compressive strength of the mortars, with up to 15% of biochar the compressive strength at 28 days of curing decreases by only 4Mpa (from 44.7 to 40.6). Furthermore, at only 5% biochar concentration the data show that the mortars have a 75% $CO_2$ sorption, giving evidence of the carbon sequestration potential. Another study looks in detail at the difference between saturated and unsaturated with $CO_2$ biochar in mortar mixture [56]. It concludes that the use of saturated biochar triggers off carbonation, which affects the strength development and porosity of mortar. Biochar saturated with $CO_2$ can control the ingress of water into mortar primarily due to fine particle size, but the water absorption is drastically increased. Therefore, it is recommended to use unsaturated biochar as a means of sequestration of stable carbon in cement composites. It was interesting to find out that in a previous publication by the same research team it was discussed that saturated CO2 biochar can have an enhanced carbon sequestration potential [56]. Such evolution of the research perspective is encouraging to researchers in the field of sustainable cementitious materials through the perspective of biochar. This shows that there is a need for further and more in-depth research before biochar-cementitious composites become marketable to the industry in a convincing manner.

Furthermore, it is important to point out that the type of organic material used to produce biochar would produce biochar with different carbon content. There are two main factors to be taken in account: the amount of carbon inherent in different types of feedstocks and the production process. The International Biochar Initiative classifies the organic carbon content into the following three categories [9]:

- Class 1 = >60% (e.g., from plant and tree waste)
- Class 2 > 30% < 60% (e.g., from poultry manure mixed with organic bedding material, paper sludge)
- Class 3 > 10% < 30% (e.g., from cow manure, sewage sludge).

This classification proposes that it is more desirable to use plant or tree waste feedstock to produce biochar. Another aspect to be taken into account is the transportation of the material. The closer the source is to the manufacturing facility and/or site the lower embodied carbon and therefore the higher carbon offset is generated.

The above-discussed studies on biochar as a carbon sequestering material in cementitious mortars demonstrate not only the growing research interest in the field but also that it is backed up by data showing the potential that the integration of biochar in those material systems has. These studies are part of a larger body of research that aims to combat the carbon emission of concrete construction while making as little change to the construction method as possible. I believe that to make a real and disruptive impact on the industry we have to consider not only how to improve the material but also how to design better with the improved material.

#### Vegetation Compatibility

As previously stated, soil fertiliser products are one of the main widely recognised applications of biochar. There is persistent evidence that charcoal made of biowaste can improve the fertility of soils. The first notions of the positive impact that biochar has on vegetation have been associated with the "Terra preta" soil type. "*Terra preta*" has a characteristic black colour due to its high charcoal content. It was created by farming communities between 450 BCE and 950 CE in the Amazon Basin to combat the low fertility of the local soil. The biophilic properties of biochar have been recorded and studied ever since.

In the field of architecture, the biophilic properties of biochar have not been widely explored; however, there are some studies that demonstrate that biochar improves the vegetation compatibility of vegetation concrete. It was demonstrated that in pervious or vegetation concrete, biochar can accelerate plant growth and provide a healthy microbial environment at 5% content by weight [58]. Additionally, biochar pervious concrete samples show both greater compressive strength and splitting tensile strength when the biochar content is below 6.5%, above that concentration these strengths are compromised [39]. These studies outline that there is still room for future research in order to better understand how biochar can be used to promote growth and biodiversity in the built environment. Furthermore, it is suggested that the vegetation compatibility and even possible growth-enhancing properties can be beneficial to the end-of-life of biochar-cementitious composites.

## Mechanical Performances

### Compressive Strength

The compressive strength of biochar cementitious materials has been rigorously investigated within the past decade. It has been demonstrated that the mechanical properties differ based on the biochar type, content, and pyrolyzing temperature. The various studies show different trends when it comes to the effects biochar addition has on the compressive strength of concrete and mortars. Overall, most studies agree that a high concentration of biochar compromises the strength of the composite while low concentrations (below 2%) can improve the strength due to better hydration. It is also agreed that the effect of the type and origin of the biochar has a great effect on the mechanical properties of the cementitious composite and calls for further investigation and mapping out of these differences. For example [2], investigated the compressive strength of biochar produced from rice husk, poultry litter, and paper mill sludge. Concrete blocks with 0.1%, 0.25%,0.5%, 0.75%, and 1% biochar in relation to the total volume of the composite were produced. Concrete with biochar obtained lower compressive strength than conventional concrete. After 28 days of curing the study found that the 1% addition of biochar improved the strength of the concrete. The researchers encouraged the use of a higher percentage of biochar in concrete production without surpassing 1%. By further investigation, these results were explained by the improved hydration during the curing process.

The study of [8] supported the observations of [2]. The compressive strength of concrete with the addition of biochar derived from dry distiller grains was investigated. In particular, the study looked at the effects of replacing sand and aggregate within the composite with 1.2% and 3% of biochar. The findings showed a minor increase in the mechanical properties after the addition of biochar. The addition of 3% biochar yielded maximum strengths of 21 MPa (when replacing sand) and 22 MPa (when replacing aggregates).

In a study by [19], the optimum concentrations of biochar for increasing the compressive strength of cement mortar were found to be 1% and 2%. When compared to standard mortar, a significant increase of 22% and 27% was observed. Following that, biochar addition beyond 2% resulted in a reduction in strength.

Furthermore, [4] reported maximum strength on the concrete samples with added 5% bagasse biochar. In contrast, [32] observed a decrease in compressive strength when as high percentages of biochar as 5% were added. It was suggested that this decrease was caused by the high-water retention capacity of the biochar. Based on these findings, we can conclude that the compressive strength of the concrete is highly influenced by the feedstock used in the production of biochar [45], also agreed that the properties of the feedstock material have a great impact on the compressive strength of the composite. By comparing the outcomes of the above-mentioned studies, we can conclude that the feedstock, pyrolysis temperature, and particle size can considerably affect the mechanical properties of biochar/cementitious composites, regardless of the biochar content.

Some alternative research focusing on high-performance concrete shows that biochar may not be suitable for this application. [11] investigated the effects of replacing quartz powder with saw dust-based biochar at 2% and 5% in ultra-high-performance concrete. The results after 28 days of curing showed a reduction in the compressive strength by 13% and 14% respectively. The authors suggested that this is due to the biochar's poor properties in comparison to the other constituents (silica fume, silica sand, and quartz powder) in the ultra-high-performance concrete.

Furthermore, [31] investigated how biochar and MgO will affect the compressive strength of concrete when used in a synergetic matrix. A weed tree-based biochar was used and added at 2%, whereas the MgO was added at 4 and 8%. The study showed that MgO in higher quantities reduced the strength of the composite but the addition of biochar to the MgO counteracted that reduction in the long run and therefore had an overall positive impact. Adding 2% of biochar to the 8% MgO resulted in an increase of 6% in comparison to the control sample after over 3 months of curing.

One of the few studies where higher concentrations of biochar have been examined is [35]. The study investigated the effects of biochar addition to cementitious mortars in three different proportions (5%, 10%, and 20% of cement weight). The compressive strength of the biochar mortars at room temperature was recorded at 35, 39, 28, and 16 MPa for 0%, 5%, 10%, and 20% biochar addition, respectively. Similarly, to other studies, the conclusion is that the addition of biochar in higher quantities than 5% leads to a decrease in compressive strength. Furthermore, it can be concluded that even though the effects of feedstock type, pyrolysis temperature as well as particle size have an undeniable effect on the mechanical properties of biochar-cementitious composites, high concentrations of any form of biochar will always lead to a decrease in the compressive strength. The compressive strength of concrete is directly linked to its composition. It is demonstrated that by introducing biochar into the mixture the compressive strength decreases. In this research, the above state correlation between compressive strength and biochar concentration will be used as a design driver for functionally grading the amount of biochar in cementitious composites.

#### Tensile Strength

Concrete is known for its weak tensile strength which is improved by the addition of reinforcement. Flexural strength is a metric that represents the tensile strength of homogeneous materials such as concrete and mortar. The rule of thumb is that the flexural strength of concrete is about 10–20% of the compressive strength. There are studies examining the tensile strength of biochar-cementitious composites. Cracks in the cement structure may form because of factors such as stress concentration, drying, and shrinkage, which may increase under loading [1]. As a result, microcracks may develop into macro cracks or become connected to the adjacent microcracks, forming branches, and resulting in failure. Another important consideration is the brittleness of the concrete materials, which has a direct impact on the tensile strength of the cement. Biochar could be used as an efficient particle reinforcement to increase the tensile strength of cement.

Most of the studies that investigate the effect of biochar addition on the tensile strength of the biochar-cementitious composite agree that with about 1% addition of biochar the tensile properties are improved [15, 35]. It is suggested that the higher specific surface area of the biochar is the main reason for the increase in flexural strength, which contributed to the enhanced interaction with the matrix. It is also evident that the type of feedstock used had a great impact on the tensile enhancement. For instance, studies with hazelnut shells, cherry pits and peanut shells proved more beneficial in comparison to coffee powder and sawdust [28, 30]. It is worth noting that, based on the particle size, type, and preparation of biochar, different concentrations are required to optimise different mechanical properties. The concentration also affects the amount of water needed to improve the performance of concrete.

#### Fire Resistance

Studies on the fire performance of concrete have shown that, compared to building materials such as steel and wood, concrete demonstrates the best fire resistance [13]. The addition of reinforcements further increases the thermal stability of the concrete. However, according to previous research, the size and form of the reinforcements may not have a significant influence on thermal stability [43]. In addition, reinforced concrete exhibits an increase in strength up to 450C and decreases as the temperature is elevated beyond 600C (Jackiewicz-Rek et al. n.d). When produced at high temperatures of pyrolysis, biochar creates strong C–C covalent bonds that make it very stable and insusceptible to temperature elevation. Even though fire resistance is not the focus of the research, it is important to attain a deep understanding of the impact biochar has on various properties of cementitious composites. Based on the literature review it is suggested that this will improve the fire resistance of cementitious composites such as concrete.

### 2.3.2 Qualitative Performances

Thermal Conductivity

The thermal conductivity of concrete is varying from 0.62 to 3.3 W/(mK) for standard concrete, or 0.4–1.89 W/(mK) for concrete with lightweight materials [6]. Based on a study of nine concrete samples containing varying quantities of biochar it has been established that biochar has a positive effect on the insulating properties of the concrete. It is suggested that this effect is due to the high porosity and the low thermal conductivity of biochar (Berardi and Naldi, 2017). Even though there the research showed some inconsistency with thermal conductivity of samples with biochar concentration below 5% the effects of poor distribution seem to be negated at higher biochar loading levels, demonstrated in the samples containing 10% and 12% by weight.

Other research also backs up the findings and shows that increasing the aggregate volume fraction increases the thermal conductivity of the concrete sample [36]. However, these studies are typically performed at much lower water to cement ratios, so the excess water content that the biochar demands may have an unexpected impact on the insulating properties. Generally, the thermal conductivity of a material decreases as the material density increases. However, it is possible that this could also come down to the build-up of the biochar.

Moreover, the thermal conductivity of the concrete samples is consistent across the temperature range. This shows that the biochar would be effective in insulating buildings in different weather conditions. Biochar addition has a positive effect on improving the thermal insulating properties of the concrete [8]. The results of this study show that biochar addition improves the thermal resistance of the concrete, even at lower concentrations. However, the insulation would still need to be used in building applications with the concrete incorporating biochar, but the decreased thermal conductivity would undoubtedly contribute to improved thermal efficiency and limit thermal bridging effects.

An intriguing study published in the “Science of the Total Environment” journal suggests a new perspective of biochar as a building material with improved hygrothermal properties [36]. It was demonstrated that biochar-mortar can be used as a functional building material to improve the hygrothermal performance of the building envelope. Two types of biochar were compared within a biochar-mortar composite with a mixing ratio of the biochar from 2 to 8%. The thermal conductivity of biochar-mortar composites was decreased as the biochar addition increased. Furthermore, the water vapour resistance factor of biochar-mortar composites increased by 50.9% compared to the reference specimens. The study proposed that biochar-mortar composites can contribute to humidity control without facilitating mould growth and additionally improve the thermal insulation of cementitious mortars.

#### Humidity Regulation

As biochar is created through the process of pyrolysis it commonly has high porosity and surface area on a microscopic level. This can vary based on the conditions of pyrolysis and type of feedstock but often the produced biochar has high water retention capacity due to its porosity. As previously stated, the most common use of biochar is in the agriculture industry, where it serves as a fertiliser that retains moisture while preventing mould growth. However, the inherent relation between biochar and water opens the possibility for other applications in the fields of water purification and construction.

Looking into biochar applied in previous concrete, studies show that by increasing biochar content, the water adsorption increases, and the porosity of the specimen decreases which helps in regulating the growth of microorganisms [57]. Furthermore, when used in pervious concrete pavement blocks, biochar can help reduce surface runoff, purify water pollution, and mitigate the urban heat island. An investigation on how to prolong the evaporative cooling effect of paving blocks by incorporating biochar particles, as hygroscopic filler, show that replacing a small quantity of cement by biochar could effectively improve the evaporative cooling performance [50].

#### Acoustic Dampening

Sound absorption is the loss of sound energy when sound waves come into contact with an absorbent material such as ceilings, walls, floors and other objects, as a result of which, the sound is not reflected back into the space. Acoustics comfort is an increasingly important topic between architects and designers due to its role in boosting productivity and reducing anxiety among other benefits. One of the metrics used to measure sound absorption is the sound absorption coefficient (SAC). The SAC for plain cast concrete is about 0.02, indicating that about 98% of the sound energy is reflected by the surface. Even though acoustics is a complex field of study, where many parameters have to be accounted for, designing for specific acoustic conditions can be tricky. The three main variables to be taken into account when designing spaces for acoustic comfort: are surface geometry, materiality and depth of spatial separator.

Biochar as an amendment for cementitious composites is shown to improve the SAC over a range of frequencies [8]. The study compares biochar to activated carbon, and even though both the addition of biochar and activated carbon had a noticeable impact on the sound absorption across the entire frequency range. It is suggested that the sound energy dissipation within the interconnected pore networks in the concrete created by the biochar addition, was responsible for the high sound absorption coefficients. Even more encouraging is that biochar seemed to have the same effect as the activated carbon in this regard, with both the 10% and 15% samples showing near identical curves as that of the concrete with the 7.3% activated carbon. While this could be due to the higher concentrations of biochar, it would be expected that the considerably higher surface area and associated porosity of the activated carbon would result in higher sound absorption properties.

## 3 Digital Matter and Intelligent Constructions

The architectural applications of biochar have been studied in several projects developed in the Digital Matter and Intelligent Construction (DMIC) research studio taking place in the first year of the Master of Advanced Architecture in the Institute for Advanced Architecture (IAAC). The DMIC studio tackles the environmental challenges of the building sector with research on the implementation of advanced digital technologies of computational design, material computing, human–computer interaction, and artificial intelligence coupled with the latest tools in digital and robotic fabrication. The studio introduces a model of materially responsive and circular architecture that presents possibilities for designing novel performances and dynamic metabolisms in the building industry.

Starting from allocating problems and opportunities in the local context, each year students aim to identify potential resources that can be upcycled into performative and adaptive building components for different architectural features. Students dive deep into analysing material opportunities that are embedded into the fabrication process, creating a coherent and informed narrative of the material life-span while using computation techniques and digital fabrication in order to establish workflows to design more sustainable and contextualised buildings. The design studio researches the implementation of computed, active or zero emissions material systems.

Biochar is studied as a carbon-negative matter that can augment and engage certain material performances. During the development of the below-discussed projects, the focus was on investigating the different applications of biochar in terms of a material matrix, fabrication techniques and architectural design. Various mixtures were developed and tested for mechanical properties, thermal insulation and humidity regulation. Fabrication techniques from casting to robotic material allocation were explored in order to allow design freedom and multi-material optimisation through a functionally graded design process. Additionally, the design that manifests from the material properties was explored and proposed within the conclusions of each research project.

## 3.1 Research Introduction and Significance

As discussed in the previous chapter, biochar as an amendment for cementitious composites has been thoroughly explored from a material engineering perspective. The addition of small quantities of biochar within concrete has many beneficial properties such as carbon sequestration, improved vegetation compatibility, fire resistance, thermal insulation, humidity regulation and acoustic dampening. However, by introducing biochar to the composite matrix the mechanical properties decline. In particular, it is demonstrated that the quantity of biochar is proportional to the decrease in both compressive and tensile strength. To deal with this, the research looks into the adoption of functionally graded material and design approaches that would allow for the optimal allocation of lower or higher quantities of biochar in correspondence to the structural needs. The design possibilities of the material system are mostly unexplored, especially in the context of maximising the carbon sequestration potential aiming to mitigate the environmental impact of concrete construction.

The research looks into three case studies where the material system has been applied through a performance-driven design framework in order to demonstrate the potential and implications of the use of biochar in concrete building construction. The research hypothesis is that through the adoption of biochar-cementitious composites, within the construction industry, buildings can be transformed from carbon sources to carbon sinks. The following research projects investigate the material developments, fabrication possibilities and architectural applications of biochar-cementitious composites through an empirical study based on physical and digital experimentation.

## 3.2 Research Projects

### 3.2.1 Cast in Carbon (2019)

"Cast In Carbon" is a research project developed over the period of six months in 2019. This investigation started the research on biochar in the DMIC in IAAC. The project studies the impact of large quantities of biochar within material systems that can be used in the construction sector, initially in clay and cement composites but eventually narrowed down to cementitious composites. The project was inspired by the idea that the carbon cycle can be altered as excess $CO_2$ is removed from the atmosphere and sequestered within building structures and envelopes. The main premise is that as carbon is stored in buildings it converts them from "carbon sources" into "carbon sinks" holding carbon for up to decades. The research focuses on the physical properties of biochar as a standalone material and as a part of the material system, replacing environmentally harmful construction materials in existing scenarios.

Biochar is the material obtained when organic matter undergoes thermal decomposition under the limited supply of oxygen at relatively low temperatures (<700). It is a very stable carbon-rich material, which can sequester carbon for thousands of years. On average 1 kg of finished biochar can sequester up to 1.8 kg of carbon dioxide. A life cycle assessment is conducted to further understand the net embodied carbon of biochar (Fig. 1). The feedstock from which biochar is produced can affect the properties and carbon sequestration potential of the final material system. For instance, hardwood feedstock has a higher value of negative embodied carbon in comparison to softwood feedstock. This is due to the amount of carbon that the tree photosynthesises during the natural growth process. As biochar is commonly produced from forest management feedstock, the embodied carbon of the feedstock together with the processing, transport and pyrolysis conditions have to be taken in consideration. It is estimated that softwood biochar will have a carbon neutral embodied carbon value whereas hardwood biochar will have a negative embodied carbon value.

Biochar can be obtained from pyrolysis of biomass in the temperature ranges of 200-900 °C. The biomass is heated inside a pyrolysis kiln up to the required temperature with a limited supply of oxygen. The by-products obtained from this process are biochar, bio-oil and syngas. The temperature at which the pyrolysis occurs plays an important role in the physical and chemical properties of the obtained biochar (Fig. 2) [35–41]. Higher temperature (900 °C) results in lower density and microporous structure whereas lower temperature (200 °C) results in higher density and macroporous structure. The density and microporous structure of the biochar has a direct impact

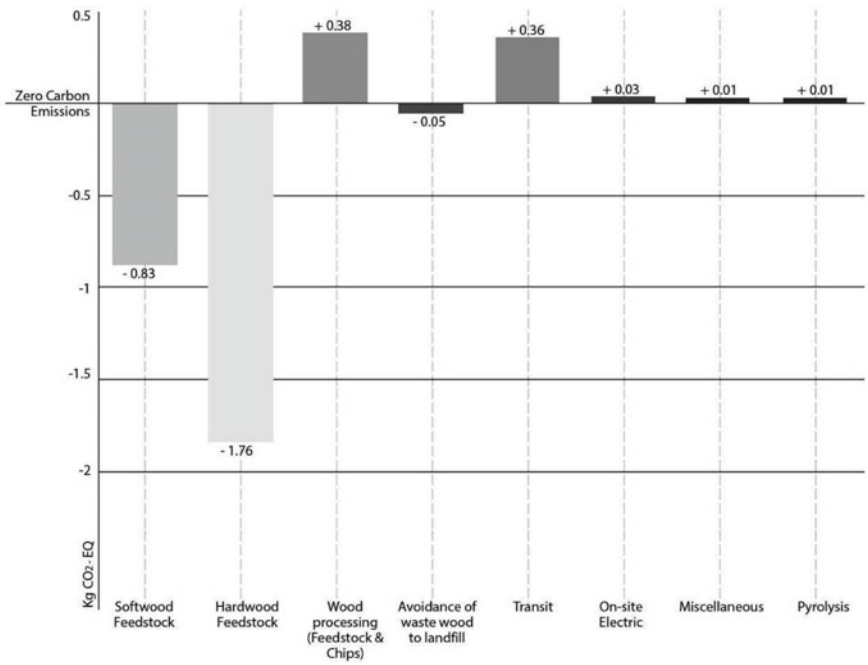


**Fig. 1** Embodied carbon in production processes to obtain biochar alongside the embodied carbon of softwood and hardwood-based biochar

on its performance including the thermal conductivity and absorption of both gases and water. The programmability of the properties of biochar with the conditions of pyrolysis opens the possibility to modify and create specific performances based on the context or minimise the embodied energy of the material.

In the first phase of the material, research biochar was explored within two composite bases: cement and clay. A range of specimens was produced to be tested for compressive strength with a hydraulic press. It was observed that the clay composites were less stable and exhibited large shrinkage. At the time, the testing equipment in the lab was limited to 100 PSI pressure. All cement-based mixtures with less than 60% of biochar have strength above the threshold in comparison to the clay-based mixtures where the samples with less than 50% of biochar were above the threshold (Fig. 3).

Furthermore, it was demonstrated that the addition of biochar decreases both the weight and compressive strength of the material. In comparison to the studies in the subchapter "Mechanical Performances" where the higher concentration of biochar within the composites was 20%, this study explored large quantities of biochar reaching 90% [35]. However, the trend is consistent as the addition of biochar above 10% has proven to be detrimental to the mechanical properties of the composites. Based on this first experiment the research continues to investigate cement-based composites as they appear more suitable for the construction sector.

Further tests on the developed biochar-cementitious mortars (BCMs) with varying proportions of biochar are conducted looking into the following performances of the material system: compressive strength, humidity retention and thermal conductivity.

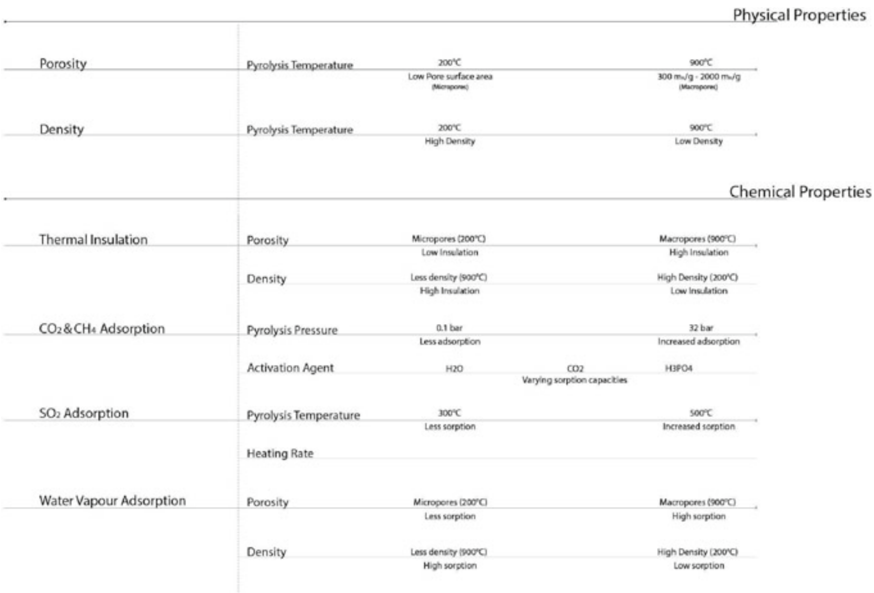


**Fig. 2** Programming biochar properties based on pyrolysis conditions

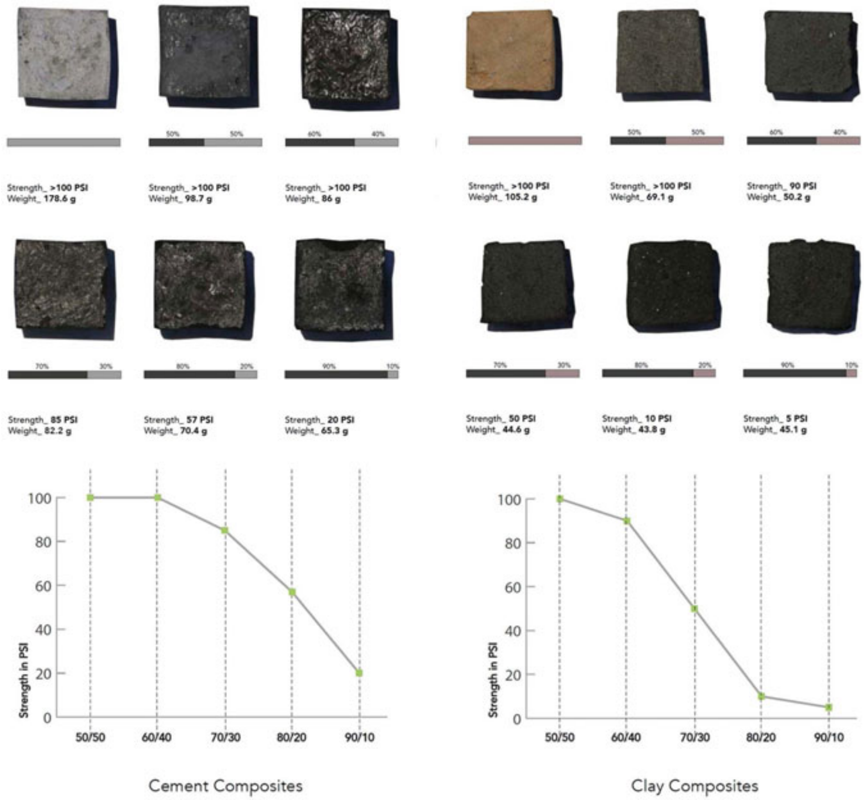


**Fig. 3** Cement composites

Multiple specimens of 50/50; 40/60; 30/70 proportions of cement and biochar as well as 100% cement control specimens are produced and left to cure for 28 days.

The following experiment is conducted and compressive strength measurements are collected using a hydraulic press at the Universitat Politècnica de Catalunya material testing laboratory. Due to imperfections on the edges of the specimens the test is not conclusive. However, it is determined that the compressive strength decreased exponentially between the pure cement specimen and the 50% biochar specimen and it continued to decrease as the biochar quantity reached 70% (Fig. 4). Further tests have to be carried out and more samples have to be tested to get a better estimate on the actual compressive strength of the composites.

Specimens from the same series are used for a water absorption test. The test is conducted within a control chamber with a humidifier over 2 days. The weight of the samples is measured thirteen times over the testing period and the relative humidity within the chamber is recorded (Fig. 5). It is evident that the amount of biochar is proportional to the decrease in weight; however, no distinct effect of the increase in relative humidity on the weight of the specimens with biochar is observed. The

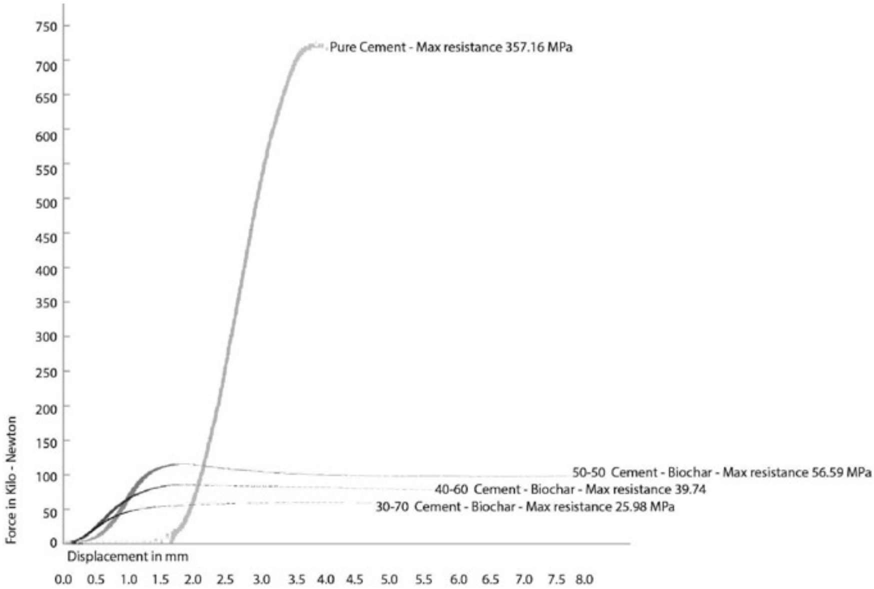


**Fig. 4** Compressive strength of the developed samples as recorded during student investigation

specimen of 70% biochar exhibited slightly higher water absorption in comparison to the rest.

Furthermore, a second test on the water absorption is conducted following a different method. The speciements are left in water for 2 h and their change in weight is measured again for 2 day. It is observed that it takes 1 h for the samples with biochar to fully hydrate whereas the pure cement samples continue hydration for the full 2 h. The 50/50 BCM specimen shows the largest water absorption and retention in comparison to all other material mixtures (Fig. 6).

The last test from the series is on thermal conductivity. Rectangular specimens with 200 × 200x20mm dimensions are developed with the same material composition. The specimens are tested using a custom thermally insulated apparatus where one side of the sample is exposed to heat and measurements are taken from both sides of the specimen (Fig. 7). The biggest temperature difference between the front and back faces of the samples is measured in the 40/60 BCM. The test is inconclusive as only one set of samples is tested however, based on the results obtained it is concluded that biochar within the material mixture can improve thermal insulation.

In conclusion, the set of experiments demonstrated that the higher percentage of biochar within the cementitious composites resulted in lowered mechanical properties, improved water absorption and thermal insulation. Further research is conducted to reflect the limitation of the material system, specifically the lack of sand, fibres and aggregates within the composition.

The "Cast in Carbon" research project proposes a modular, functionally graded design approach taking advantage of the material properties without compromising

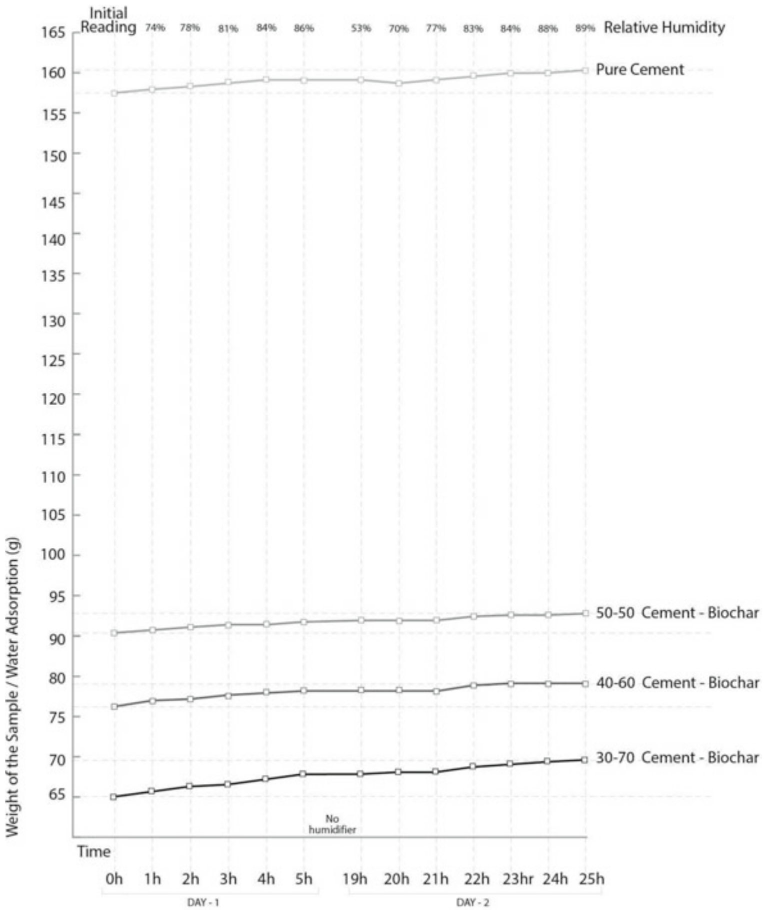


**Fig. 5** Change in the mass of the developed samples due to water absorption as recorded during student investigation

the structural integrity of the structure or building element. Two main architectural applications are studied: a vault pavilion and a curtain brick facade.

Comparing the embodied carbon, weight, strength and cost of standard clay brick with BCM bricks of 50/50; 40/60 and 30/70 proportions, shows that the BCM bricks score better on all parameters making them both more structurally performative and carbon sequestering (Fig. 8). The brick system is further developed with a study on interlocking possibilities (Fig. 9). The interlocking system is explored as an option that would minimise the need of extra mortar.

Looking at the architectural design proposals, the vault pavilion is suggested as a compression only structure taking into account that as concrete without reinforcing the developed material systems performs only in compression (Fig. 10). The vault is designed using parametric design tools, in particular Rhino's Grasshopper and the

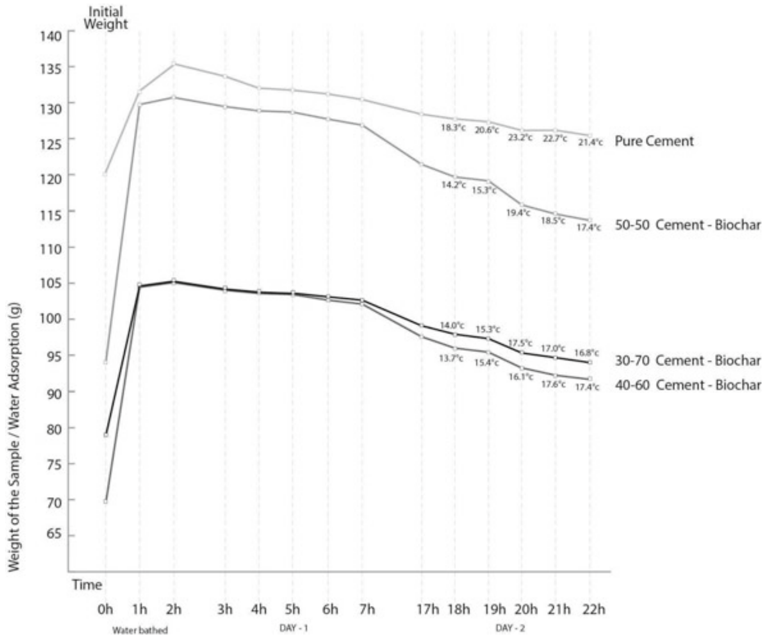


**Fig. 6** Comparison of water absorption measurements of four material compositions based on water submersion test

Karamba plug-in. The vault is functionally graded based on structural analysis. The second design application is a curtain brick facade following a similar principle but utilising other material performances such as thermal insulation and humidity regulation (Fig. 11). A final architectural vision of the first iteration of biochar architectural language with both the vault structure and the curtain brick facades is presented as a conclusion of the investigation (Fig. 12).

### 3.2.2 Terra Preta (2020)

The second research project, "Terra Preta", was developed in 2020. The research builds upon the "Cast in Carbon" investigation and explores how biochar can be used within a geopolymer rather than an Ordinary Portland cement (OPC) material system as well as the possibility of natural fibre integration within the material matrix as tensile reinforcement. Unlike Ordinary Portland (pozzolanic) cement, geopolymers do not form calcium-silicate-hydrates (CSHs) for matrix formation and strength but utilise the polycondensation of silica and alumina precursors to attain structural strength. The main constituent of geopolymers source of silicon and aluminium which are provided by thermally activated natural materials (e.g. kaolinite) or industrial byproducts (e.g. fly ash or slag) and an alkaline activating solution which polymerizes these materials into molecular chains and networks to create a hardened binder. It is

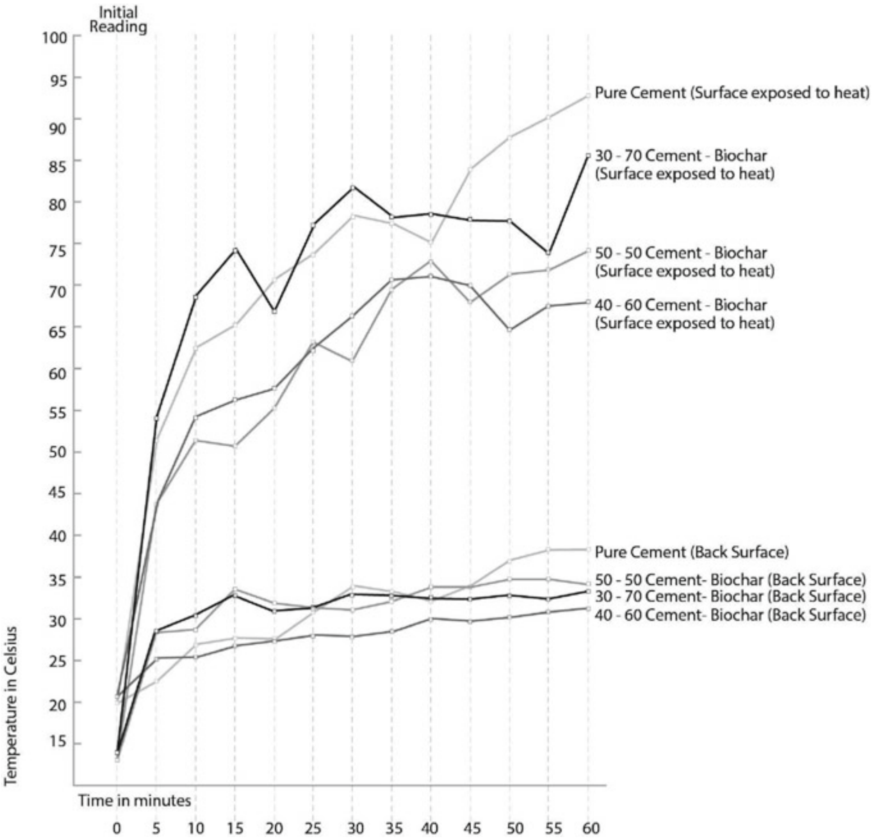


**Fig. 7** Comparison of thermal conductivity measurements of four material compositions. Data was collected with a custom apparatus

also called alkali-activated cement or inorganic polymer cement. It is considered a less environmentally harmful alternative to OPC as it has a fraction of the embodied carbon of ordinary cement.

Embedding fibres within the Biochar-Geopolymer composites (BGCs) was the focus of the "Terra Preta" investigation. Natural fibres were selected as a cost-efficient, sustainable alternative to carbon fibre or polypropylene fibres. Various natural fibres, such as hemp, jute and flax, were studied and hemp was selected for further investigation due to its superior tensile strength.

Specimens (200 mm × 50 mm × 30 mm) for flexural strength test with a three-point bending testing apparatus were fabricated with raging biochar quantity from 0 to 80% (Figs. 13 and 15). Both geopolymer and ordinary cement material mixtures were fabricated for comparison. Two strategies for integrating the hemp fibres were studied: layered and multi-directional. In the layered approach, two layers of continuous fibre in the longitudinal direction located 5 mm above the button and 5 mm below


**Fig. 8** Comparison of ordinary clay brick and BCM bricks

**Fig. 9** Interlocking brick study

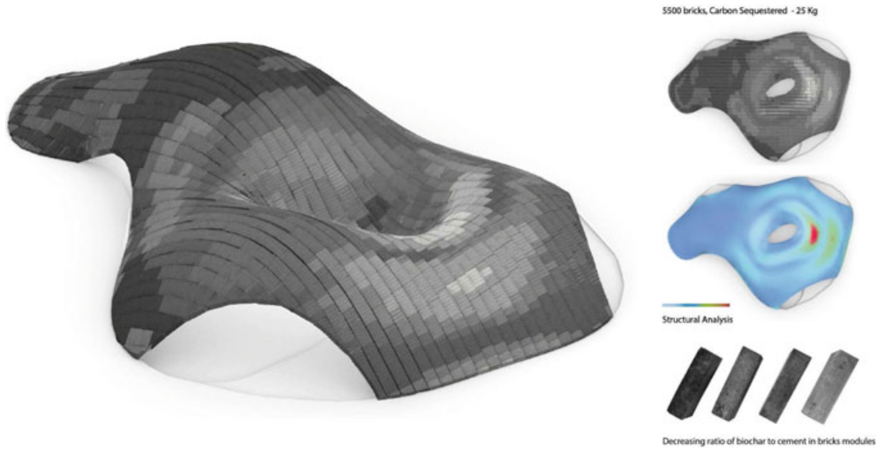


**Fig. 10** Vault pavilion architectural proposal

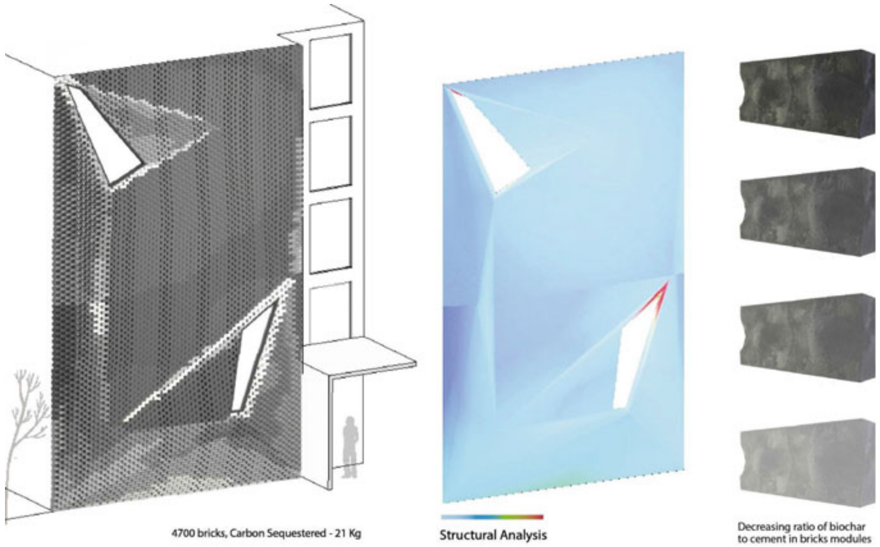


**Fig. 11** Curtain brick facade architectural proposal

the top of the specimens are pre-tensioned on the mould before casting. Extra sets of fibres in the lateral direction were positioned through the middle of the specimens using the same strategy (Fig. 14).

The project was developed during the first wave of COVID-19 and the fabrication laboratory was closed, leaving the physical testing to the findings disclosed in Fig. 14. Based on the experiments it is suggested that the flexural strength of specimens with layered hemp fibres is higher than the multi-directional fibres. The BGCs exhibited

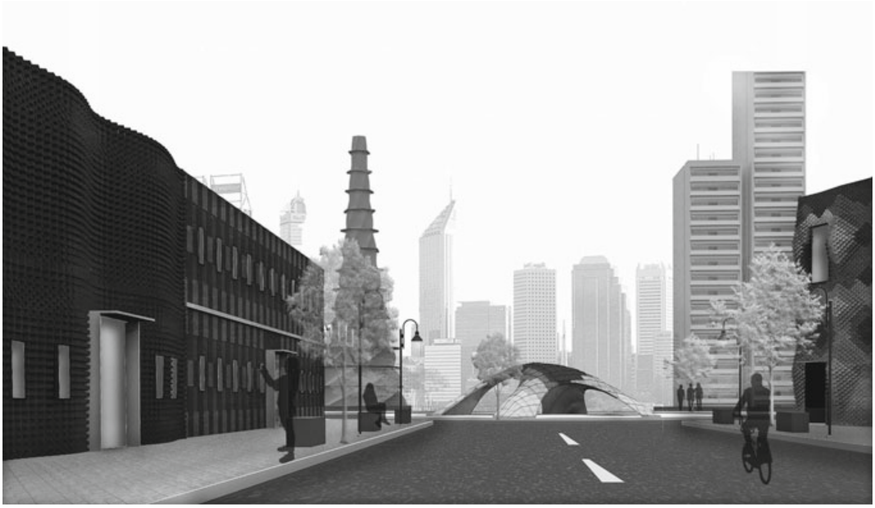

**Fig. 12** "Cast in Carbon" architectural vision for carbon sequestering architecture

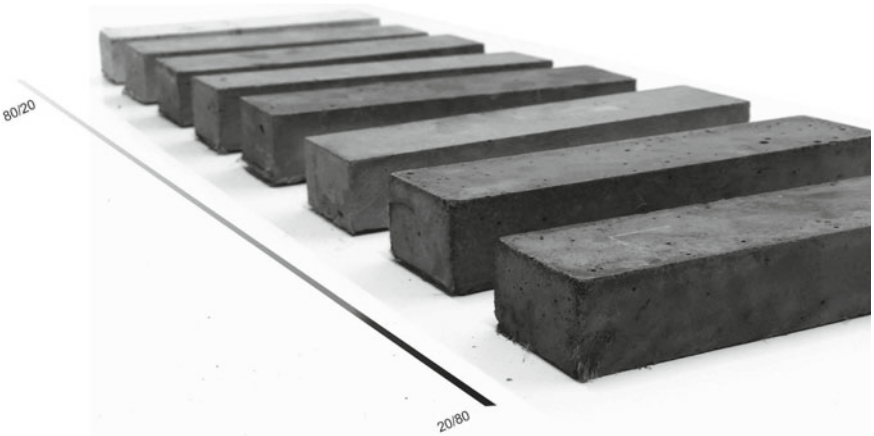


**Fig. 13** Specimens with a range of biochar proportions within geopolymer-based composites

higher strength than the BCMs but more tests have to be conducted to verify the findings.

The architectural vision, proposed by the groups of students, is of a monolithic structure with a large mass, maximising the carbon sequestering capacity of the BGCs. Rhino's Grasshopper was used to generate the bulky geometries using the structural analysis and optimization plug-in Millipede. This computational design process was coupled with the Monolith plug-in which allows for a volumetric material distribution and was used to allocate a functionally graded BGC material on

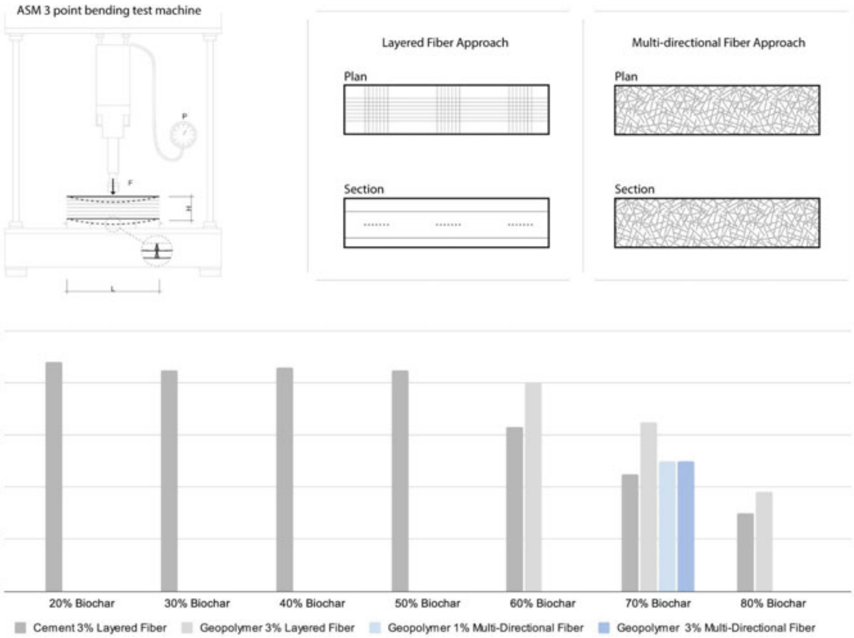


**Fig. 14** Comparison of the flexural strength of BCMs and BGCs of specimens with and without hemp fibre

**Fig. 15** Specimens after flexural strength testing

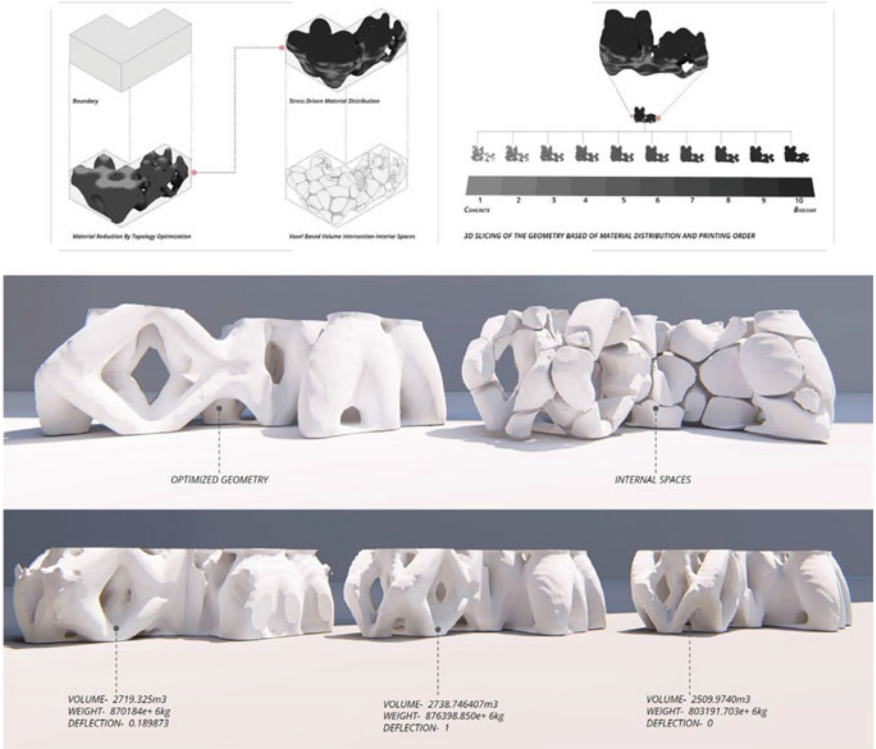


**Fig. 16** “Terra Preta” architectural vision and computational approach

the optimised geometry (Fig. 16). The process is to be developed further to obtain more informed design solutions. After six months of investigation the research was closed. The architectural vision served as a demonstrator of the radically different architecture that can be generated with a materially-driven approach towards carbon sequestering buildings.

### 3.2.3 Carbon Copies (2021)

The last case study on the topic is titled “Carbon copies”. The research project is focusing on the development of an automated bi-material concrete casting technique within a functionally graded design that provides a sustainable and material-efficient construction method compatible with the industry utilising a carbon negative BCM material system. The research builds up on the previously discussed research within the “Cast in Carbon” and “Terra Preta” case studies.

The research proposes that biochar is used as a partial substitute for cement, thus facilitating material savings and substantially lowering the amount of embedded carbon in concrete structures. A system for robotic bi-material allocation within a standardised formwork is developed based on a study of structural and material optimization of standardised building elements. The aim is to minimise the use of cement by allocating it exclusively where it is structurally required and incorporating a biochar-based mix to fill the rest of the formwork, thus lowering or neutralising the embodied carbon of structural elements.

The project's methodology revolves around 3 three essential fields of exploration: materiality, fabrication and design. The material aspect informs fabrication and design elements by providing necessary information about their properties, such as consistency, viscosity, flow rate and curing time. This knowledge subsequently influenced the decisions made during fabrication and design phases. The investigation went through the stages of material exploration: manufacturing and studying the properties of BCMs; manual casting: fabrication and evaluation of multi-material optimised functionally graded structural elements; automated casting: integration of robotics into the fabrication process to achieve better control over multi-layered material deposition. The combined research on all topics showed a potential to adopt the developed fabrication workflow for the full-scale manufacturing process of prefabricated concrete structural elements.

In order to understand the principal material behaviour and properties of the composite a setup of seven manually casted prototypes are created. In the first material experiment, biochar and OPC are the materials used to create BCMs similar to the material system developed in "Cast in Carbon". The material production workflow is based on grinding and finely screening the biochar. The biochar powder is mixed with cement and liquefied with water to be able to cast the mass in moulds for curing. The base sample consists of 100% cement. In steps of 10%, the amount of cement is reduced and the proportion of biochar is increased. As biochar is absorbing water it is necessary to increase the amount of water to be able to achieve the same viscosity of cement (Fig. 17). The needed amount of water to hydrate the composite extends proportional to the amount of biochar. The water absorption leads to a strong binding behaviour of the biochar composite. After the curing time, the models are compared in terms of weight. The increased amount of biochar results in a lighter composite. Due to the higher water ratio, the biochar composite has a longer curing time.

The setup for the second material exploration experiment consists of adding sand to the biochar cement mixture. The content of sand is kept constant at a ratio of 10%. The amount of cement was reduced in steps of 10% (Fig. 17). Based on that exploration a graded layered sample is created to investigate the binding behaviour of the different mixtures. Compared to the cement and biochar composites adding sand to the mixture results in a lighter material.

The third experiment lies in investigating the composites behaviour with adding fibres to the mixture, as a continuation to the "Terra Preta" research project. The used fibres are hemp and sisal in different lengths of 5, 10 and 20 mm. As concrete has good capabilities of working in compression the fibres are added to the mixture to be able to react to tension forces. A horizontal prototype in a working principle of a beam is casted. This beam consists of three zones. The upper layer is the compression zone where the most amount of cement is used. The neutral middle layer consists of

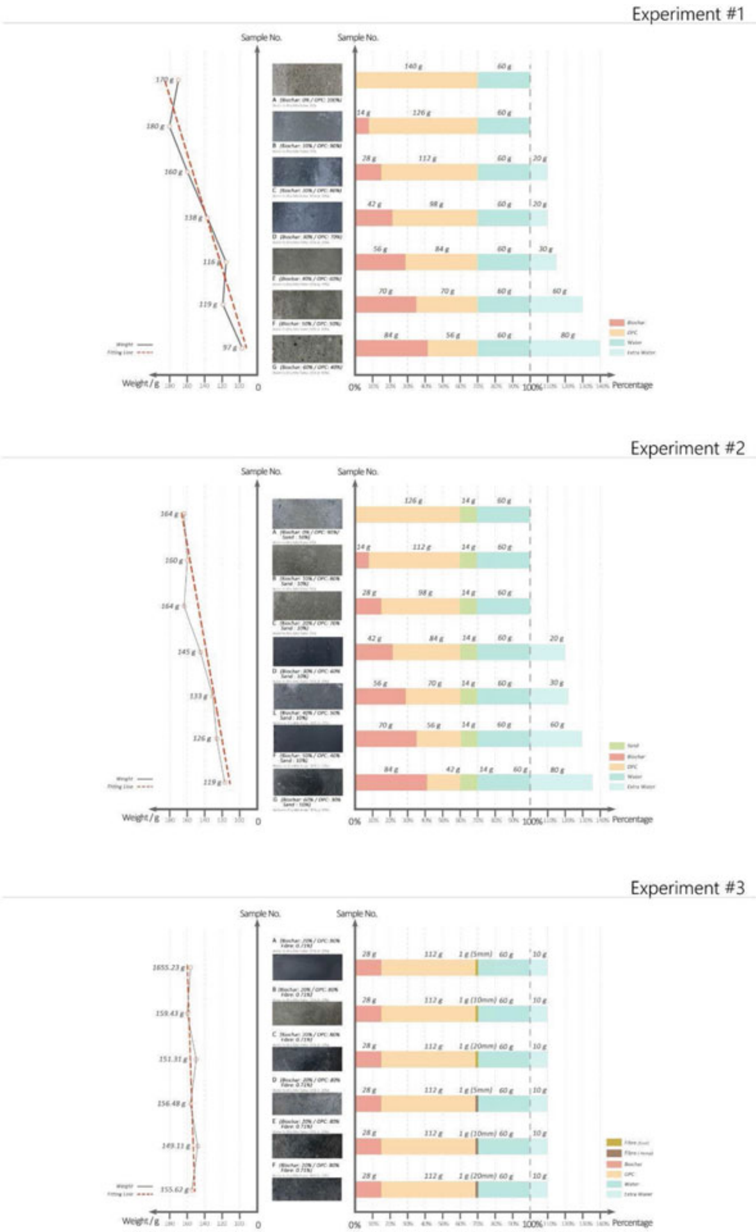


**Fig. 17** Material system development based on three key material matrix experiments

50% biochar. The third layer is the tension zone where the fibres are added to the mixture.

The samples were not tested for compressive or flexural strength. The main evaluation criteria was the weight of the samples. It was concluded that the sample with the highest ratio of biochar resulted in higher demand in water content but lowest mass.

The developed computational workflow introduces a complete building element manufacturing process for structural elements that is based on data acquired from conducted material experiments and the precedent research projects: "Cast in Carbon" and "Terra Preta". Based on the optimization data acquired from such plugins as Karamba and Millipede, a customised G-code for robotic arm ABB140 was programmed to prefabricate these building elements for subsequent assembly on-site of construction (Fig. 18).

Throughout the investigation the goal was to produce a physical prototype based on the structural and material optimization of a scaled down beam sample. Based on the input parameters for computational protocol, such as target density, cell size, load and support cases, a target optimization result was acquired, clearly demonstrating the distribution of two materials for casting process that still uses conventional formwork, but allocates both cement and biochar-based mixes exclusively where it is structurally required (Fig. 19).

Initially, manual casting was used to test bi-material allocation with a BCM and cement-based mortar mixture. It is essential that the interface between the two mixtures is studied in detail and the fabrication process allows for precision and control of the material allocation. For this purpose, a set of fabrication methods were

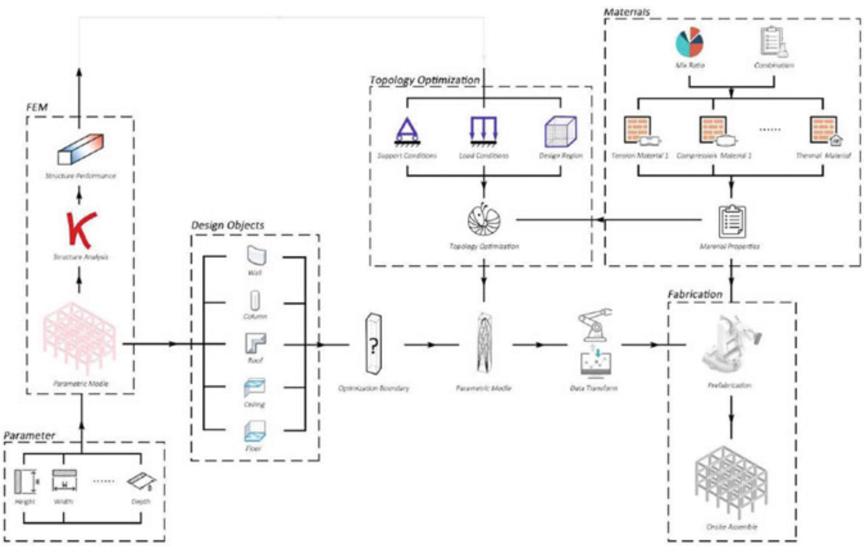


**Fig. 18** Computational workflow

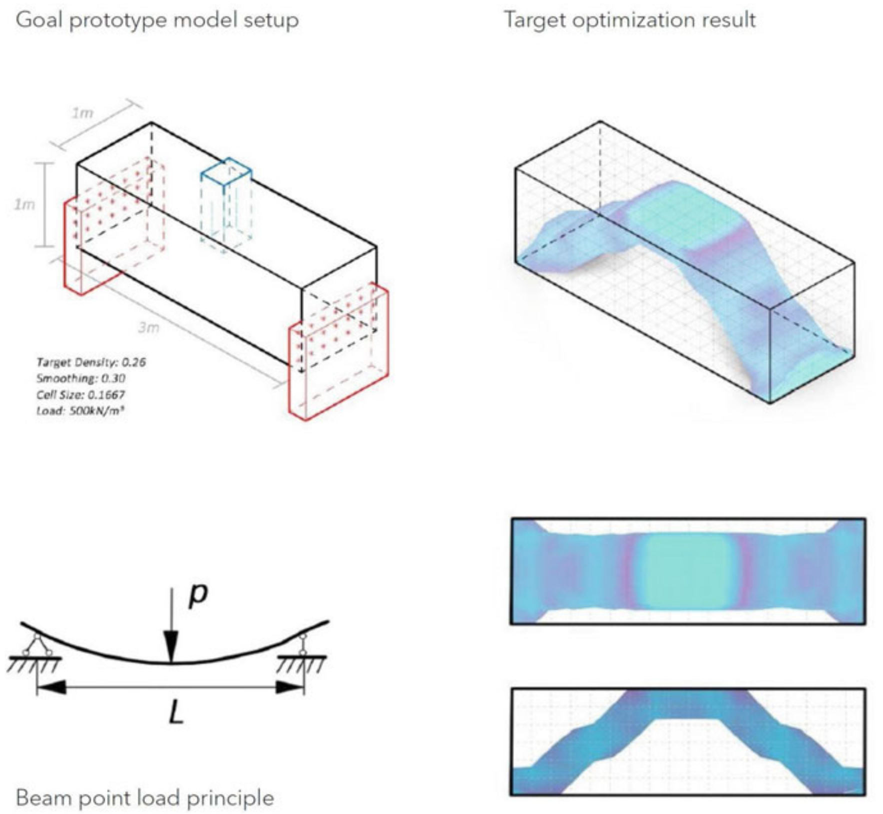


**Fig. 19** Topological optimisation used to inform the material distribution of a scaled down beam to be used in the fabrication process

developed, executed and evaluated within a holistic approach. The proposed fabrication strategies were distributed in two categories: physical boundary (techniques that require the use of guiding separators for clear material deposition) and seamless casting that investigated binding behaviour between two mixes (Fig. 20).

Through evaluation of the physical prototypes of all of the explored fabrication methods, it was concluded that the best results were achieved using the pouring techniques (Fig. 21).

Based on the results of manual casting, the stage voxel grid technique helped to achieve the most accuracy of material pouring. To overcome the technique's limits in the project required the integration of robotics into the fabrication process that would provide better control over multi-layered bi-material deposition. The project revisited the topic of material exploration in order to create two suitable mixture compositions for the robot and in addition investigated the aspects of material deposition timing, robot tool path, end effector configuration and prototype reinforcement options (Fig. 22).

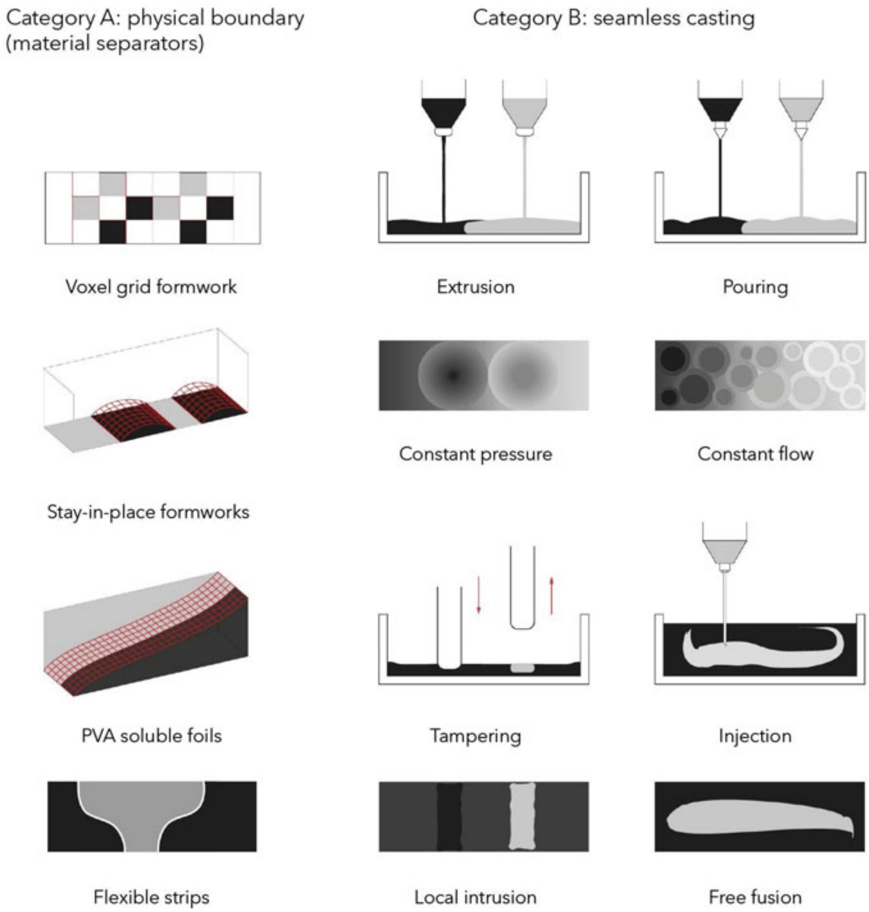


**Fig. 20** Diagrammatic representation of manual casting fabrication techniques

The first iteration end effector was implemented with a Y-connector that would allow interchangeable bi-material outputs through a single nozzle. After several experiments, it was discovered that due to the fact that mixtures have different densities they tend to disrupt the overall flow in the Y-connector loop, which proves them to be sensitive to pressure. Furthermore, segregation in the biochar-cement mixture was happening due to large biochar particles that absorb water and accumulate at the bottom of the cartridge thus blocking the nozzle. Lastly, a biochar-cement mixture containing 40% of biochar was not suitable for robotic fabrication due to its high viscosity and quick water absorption. As a consequence, two new mixtures containing 20 and 30% of biochar were put to trial to test their performance. The mixture containing 20% biochar was defined as a new working mixture.

Based on the performance of the first end-effector iteration the second robotic fabrication setup went through significant improvements. More accurate pressure

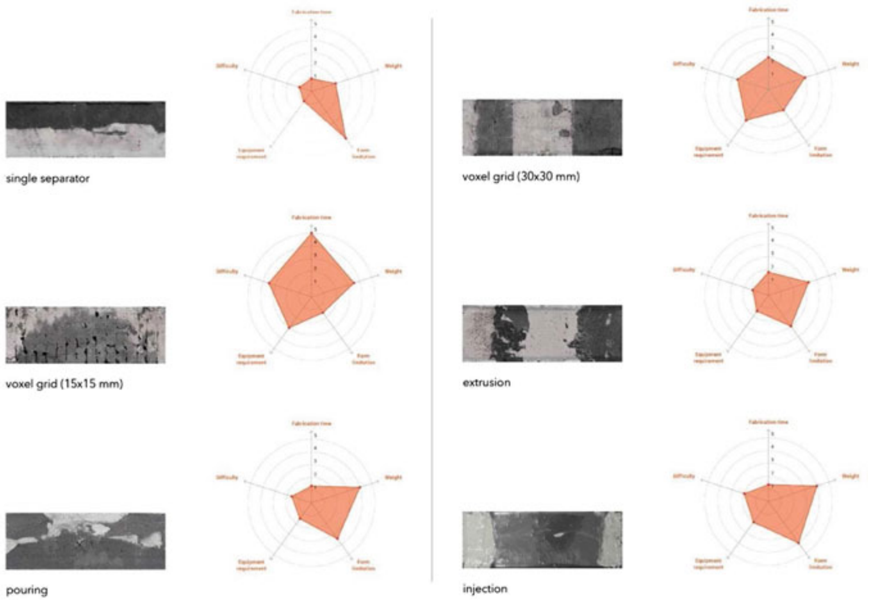


**Fig. 21** Prototypes of the tested manual fabrication techniques and their evaluation

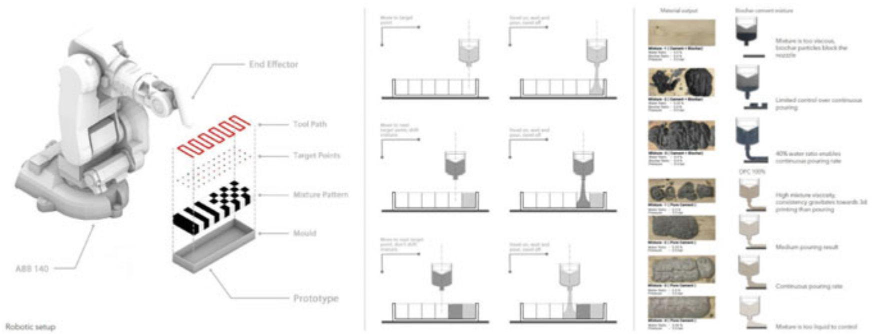


**Fig. 22** Robotic fabrication experimental set-up and initial tests

control was achieved by providing the setup with two independent pressure control terminals for each working mixture. The initial end-effector was redesigned for faster assembly and disassembly to make sure that each pouring cycle operates within the same time frame between the end of the mixing stage and the start of each layer of material deposition. Most importantly, it was decided to use two separate nozzles for each working mixture, so the pressure inside the cement cartridge would not affect the material output of the biochar-cement cartridge. Finally, a mediator device (pinch valve) was implemented into the setup to refine material deposition timing by blocking the flow at a specific point, thus distributing equal amounts of material deposition for each voxel (Fig. 23).

Reinforced concrete frame building structures are composed of a network of columns and connecting beams that form the structural ‘skeleton’ of a building. Initially, the optimisation process was applied to the entire building but this method was not proven ineffective and a second approach was taken where the building

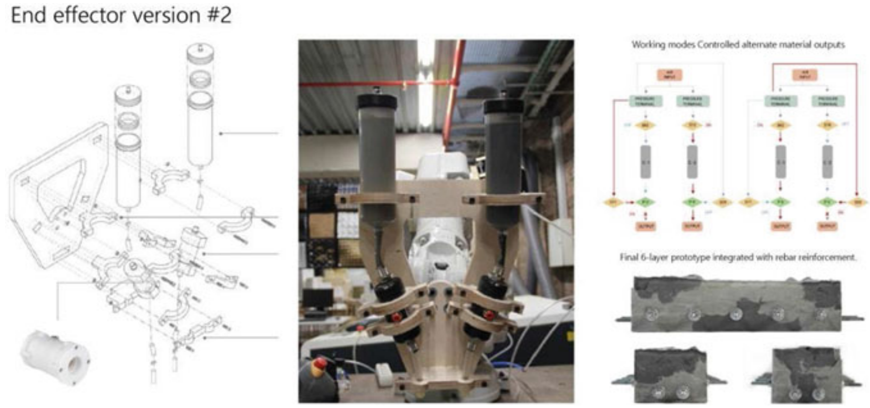


**Fig. 23** Final robotic fabrication set-up

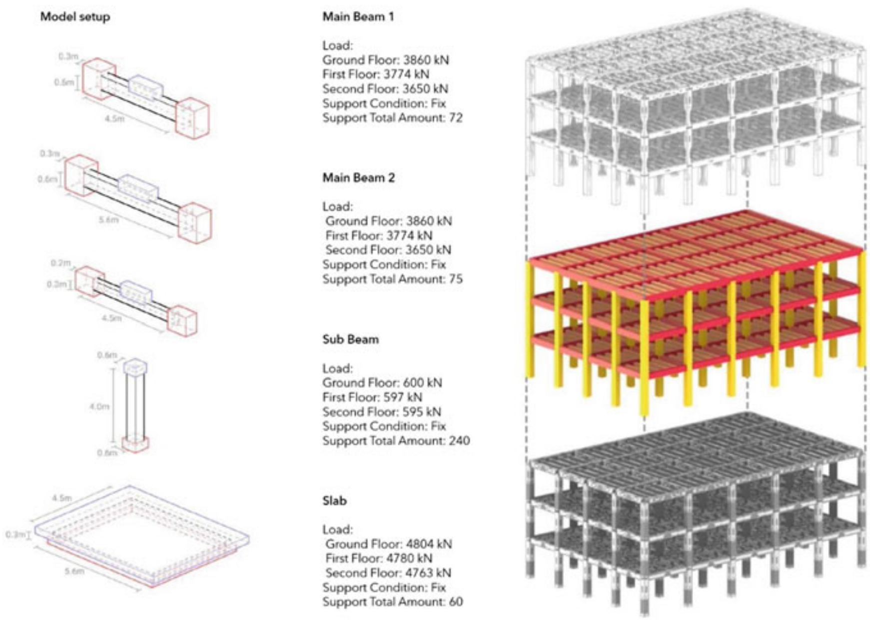


**Fig. 24** Material optimisation strategy on a building scale

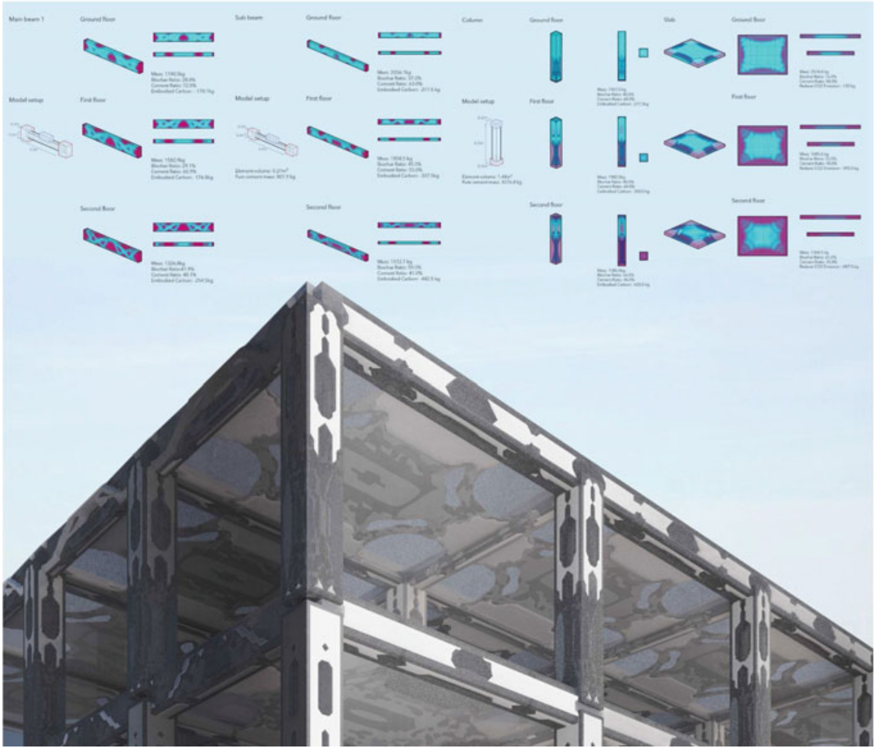


**Fig. 25** "*Carbon Copies*" architectural vision of bi-material optimised structural elements

elements are extracted and optimised individually. Material optimization was applied to four structural elements: main beam, sub-beam, column and slab (Fig. 24). The elevation of the elements was also taken into account as the higher floors have to take fewer loads and therefore can have a predominantly biochar mixture.

## 3.3 Conclusions

The global environmental challenges are calling for novel solutions and sustainable practices in the fields of architecture and construction. In order to respond to the SDGs agenda, the research looks into strategies for integrating biochar as an aggregate for carbon–neutral cementitious composites within a materially driven design process. The aim is to propose innovative solutions for construction materials and processes towards sustainable architecture.

The research chapter uses three case studies and examines fabrication strategies as well as new techniques for material allocation and performance-driven design toward carbon-negative materially informed building elements. The material systems are developed over three distinct research projects under the same agenda, starting with investigating how biochar can be integrated within clay and cement mixtures. The second interaction looks into the possibility of moving away from OPC to geopolymer-based composites and how natural fibres can be incorporated into the mixture. The final project creates a mixture for robotic fabrication for bi-material allocation of BCMs. Due to the identified impact of the addition of biochar on the structural performance of the mixture as well as the carbon sequestration potential, it is proposed that a multi-material allocation would allow for an increase in the carbon sequestration without compromising the structural properties. This aspect is crucial for the development of both the material system and the fabrication process.

Fabrication techniques from manual to digital and eventually to robotic fabrication were studied and tested. The first project explores the modular and discretised approach to functionally graded structures and building elements. This allows for mass fabrication of modules with different properties that can be arranged based on computational optimisation of performances such as thermal insulation, humidity regulation and structural integrity. The “Cast in Carbon” case study demonstrates the possibility of obtaining architectural solutions that are tailored to multi-performance architectural elements and structures within a functionally graded material system.

The second architectural application is on monolithic structures. This proposal focuses on design without considering the fabrication process which limits it to a speculative outcome. The final case study “Carbon Copies”, explored the intersection of material, design, and fabrication, focusing on structural performance. The strength of the final proposal is in the pragmatic approach that investigated how robotic fabrication can be used to obtain bi-material deposition. The three case studies show the evolution of the research from a material and fabrication perspective, concluding with a BCM material system that can be applied to a functionally graded design informed by computational simulation and optimisation processes. A range of architectural applications are proposed and even though the research is still in development it demonstrates a possible change in the design practice that is driven by sustainable material systems.

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# DigitalBamboo_Algorithmic Design with Bamboo and Other Vegetable Rods

**Stefan Pollak and Rossella Siani**

**Abstract** Algorithmic design software is widely acknowledged as a tool to manage complex design tasks and to enhance material optimization, structural performance, ergonomic needs or similar aspects. The present paper investigates how these tools can be applied to projects that use an important amount of non-standardised, natural materials. The use of renewable and locally sourced materials is becoming mandatory if we accept the challenge of providing an appropriate built environment for a growing world population. A special focus is given to vegetable rods such as giant reed and bamboo. Building tradition provides uncounted examples of how humankind employs natural fibres to erect or ornate its shelters. Some of them can inspire new uses to be applied in contemporary architecture. The aforementioned digitally controlled design processes are normally meant to feed so-called computer aided manufacture processes. Such methods generally need highly standardised materials. The use of renewable materials in such a framework is often impossible due to intrinsic irregularities of natural resources. Can this gap be bridged? The present paper illustrates the design-and-build technology *DigitalBamboo* thought to conciliate the two realms of natural building materials and algorithmic design control. The method has been conceived for experimental projects made of Italian bamboo in the form of strips but can be applied to other vegetable fibres or rods and to other geographical contexts. The investigated technology includes appropriate communication tools to bridge the divide between designer and builder. The illustrated technology is based on manual assembly of digital data and includes ways of transposing geometric entities into topological textures, physical nodes and structures.

**Keywords** Natural materials · Algorithmic design · Appropriate fabrication · Gridshell · Assembly maps · Nodes

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_32

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns

## 1 Introduction

The fourth industrial revolution allows architectural design along with its workflow control, the construction itself, and the performance monitoring to be more and more implemented by computation and automatised processes [1].

*DigitalBamboo* is an experimental research that applies algorithmic design approaches to bamboo, a natural material with interesting structural and expressive features.

The inquiry is part of the broader research line *DigitalNature* [2], which investigates the meeting points between innovation and tradition, between advanced design and locally sourced natural materials.

The main challenge of this research is to adapt Industry 4.0 processes, which generally imply numerically controlled machines or robots [3] and highly standardised products, in order to make them cope with natural materials in their raw form. An original method is proposed to deal with this delicate step.

Using a material in its natural form, with a few processing steps to reach the assembly phase, reduces the impact of the product life cycle assessment [4, 5], both in the initial pre-production phase and in the disposal phase.

Traditional building models with regrowing, natural materials are implicitly circular and provide benefits both for the environment and the local economy. Such good practices can increase their effectiveness and multiply their positive effects on the ecosystem if associated with more complex control tools.

The increase in process-complexity that comes along with the combination of digital tools with physical production means can allow for an improvement in performance and hence for a better management of resources. This opens new perspectives with respect to sustainability, a concept that is transforming itself from a merely conservative approach as defined in the Brundtland Reports [6] or in concepts like *Décroissance Sereine* [7–9] towards a more active attitude as witnessed in the 17 UN Sustainable Development Goals. Similarly to what happens in mature living organisms, where a growth in complexity takes the place of a physical growth, this can be seen as a passage from a quantitative towards a qualitative growth [10].

The use of algorithmic generative design combined with construction processes that make use of natural materials endeavours a specific niche of this perspective.

## 2 Physical and Digital

### 2.1 *Fast Growing Plants as Building Material*

In a circular perspective, the use of vegetable material is crucial. Canes like giant reed or bamboo are largely available in many regions of the world and have a rapid growing cycle, i.e. if compared to timber. Reed canes like *Arundo donax* can be found all around the Mediterranean Sea and in the Middle East. Similar species grow in other continents. The areas where bamboo is native include almost all tropical regions of Asia, Africa and Latin America, but most of the 1.600 known species can grow up to a latitude of 41° North and South [11]. Vegetable rods are commonly used as building materials. [12–18]

The present research focuses on bamboo grown in Italy, mainly *Phyllostachis viridiglaucescens*. This species can provide culms of up to 11 m of length. Its diameters appear in a range between 40 and 80 mm with a wall thickness of mature material that reaches 4 to 5 mm.

The diameters vary along the culm with a maximum at approximately 1 m from the ground and then a constant decrease towards the top. This constrains the cane's bending behaviour, which typically has larger radii in its lower part and the possibility of tighter bends in the upper part. The result is a characteristic asymmetric arch.

Bamboo strips are an alternative to round culms. To source them whole canes can be divided with a splitter, a cutting tool with 3, 4, 5 or more blades, according to the diameter and to how broad the strips shall be. The bending behaviour of strips has less constraints compared to entire canes which allows for freely designed shapes. Freshly cut, 3 cm broad, green strips of *Phyllostachis viridiglaucescens* can bend with a radius as small as 35 cm.

### 2.2 *Digital Design and Production Tools*

Algorithmic design [19–22] (also defined parametric) makes use of specific, so-called generative software, whose use is growing in industry 4.0. The final design conformations emerge from a set of pre-established relations and the results vary as the parameters vary in a form finding process [23–28]

Generally, the algorithmic design work is associated with CAD/CAM processes, and thus allows to carry out mechanised production processes with a numeric control [29]. Such computer numeric control machines (CNC) can process various materials, even of natural origin, but with one common feature: the format of the materials is standard.

In the case studies presented here the bamboo material is used in its natural form, in whole rods or strips, and as such the format varies in thickness, length, weight, as well as for the numerous irregularities it presents on the external surface.

The need to use bamboo in its natural form has triggered the creation of a specific construction process, capable of translating digital data into very precise manual operations, so as to combine the advantages of parametric performance control with a constructive model which is close to tradition. This allows us to incorporate consolidated solutions or to involve specific locally available skills.

## *2.3 The Case of Triaxial Bamboo Strip Gridshells*

Gridshells are lightweight constructions made of linear elements and nodes that collaborate in order to reach an efficient structural performance [30]. Strips of split bamboo can be used as building material for such works.

This study examines methods of digital design to control shapes and performances of such gridshells (Fig. 1).

The bamboo strips are organised in three layers according to their orientation (horizontal, left and right). The three families of axes cross in a mesh of nodes, each node joins three strips, one from each layer.

The digital model contains all the needed information in terms of proportion, size and scanning of the parts. The tolerance between the digital and the physical model is in the range of a few millimetres; a tolerance that does not affect the building's performance but, on the contrary, allows for more leeway while dealing with the natural material's peculiarities.

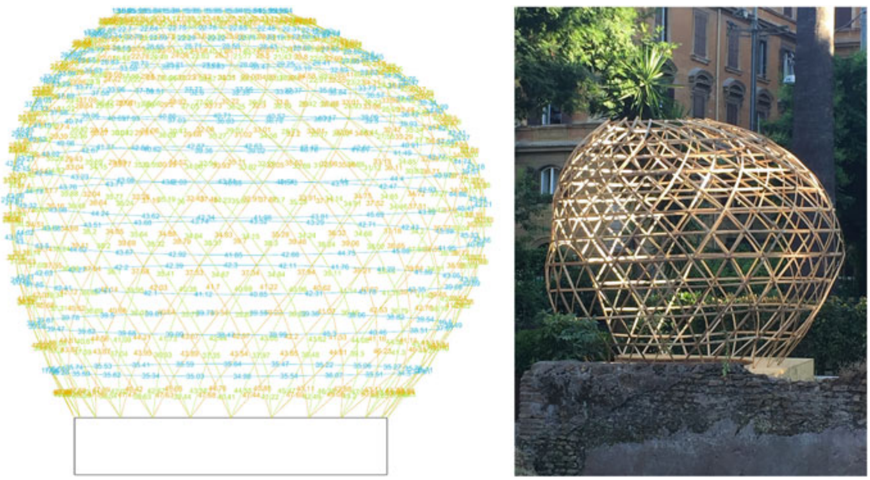

**Fig. 1** *Pagurus urbanus pacificus*, a leisure pavilion in a public garden in Rome as a virtual model and in built reality

# 3 Digital and Empirical Information Management

## *3.1 Morphogenetic Design*

The digital design is developed with *Rhinoceros* [31] combined with the plugin *Grasshopper* [31], a generative software for parametric design. The design phase, or in other words, the development of the virtual project [3] is divided into two steps: the definition of an algorithm and the application of differentiated parameters for the single case [23, 24].

The virtual project represents, like the genotype of an organism, a range of formal possibilities that determine the specific case, the phenotype (Fig. 2).

The morphogenesis of a formal composition is in relation with the most suitable parameters for the project's logic and function. Along with the freely chosen parameters that shape the design, the algorithm can be fed with information on the material's physical constraints such as bending radii, torsion data as well as structural parameters, environmental factors, functional or even cultural data.

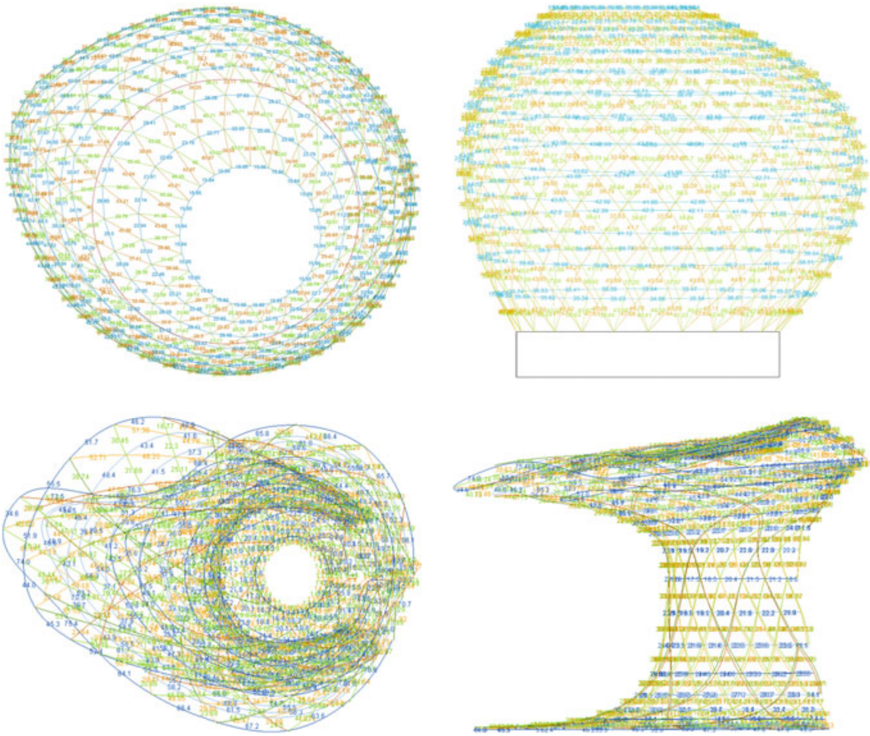

**Fig. 2** Two projects (*Pagurus*, Rome 2019 on the left and *Jinen* for Tono Mirai, Venice 2021) compared. The top views highlight the origin of the two designs from a common genotype while the side views clearly show the phenotypic peculiarities

### 3.2 Curvature and Torsion as Parameters

The data on minimum curvature constrain the composition's formal possibilities. The local datum affects the global behaviour, determining variations on the composition.

The curvature analysis (Fig. 3) refers to the curvature of individual strips, organised by warping or to the surface that determines the overall shape of the structure. The analysis of single strips allows us to investigate possible criticalities of different variants. Once bending radii that are inappropriate for the available material are detected, the design can be modified with a reiterated feedback process until a suitable result is reached.

The analysis of the surface curvature is represented by a graph with a colour gradient which, in our example, goes from red (maximum) to yellow (minimum) and defines the degree of curvature of the surface in relation to the minimum and maximum of the specific template (Fig. 4). It is a less precise tool compared to the previous one, because it does not provide absolute but only relative data. It is not

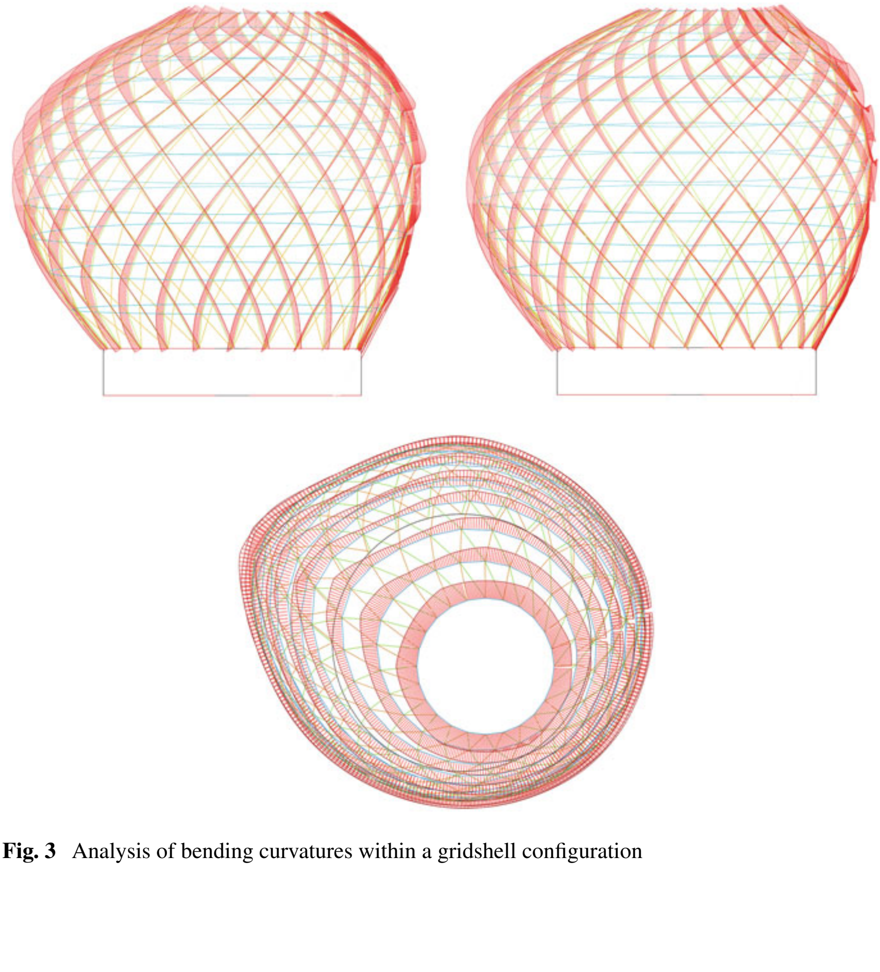

**Fig. 3** Analysis of bending curvatures within a gridshell configuration

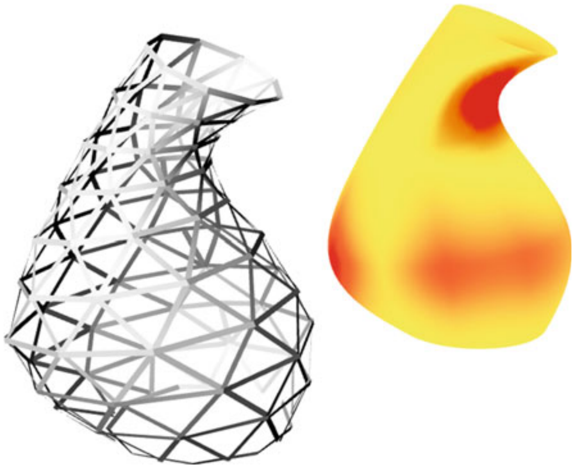

**Fig. 4** Surface curvature analysis. Red highlights areas with excessive bending stresses

fruitful to use it in the definition phase of the project, because it does not determine the points that exceed a certain degree of curvature, but it is very effective in the phase of detail design.

The singular (non-standard) nature of bamboo makes it possible to distinguish the strips in relation to the variations in performance that come along with their dimensional features. Having a simplified scheme that identifies the points that require a greater bending effort, allows to better distribute the material with respect to flexibility and extend the optimization process throughout the whole construction phase.

The bamboo strips, in addition to curvature, are subjected to twisting. As for the bending behaviour, the study phase can highlight critical points of torsion and thus warn the designer. In some cases the torsional effect can enhance the material's natural resistance within the gridshell. Most criticalities can be faced with empirical adjustments. As an example, longer screws can be used for those nodes where the torsion is expected to be higher. The loser spacing between the three layers of strips allows for a reduction in torsion. Manual dexterity and some experience in handling the material can empirically solve such situations.

## *3.3 Shape Optimization*

Generative software allows for shape optimization in relation to endogenous and exogenous parameters.

Endogenous parameters include the limit figures for curvature and torsion. While in the process of analysing such data, as described above, is a matter of verification, the same information packages can drive the optimization approach in a process of morphogenesis. The implied numerical values can make a solution emerge that can be considered as optimal with respect to the examined data set.

When gravitational forces and exogenous weight forces are combined with the material's features, structural morphogenesis is possible.

Other plug-ins, *Kangaroo* [32] and *Karamba* [33], are added to the Rhinoceros + Grasshopper [31] software system, which simulate the physical behaviour of structures. The structure's final shape emerges from the forces it is subjected to. In bamboo gridshells, this structural optimization work allows for experimentation with complex yet stable compositions.

Climatic factors such as sun or wind patterns can determine a morphogenesis for the optimization of environmental comfort. In this case the bamboo gridshell becomes the supporting structure of shading systems or corridors for cross ventilation.

### 3.4 Quantity Design

Working with parametric software allows us to keep a large amount of numerical data related to the project under control in real time. This can include material quantities.

For example the software can help in defining the total length of the bamboo strips, from which the number of whole rods is easy to obtain. Further data include the actual number of strips with its specific length. These data are also organised in groups according to the shell's wrap. Knowing the length of each strip allows for a resource optimisation while choosing the material to use. It also helps in defining the additional amount of overlap material to consider for those strips that can't be built from one single piece. The number of nodes, another information that can be assessed in real time, corresponds to the number of connectors needed.

Keeping the quantities under control while designing also allows to adjust the outcome according to changes in material availability or budget.

Designing with real time quantity control speeds up the construction process, ensures greater precision and helps to reduce waste.

### 3.5 Digital Models for Triaxial Bamboo Strips Gridshells

The digital model of the bamboo gridshell is generated by a surface, which follows the logic of morphogenesis and formal optimization and is then divided into a triaxial pattern that discretizes the surface in triangles and vertices. In the physical translation, the pattern's edges correspond to bamboo strips with a width between 25 and 30 mm and a thickness of approximately 5 mm, while each vertex represents a node or connection.

As the morphogenetic process includes specific parametric data on the material's behaviour, specific constraints come as a result. With respect to the described bamboo strips, the distance between two distance points varies in a range between 10 and 50 cm. A smaller distance would make the assembling process difficult while meshes with more than the said maximum distance could lead to buckling effects and affect the object's overall stability.

Even in the various compositions, the three axes have a similar organisation: the first axis is composed of arches or closed circles, the other two cross along the first with an opposite inclination.

The model is represented in a simplified way through the segments between the nodes in which each strip is discretized. The overall form is already readable, however in order to have a graphic representation which is more consistent with the final result, strip thickness or colour information can be added.

### *3.6 The Translation from Digital to Manual*

In order to translate the virtual model into built reality some additional passages are needed, especially with respect to how the flux of information from the software to the building site is managed. The steps of this process are: definition of the virtual model, prefabrication, assembly. The prefabrication process consists in pre-perforating each strip with its connection holes in the exact position.

The virtual model already contains the indication on where to drill, a geometric entity that corresponds to the distance between two specific nodes. It is actually possible to visualise this information as a cloud of figures; a suggestive but not easy to read representation. The need for readability comes along with the fact that the natural material requires to be processed by humans. An assembly map with a specific level of abstraction solves this gap (Fig. 5).

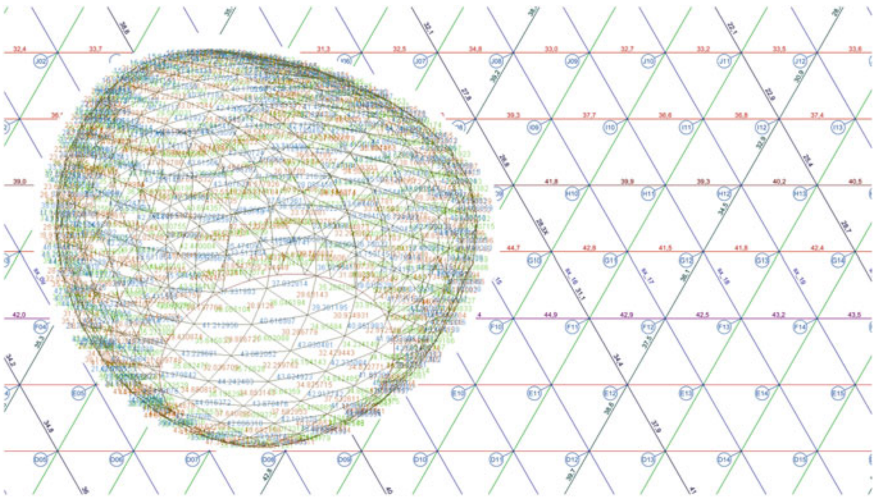

**Fig. 5** Numeric assembly map. The number cloud (left) represents the actual shape while the abstract plane representation makes the manufacturing possible

A special script allows to project each distance-figure onto a grid of equilateral triangles just for the sake of graphic order. For every strip to be used in the final work, this simplified representation makes it easy to deduce the following information:

- _total length,
- _alphanumeric code attributed to the strip,
- _distance between each node,
- _alphanumeric code attributed to every node.

This last information is crucial for the passage from prefabrication to final assembly where nodes with the same name have to be joined with a connector element as shown in Fig. 7.

### *3.7 Nodes and Joints as Control Entity*

Bamboo strips can mainly be connected in two different ways. If interwoven in patterns that are tight enough, it is possible to generate stiff curved shapes that can stand only through friction. Such weaving patterns can be bi-axial (warp and woof) or tri-axial with a pattern of hexagons and triangles (Fig. 6).

As an alternative, bolts or other punctual connections can be used to join different layers of strips. According to the design's overall character, iron bolts or timber pins can serve as connectors to hold a grid pattern in place (Fig. 7).

In both cases it is important to consider the right bolt or pin diameter which has to cope with the strip's width in order to balance connection strength with the fact that the strip shall not be injured too much. The connector's length varies according to the degree of curvature and torsion in the various positions of the shell surface.

The described nodes are reversible which allows disassembling and reassembling the structure several times, an additional benefit in terms of circularity.

**Fig. 6** Woven shells with bi-axial (left) and tri-axial (right) patterns

**Fig. 7** Iron bolts (left) or timber pins with hemp rope (right) as node-connectors

Triangular patterns are the most used due to their intrinsic stability. At the same time triangular meshes are also easy to control with algorithms. In the virtual model the physical node is nothing else than the intersection of three axes.

In the built reality, the three orientation axis lay on three overlapping layers which requires an offset adjustment of the virtual model that takes the strip thickness into account.

### *3.8 Construction*

The gridshells are assembled manually with simple tools: saws, drills, screwdrivers and similar carpentry tools. The precise execution of the indications contained in the assembly map shown in Fig. 5 makes the designed shape appear progressively.

At the end of a correct execution the final design exactly corresponds to the morphogenetically designed virtual model (Fig. 8).

## 4 Conclusions

The use of locally sourced natural material in architecture is getting of crucial importance if we want to shape appropriate spaces for a growing world population. Facing the increasing complexity that comes with global interconnection and always more rapid new scientific notions, calls for control tools in all design stages.

Methods that can make the non-standard, natural peculiarities cope with algorithmic (or parametric) design tools have to be found. *Digitalbamboo* is a first attempt to make these two realms come closer to one another in a perspective of defining a new architecture that is natural and digital at the same time.

**Fig. 8** *Jinen* for Tono Mirai (design: Tono Mirai; technical implementation: Salvatore, A., Siani, R., Pollak, S. - Venice 2021) and *Pagurus urbanus pacificus* (Rome 2019) built

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# Virtual Reality Application for the 17th International Architecture Exhibition Organized by La Biennale di Venezia

**Giuseppe Fallacara, Ilaria Cavaliere, and Dario Costantino**

**Abstract** This paper aims to investigate the use of Virtual Reality (VR) as a support for expositions and cultural events through the presentation of a case of study related to the 17th International Architecture Exhibition organized by La Biennale di Venezia. The idea for this experimentation was born during the period of Covid-19 pandemic, in which it was impossible to travel freely. The goal was to make part of the exposition available to be visited virtually all over the world, in hubs equipped with VR headsets. Thanks to a collaboration with the organizers of the exposition, a VR app has been developed in order to allow people to visit the Giardino delle Vergini, which for several years has hosted the Italian Pavilion and where this year were placed the installations of prof. Giuseppe Fallacara and his research team together with the works of other international firms. Ethic matters have been taken into consideration during the app development. The VR app has been developed non to be a mere reproduction of the original site, but to be an alternative experience of visit. This work can bring two apparently contradictory advantages: on one hand the differences between virtuality and reality can encourage people to travel and visit the exposition in Venice; on the other hand, barriers of place and time are overcome. Therefore, everyone can visit the Giardino delle Vergini, even people who can't move.

**Keywords** Virtual reality · Extended reality · Virtual architecture · Biennale di Venezia · Virtual tour

**United Nations' Sustainable Development Goals** 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_33

# 1 Introduction

This article aims to describe a work made for the 17th International Architecture Exhibition organized by La Biennale di Venezia, titled *How will we live together*?

The exhibition had to be held in 2020 but it had to be postponed due to the pandemic, therefore it was inaugurated in May 2021. The pavilion called *Porzione d'infinito*, designed by prof. Giuseppe Fallacara and by the architect Maurizio Barberio, was selected for the Italian Pavilion and was placed in the Giardino delle Vergini, at the Arsenale of Venice.

All the problems and the restrictions connected with Covid-19 brought the authors to reflect upon the theme of accessibility of museums, expositions and cultural events and encouraged to think about potentialities of VR and the benefits that this technology could bring to tourism and culture disclosure. It has been demonstrated that Virtual Reality applications help stimulate potential tourists to actually visit physically the places virtually explored and enhance the appeal of less known sites [1].

This topic is linked to the eighth goal of the United Nations' Sustainable Development Goals and deals with decent work and economic growth, since tourism is an important part of one state's economy.

## *1.1 What is Virtual Reality?*

As stated in [2], Most popular definitions of virtual reality make reference to a particular technological system. This system usually includes a computer capable of real-time animation, controlled by a set of wired gloves and a position tracker, and using a head-mounted stereoscopic display for visual output.

For Greenbaum Virtual Reality is an alternate world filled with computer-generated images that respond to human movements. These simulated environments are usually visited with the aid of an expensive data suit which features stereophonic video goggles and fiber-optic data gloves [3].

Even though Virtual Reality seems to be considered as a brand new technology, it is not. As a matter of fact, the history of Virtual Reality, or better said Extended Reality (XR)—which is the group of technologies that includes Virtual Reality, Augmented Reality (AR) and Mixed Reality (MR)–, starts in 1832, when the first attempt of enhancing the concrete reality was made thanks to the invention of the stereoscopy by Sir Charles Wheatstone. That said, the evolution of the virtual technology as we know it today starts from the '60s, when Morton Heilig invented the first example of immersive cinema called Sensorama. Of course, Heilig made just a first attempt that was too heavy, complex and expensive to be spread, but at the same time it was extremely inspiring and became the starting point of an almost sixty years process that has not ended yet.

After Sensorama there were many other experimental tools indeed, such as the Sword of Damocles in 1965 by the Turing Award winner Ivan Sutherland, who was also the inventor of Sketchpad. In this case, too, the technology was raw and uncomfortable and the headset was heavy enough to require a particular coupling system hooked to the ceiling (which is the reason why it was called as it was).

Over time these flaws were corrected more and more, and researchers started to focus also on new ways of showing digital worlds, since Virtual Reality environments consisted of wireframe rooms only. Therefore, the first example of Google Street View was made with the name of Aspen Movie Map in 1978 by the MIT, demonstrating for the first time the real power of immersive experiences as a tool to virtually walk inside a real city.

Many other technologies came one by one after that, such as: Vcass by Thoms Furness in 1982, Vived by Nasa Ames Research Center in 1984 and then the Virtual Windtunnel, Cave, Boom, etc. up to the first head mounted display as we know it today, that is the Oculus Rift, invented in 2010 by Palmer Luckey [4, 5].

From 2010 software and hardware improvement became extremely faster and this situation allowed to overcome all the limits that Extended Reality tools had had since the very beginning of the 2000s, especially in terms of graphics.

Today not only a headset is more affordable than before, but there are many free softwares that allow anyone to even create his own virtual reality executable.

### *1.2 VR for Heritage: State of the Art*

Of course, the one described in this paper is not the first attempt to use this VR in order to enhance the cultural field. International studies have already evaluated the efficiency of Extended Reality applications, that are considered a very efficient way to transmit knowledge [6]. The benefits of the use of both VR and AR have been highlighted through specific experiments referred especially to historical heritage and museums [7, 8].

The first experiments were conducted between the end of '90 s and the early 2000s and they were associated to very uncomfortable situations, in which people had to move around with a heavy equipment.

An example is Archeoguide [9], a project developed in 2001, whose aim was to enhance the archaeological site of Olympia through the use of a VR/AR app. Tourists had the possibility to use three different devices—a laptop, a pen tablet or a palmtop—to see virtual reconstructions of monuments, artifacts and life on top of the existing ruins and landscapes. The most complete experience was offered by the laptop unit, which was composed of a laptop—which had to be carried in a backpack by the user—a USB web camera, a digital compass, and a head mounted display.

Fortunately, as we already said, this technology has been far improved and research on the theme of its connection with educational purposes have been carried on, because of the promising results obtained in the past.

A study carried out by the Department of Leisure and Recreation Management of the Ming Chuan University, in Taiwan, [1] has shown how the use of VR is an effective way to encourage people of every age and social background to visit places that aren't popular destinations among tourists. Furthermore, the study confirms that VR simulations help to understand if and how the chosen places can be equipped to encourage sustainable tourism.

At the same time Virtual Reality can increase people's capability of perceiving and understanding places. Another study conducted by a rich group of cultural centers and universities—among which the Raymond Lemaire International Centre for Conservation in Belgium, the Carleton Immersive Media Studio in Canada and the Assiut University in Egypt [10]—has indeed shown that VR experiences allow users to easily recognize materials, features and details of the things they see as well as dimensions and state of conservation. Moreover, Virtual Reality raises the awareness of users about cultural heritage and helps experts in their research.

A study conducted by the Polytechnic of Milan in 2019 [11] has demonstrated that VR and AR reconstructions of monuments—in this case a digital twin of the Basilica di S. Ambrogio—in which also an interactive session is included, enrich the experience of casual users and experts, who can deepen their knowledge depending on their interests and purposes. Above all, Virtual Reality sessions open visitors' mind, giving them different perspectives on cultural heritage, and at the same time give monuments the chance of reaching a wider number of users.

This happens because Virtual Reality applications are conceived to enhance the users' curiosity, through an amusing and intriguing setting. This is the basis of the so-called *gamification* [12, 13], that brings to the production of *serious games*. Serious games can be effectively considered video games with goals and objectives that must be achieved, making the global experience stimulating and more effective [14, 15].

Of course, lots of other Extended Reality studies and experiments have been conducted in the latest years, especially because of the extreme development of technology, which has gone far beyond the limits found in many scientific papers from the early 2000s [16].

Since then and especially since 2010, when the first prototype of Oculus Rift was built, experts from different knowledge fields—architecture, engineering, medicine, archeology, design and computer graphics, etc.—kept doing research that underlines the importance of immersive experience in order to enhance cultural heritage and events [17], also looking for new ways of connecting virtual and physical world. Another experiment made at the University of Geneva, in Switzerland, has been carried out trying to develop the virtual experience with digital characters acting a storytelling drama on sites like Pompei [18].

Therefore, in a difficult historical moment such as the Covid-19 pandemic, which prevented people from being able to move freely, the use of VR became a strategic way both to take part in the Exhibition held in Venice and to think about important contemporary problems, for example the topic of virtual representations and digital twins as a way to enhance cultural heritage and the desire of phisically visiting it.

La Biennale di Venezia Foundation has clearly taken sides against the idea of creating a simple replica of the exhibition due to the risk that this operation could lead the exhibition itself to lose value. For this reason, it is necessary to specify that we focused only on one part of the Italian Pavilion, the Giardino delle Vergini, where it was possible to visit not only *Porzione d'Infinito*, but also the pavilions designed by Zaha Hadid Architects and Tecno, by Orizzontale, by David Turnbull (together with other designers), by Gianni Pettena and by Pongratz Perbellini Architects (together with Dustin White and Dario Pedrabissi). Furthermore, it is necessary to specify that an exact replication of reality has not been carried out: even if the aim was to reproduce the context of the garden and the installations as faithfully as possible, a simplification has sometimes been carried out in order to provide the general idea of the project linked to an alternative user experience.

## 2 The Method

The VR executable was made using the free software Unreal Engine 4, while for the 3D modeling and the texture mapping Rhinoceros and 3D Studio Max were chosen. The process consisted basically in three phases: the reconstruction of the context, the optimization and placement of pavilions, the interactivity implementation. Part of this work, especially the context modeling, has been done with the help a group of three more people—Maria Lucia Valentina Alemanno, Alessandro De Bellis and Isabella Giordano—in order to reach the best result possible.

As a matter of fact, the virtual reconstruction of a specific environment or architecture is a complex process that requires many different abilities linked to no less different fields of knowledge such as computer graphics, architecture, visualization, programming and 3D modeling.

### *2.1 The Context*

The first step was the digital reconstruction of the Giardino delle Vergini, in which the models of the various pavilions had to be placed.

The garden is part of the Arsenale della Biennale, a building of the pre-industrial era. The Arsenale consists of a series of construction sites, where Venice fleet was built. It hosts part of the Exhibitions organized by La Biennale Foundation since 1980 and the site has been enhanced since 1999 thanks to a valorization program. The Giardino delle Vergini, which is accessible since 2009, hosts part of the Italian Pavilion. The garden is made of a wide green area surrounded by historical brick buildings [19].

From a practical point of view, the approach to the situation was not easy. As a matter of fact, in normal conditions working on an existing place would require a long session of inspections with the help of cameras and drones in order to carry out surveys that help to have an accurate three-dimensional clone of the intervention area. This is necessary to make all the subsequent operations more coherent and precise and to give the future users a sense of total immersion that makes them feel part of the virtual scene and that guarantees the VR executable not to be "reduced" to the same perception of a video game. This is not an easy operation because of the technical limitations of viewing via headset and the deleting of many physical characteristics of the human body. At the same time this issue is fundamental: the more an individual is involved, the more it will be easy to forget the outside concrete world, leading the user to the best Virtual Reality experience.

In this case it was impossible to personally visit Venice due to the pandemic, so it was firstly necessary to resort to Google Earth: the free software made available by Google allowed the extraction of a three-dimensional reproduction of the land and a high quality orthophoto. Moreover, several screenshots were taken through the Street View tool. These data, together with some photographs of the site and a CAD planimetry sent us by the curator of the 17th International Architecture Exhibition of Venice Dario Pedrabissi, were fundamental both for the three-dimensional modeling and for the rendering of the place.

It is important to focus on the optimization strategies adopted during this phase, since the context was the most complex element in terms of polygons account and materials to render and a bad optimization would have inevitably compromised the virtual experience.

The model extracted from Google Earth was processed using Sketchup and was useful to evaluate terrain heights. It was possible to notice that there weren't significant depressions or elevations, therefore terrain was approximated to a plane, in order to have the lowest amount of polygons and to simplify the scene. It was split in different portions according to the different soil materials (grass, concrete and pebbles) with the help of the ortophoto. The single planar parts were mapped and then imported in Unreal Engine, where proper materials were applied.

The Google Earth model was useful also to obtain the correct dimensions of the buildings surrounding the garden. The volumes of these buildings were transformed into more accurate models using Rhinoceros.

A special focus should be done on the arched building, which was the nearest one to the area where installations were placed and that required a good compromise in terms of optimization and realism. This building was treated as a modular one, therefore a single arch was modeled and repeated. The measure of a single module was obtained dividing the total length of the building for the number of arches. Of course, it is important to underline that the purpose of this work wasn't to obtain an accurate survey of the site, but to have a light 3D model that globally appeared as similar as possible to it.

Even if the dimension and the global geometry of the module is always the same, it is possible to distinguish four variations looking at the photos: a module with a simple wall, a module with a round arched window, a module with a pointed arched window and a module with both a pointed arched window and a door (Fig. 1).

In order to have a good optimization, it was impossible to have a different model for each variation of the arched element, therefore the differentiation was made using custom textures that could be applied to the same 3D object (Fig. 2). When strictly

**Fig. 1** The different variations of the arches. Photo taken from Google Earth's Street View

necessary, a few 3D objects were added to increase the realism (for example sills or jutting brick arches).

Furniture elements as lamps and trash cans were modeled and placed referring to the photos in order to improve the realism of the scene.

For the lighting a HDRI sky with low sun was chosen and some parameters were modified in order to increase the contrasts of the scene.

Vegetation choice and placement required some time and various trials, since it is what influenced the performances of the VR application the most. Some lowpoly tree models similar to the real trees of the garden were chosen and placed with the help of the photos and the planimetry. We tried to scatter different types of 3D grass, but the FPS always dropped dramatically, so we decided to use a grass texture. We modified some parameters of the grass map included in the Unreal Engine starter content, in order to increase variation and reduce the perception of a texture repeated all over the place.

Finally, some decals were used to simulate stains and imperfections.

## *2.2 The Pavilions*

After the setting of the context, we proceeded with the optimization of the pavilions. Most of the designers gave us high resolution models, so we had to obtain simpler models, deleting details and reducing the number of polygons as much as possible.

Only Gianni Pettena's and Zaha Hadid Architects' ones were modeled from scratch because the authors provided only 2D drawings.

As we already said in the introduction, not all the installations were rendered to look exactly like the real ones. For example, in the case of Christian Pongratz's

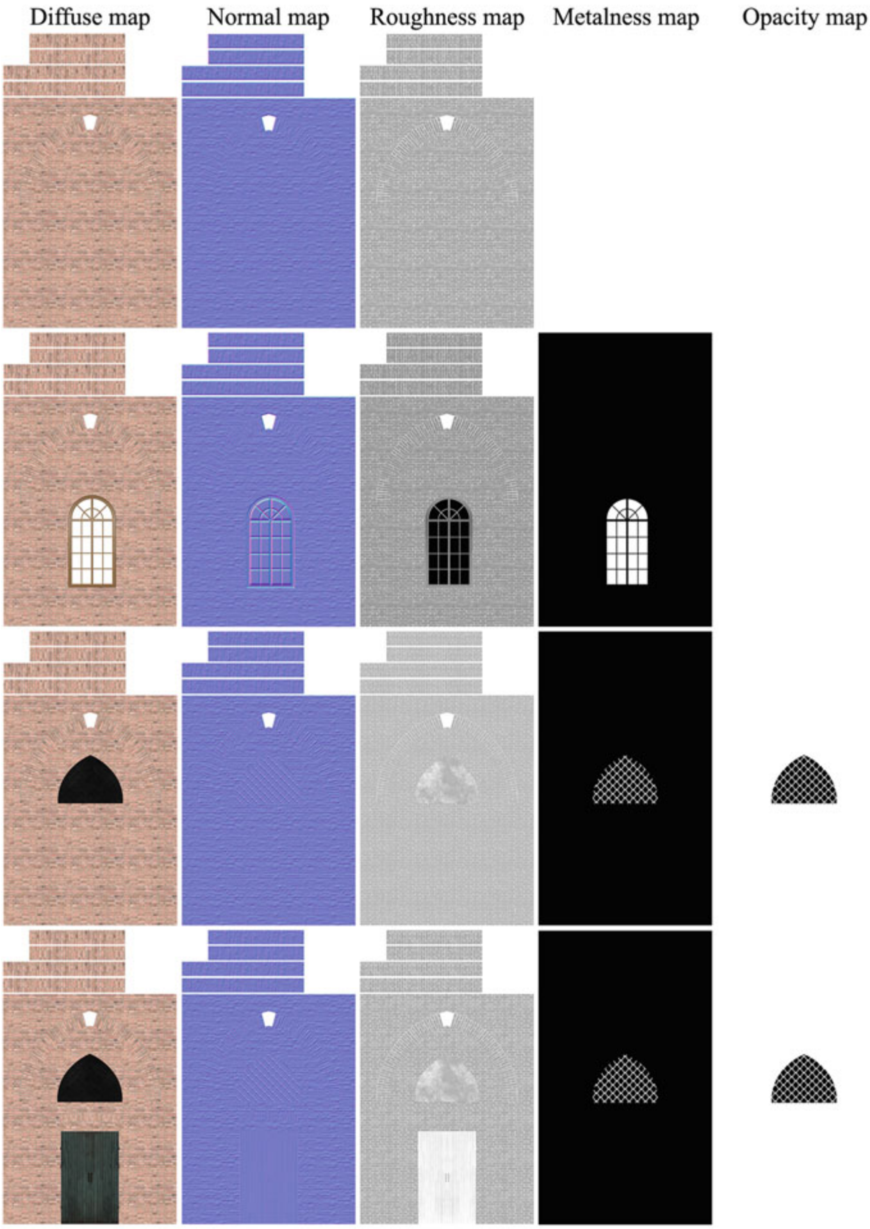


**Fig. 2** The textures used for the variations of the module

pavilion, the designer himself requested the model displayed in VR not to be reproduced neither with its real materials nor in a photorealistic way, but it had to be a white painted version of his project that could allow a deeper focus on its geometry.

We treated similarly David Turnbull's pavilion, too (Figs. 3, 4, 5 and 6).

**Fig. 3** A comparison between the digital reproduction of the garden and the photos taken from Google Earth

**Fig. 4** A screenshot of the VR application environment. From the left: *Flux* (by Giuseppe Fallacara and Maurizio Barberio), *Watershed* (by David Turnbull with Fred Avitaia, Lorenzo Bertolotto, Marc DiDomenico, Saul Golden), *Archipensiero* (by Gianni Pettena) and *Crispr-Locus* (by Pongratz Perbellini Architects with Dustin White and Dario Pedrabissi)

**Fig. 5** A screenshot of the VR application environment. From the left: *High-Performing Urban Ecologie*s (by Zaha Hadid Architects with Tecno), *Prossima Apertura* (by Orizzontale) and *Flux* (by Giuseppe Fallacara and Maurizio Barberio)

## *2.3 Interactivity*

Interactivity is the basis for a good VR experience, since the possibility to explore, interact with objects and acquire information is what distinguish an app from a simple 360° image.

Given the extent of the garden, it was impossible to explore the area just walking around in a room with the headset on, so a teleport system was set up. This way the user can move with the help of a luminescent indicator, which shows the destination of the teleport (Fig. 7).

Future developments of this research may be linked to tests carried on expert and casual users in order to evaluate their feedback and use them to improve the experience.

We tested a navigation system based on the use of joysticks, too, but at the end it was rejected because it caused more problems of motion sickness than the teleport system.

Then we decided to further improve the VR experience providing some information about each pavilion. To do so we added the official descriptive panels of the exposition, which appear when the user goes near the installations (Fig. 8). In order to indicate the precise area where the panel appears, we put in the scene some luminescent info signs.

In the case of the Pettena's pavilion, which is an anamorphosis, a luminescent signal was placed on the floor in the exact point where it would have been possible to perceive the false perspective generated. This is a way to make the user immediately grasp the meaning of the artefact itself, without any other explanation (Fig. 9).

**Fig. 6** A comparison between the real Christian Pongratz's Paviliom (photo By Pongraz Perbellini Architects) and the digital one

## 3 Ethical Matters

Creating a digital twin of a real place or architecture is not a simple operation, not only because of the required technological skills, but also because of what we may call an ethical problem. As a matter of fact, the digital world is something that can be completely controlled by its creators: situations, events, sounds, everything is guided by just one hand. This means that this world can be shaped and guided in

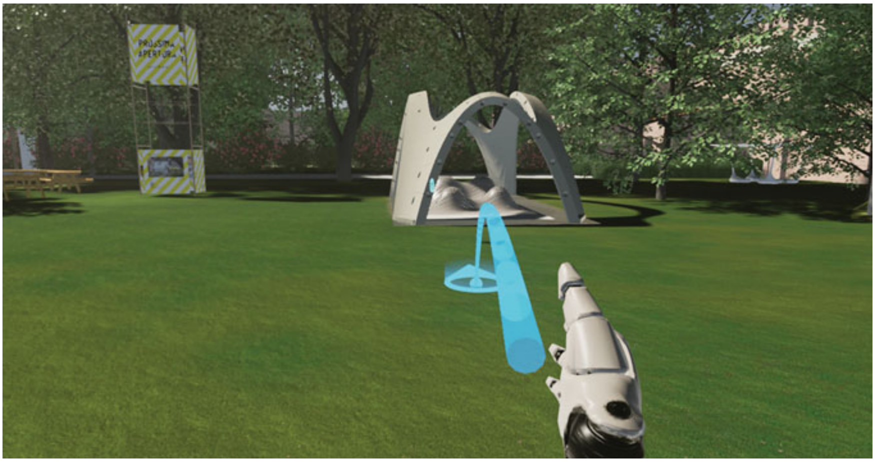

**Fig. 7** A screenshot of the teleport indicator


**Fig. 8** A screenshot of one of the information panels

one direction, maybe choosing to give a user just a specific view in order to evoke specific emotions, feelings and thoughts.

This is an important matter that must not be underestimated, especially considering the topic of the Metaverse, that's spreading today especially because of advertising actions made by big companies like Facebook.

Lorenzo Scaraggi is a famous italian storyteller and videomaker who has experienced the use of virtual reality both as a user and as a creator of contents like immersive movies and this experience gave him the chance of thinking about the moral matter behind the extended reality experiences.

**Fig. 9** A screenshot which shows the signal for the correct perception of Pettena's anamorphosis

[…] The risk is that the new range of emotions coming from the use of this technology is conveyed in the worst way: in a consumerist dictatorship where those emotions become a coercive vehicle for opinions, moods, political orientations, easy consent» he wrote.

I think of a world of isolated people wearing headsets and whose emotions become invisible threads maneuvered from above; something far more powerful than what happens with social networks; something that gives us the power of talking to the heart of the large masses through an algorithm, creating a place where we decide what they want, what they buy and what they choose. So, what we need to do as a responsible society is to shift the focus of virtual production onto culture and onto a representation of reality as clear as possible […] [20].

These quotes can help us also explain the reason why it is important not to build an exact replica of the real world, as already said. The real advantage that immersive visualization brings is strictly linked to a well balanced relationship between virtual and physical so that they do not harm each other. Also, it is important for what it may concern the topic of emotions and feelings, which has been already discussed.

Virtual places, also the fictitious ones made for videogames, are catalysts of emotions just like books and movies. In this regard, during an interview published on IoArch Magazine n. 93, the architect Eric de Broche des Combes from Luxigon Studio said: «I personally have played World of Warcraft for ten years (although I should maybe not have), and for me these places really exist. I remember them; I discover new ones exactly like visiting Rome, or Milan. For me they do exist. The interesting part of the story is that, psychologically speaking, there is an emotional involvement with these places, which is similar to the one you commonly experience in reality. They are cognitively and (to a certain extent) physiologically real. Of course, you do not experience pain, death and things like that, but most of what you normally experience like empathy, love, aesthetic appreciation, do exist and are reflected in the environment, even though it is virtual» [21].

This is important to reflect on the possibilities given by Virtual Reality for cultural purpose, since interactive experiences, and in particular the immersive ones, produce a much greater involvement of the user than other traditional educational tools, as written panels, oral explanations, etc.

## 4 Conclusions: Potentials and Limitations

In conclusion, Virtual Reality is an instrument with a high potential for the enhancement of cultural heritage, and to increase the collective participation in events all around the globe.

On one hand VR applications can be used to improve the experience of a real tour in a museum or in a cultural site giving the user additional information. On the other hand VR executables can be sent everywhere and can become a means to break down barriers and to keep people all over the world able to visit a specific place and to interact with it. Especially after the Covid-19 pandemic, when limitations prevented people to travel, virtual tours have increased their popularity and it is important to reflect on the possibilities offered by immersive experiences as new means of knowledge acquirement and cultural entertainment.

Of course, it is necessary to underline that Virtual Reality cannot and must not be used as a mere substitute for reality, but rather as a way to build augmented and alternative visions of the reality itself in order to allow to grasp different facets and to acquire additional information in an uncommon way.

Moreover, this kind of parallel experiences can encourage people to visit the real places and discover their concrete side, bringing benefits to the tourism field, which almost completely stopped because of the Covid-19 pandemic.

In this paper we have described the entire process for the creation of a VR application of a cultural site. Of course, even if the technology has great potentials, it still shows some limits. Firstly, this kind of executable requires time and specific skills to be correctly realized; moreover, complex Virtual Reality executable still need specific tools to be used. Even though Augmented Reality is more and more used through smartphones, virtual reality is still mostly linked to headsets and workstations, which can be expensive and difficult to move. In order to obtain the best result in terms of education, it must be sent to schools and organizations that already have specific laboratories. In our case, with the help of prof. Christian Pongratz, we were able to share the app with the New York Institute of Technology, which has labs equipped with various Oculus headsets.

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# Towards a Digital Shift in Museum Visiting Experience. Drafting the Research Agenda Between Academic Research and Practice of Museum Management

**Giuseppe Resta and Fabiana Dicuonzo**

**Abstract** This chapter reviews the state of the art in digital applications for museums and exhibitions, with a particular focus on the visiting experience. The authors have measured the gap between academic research and the current practice of museum management through a mixed-methodology approach. On one hand, the text presents the result of a systematic literature review of articles on museum digitalization that have been published since 2000. On the other hand, it includes the results of an interview with a group of experts, directors, and curators of Italian museums to understand the degree to which digitalization is currently adopted in those cultural institutions. COVID-19 is an additional factor that has been considered in terms of its impact on scientific production and museums' strategies. Such cultural institutions, having ticketing and similar forms of revenue related to physical visitors at the core of their model of economic sustainability, suddenly realized the need for a different approach to promoting art, namely forms of engagement from a distance. Within the frame of industry 4.0, it has become evident the crucial role experts play in the field of digitalization and implementation of virtual environments for the art sector. This text aims to draft a research agenda on museum digitalization for the near future, looking at trending topics, academic networks, and research geographies. The qualitative survey with experts' opinions discussed whether regular employment of digital platforms and virtual tours can engage new visitors in the long term, and established the current status of their day-to-day activities.

**Keywords** Survey · Literature Review · Digital Shift · Museum Sector · Digitalization

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_34

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 10. Reduce inequality within and among countries · 17. Strengthen the means of implementation and revitalize the global partnership for sustainable development

# 1 Introduction

## *1.1 Outline*

In the last twenty years, the digital shift in the field of art and architecture has been forming a new body of theory that encompasses: a revision of the design phase [1]; new manufacturing processes and robotic fabrication [2]; the adoption of intersectoral educational models [3]; and the introduction of virtual experiences in connection with or in replacement of existing spaces and heritage sites. The latter will be at the center of this analysis, with the intention to draft the research agenda for the museum sector facing such new paradigms as: digital twins, data-driven strategies, Virtual Reality and Augmented Reality, real-time digital representation, and visitor-computer interaction.

This chapter intends to review the status of digitalization in museums, with a particular focus on the visiting experience. In this regard, we have decided to measure the gap between academic research and the current practice of museum management. On one hand, the text presents the result of an extensive literature review of articles that have been published since the year 2000. On the other hand, the authors have conducted a semi-structured interview with a group of experts, directors, and curators of public museums to understand the degree to which digitalization is currently adopted in museums.

The digital shift in the museum visiting experience has been occurring for many decades. It started with the concept of museum computing at the end of the 1960s [4], firstly integrating archives and records and then affecting the visiting experience with the evolution of audio–video guides [5]. This text intends to lay out the updated state of the art for the issue of museum digitalization by studying the current research panorama together with trends of future strategic implementations.

Among the many impacts of COVID-19 restrictions in the last two years, the digitalization of the museum experience has secured the attention of many researchers [6, 7]. Cultural institutions devised multiple communication strategies and virtual environments to target visitors' engagement during this period. In this chapter, we will also examine how this affected the direction of academic research considering the output published since 2020, when restrictions were enforced. Simultaneously, if we are to draft a research agenda for the near future, we should be able to contextualize the pandemic event as a prominent but circumscribed occurrence. Hence, it is vital to step back to a more comprehensive vantage point from which it is possible to trace the whole trajectory of museum digitalization in academia and practice.

## *1.2 Theoretical Framework: Interaction and visitor's Experience*

Interaction in visitors' experience is usually addressed as synonymous with digital environments. Though, as pointed out by Levent and Pascual-Leone [8], sensory engagement and immersive experience can be obtained by triggering senses of smell, touch, sound, space, and memory in exhibition spaces. In this regard, Classen [9] has discussed how museums are essentially focused on the visual experience, while many masterpieces and historical artworks are intertwined with the overall bodily experience that the subject perceives. Hence, this aspect is essential to the visitor's feeling of being present in the venue and will be addressed throughout the expert interviews presented in this study. Additionally, the act of art appraisal by visitors is mediated through a behavioral code established by the institution (i.e., museum, gallery, collector), and it is not always clear how the author intended their work to be experienced in the first place. For example, if touch and manipulation are allowed, and to what degree [10]. In archaeological museums, such impasse has been solved with partial or integral 3D printed replicas of the original that would satisfy the necessity of object handling as an exploratory phase of the visit [11].

Interaction aims then at increasing the level of engagement with the subject, mainly to produce long-term involvement [12]. In this sense, engagement as "the willingness to have emotions, affect and thoughts directed towards and aroused by the mediated activity in order to achieve a specific objective" [13] would be the ultimate goal of professionals working in the field of culture.

Societies have always constructed alternative worlds to engage an audience of visitors, religious believers, gamers, etc., projecting to another environment activities or representations that the physical world couldn't afford [14]. In museums, the traditional visit can be augmented with a narrative structure (storytelling), additional content (multimedia), and immersive experience (virtual reconstructions). Bekele and Champion [15] compared virtual reality technologies in virtual heritage, examining the most used interaction interfaces: Augmented Reality (AR), Virtual Reality (VR), Augmented Virtuality (AV), and Mixed Reality (MxR). The latter is seen as the most viable option for heritage sites and museums to establish a relationship between users, virtuality, and reality, without losing the social dimension of cultural learning. In fact, the educational value of museums is seen as a primary form of interaction [16], both within and outside 3D virtual environments [17].

This bond between century-old institutions and digital interactive tools opens another issue we will address through the expert interviews: the digital preparedness of museums. Hanussek discussed the supposed enhancement of the visiting experience through ad-hoc smartphone applications, pointing out that "museum apps have not brought the impact so often promised to visiting audiences" because "professional expertise in information technology and data analysis seem still to pose a huge challenge for museums, as evidenced by the technical issues of the discussed apps and the lack of proper assessment of their user experiences" [18]. Hence, we have asked the interviewed experts to describe the consistency of the information technology personnel in their institutions, if any.

Engagement also has an online phase that is conducted on social media channels. In relation to the visit, digital content can help build the construct of the visitor's motivation before the visit, or complement the acquired information after the visit [6]. We have addressed this issue in the bibliographic review and with specific questions to the experts. It should be noted that COVID-19 restrictions have impeded physical visits, offering for a certain period a unique opportunity to measure the delivery of cultural content through online platforms only [7]. This raised the question of the degree of replaceability of online experience in opposition to onsite presence. The use of digitization and social media also has profound political implications because it is being directed by choices that imply a selection ex-ante, and received on devices that are subject to digital divide disparities [19]. Hence, authority and curation of content are not secondary to the impact on visitors' experience through social media. In turn, different platforms have different audiences, making the overall assessment fragmented by definition: while Twitter has stronger involvement with political and social issues [20], Instagram's feed is predominantly visual and has more aesthetic connections with the experience of an exhibition [21]. Contents on Facebook create virtual communities of users interested in a specific topic: it allows interaction in both directions, but at the same time users expect the cultural institution to be consistently responsive to maintain an effective engagement [22]. The creation of content is then tailored to the specific platform if museums intend to gain maximum engagement, requiring an effort in communication strategies that is constant and with a long-term perspective.

Online communication covers a broad spectrum of channels, from institutional websites to chatbots. The former is unidirectional and aimed at a generic prospective visitor; the latter is "a computer program designed to simulate conversation with human users" [23] with one-to-one interaction.

Finally, the visitor's experience can be considered interactive when the museum activates participatory projects of co-creation. This social aspect has an extensive literature and is widely studied among practitioners and researchers [24–27]. We will address it several times in the bibliographic collection and with the questionnaire only in relation to the digitalization of the visitor's experience.

This study builds upon an article on the impact of virtual tours on museum exhibitions that we have recently published [6]. We have decided to define the perimeter of the investigation through the following parameters:

- Definition of a specific setting: museum. Art galleries, fairs, temporary exhibitions, and art parks are not taken into consideration.
- Definition of a specific subject: visit. Laboratories, archives, museum libraries, happenings, and talks are not taken into consideration.

- Definition of a specific aspect of the visitor's experience: digitalization.

Other literature reviews partially cover these three elements, but none is updated, with a systematic approach, or contains all the aforementioned components. Xu et al. [28] analyzed research results published between 2011 and 2021 on the impact of technology applications on museum learning outcomes retrieved from the core Web of Science collection. Ayala et al. [29] examined research articles on audience development in museums and heritage organizations, combining results from three different databases. Serravalle et al. [30] focused their attention on research items on augmented reality in the museum with reference to the pool of stakeholders.

## 2 Literature Review

### *2.1 Methodology*

This bibliometric analysis is structured in two components that will be addressed separately in the result section. One concerns descriptive metrics in the domain of museum digitalization in terms of overall scientific production and its yearly evolution. The second looks at knowledge structures across the pool of articles considered for this research.

To collect a reliable and representative number of articles, papers were retrieved from the core Web of Science collection, containing journals in the Science Citation Index Expanded and Social Sciences Citation Index.

Bibliometrix R-package and Microsoft Excel were used for analysis. Bibliometrix is a science mapping open-source tool programmed in R that elaborates research distribution, subjects, and citations [31]. The following objectives have guided this quantitative analysis:

- Establish ground for comparative evaluation with expert interviews
- Identify research trends and specific geographies interested in the topic of museum digitalization
- Visualize the collaborative network that shares an interest in the topic of museum digitalization
- Study the use of keywords in scientific production
- Identify the most cited articles, journals, and authors.

Articles had to contain the three components that form the construct of this research: keywords "visitor", or "visit", or "engagement"; and keywords "digital" or starting with "digitali"; and keywords "museum", or "exhibition". With the Boolean operators "AND NOT" we have excluded those articles that contain the keyword "archive" as it is within the domain of museum studies but beyond the scope of our study on the visitor's experience; and the keywords "machine learning", "deep learning", or "artificial intelligence", that characterize articles beyond the scope of our study. The analysis was conducted in March–April 2022, and the records are

**Table 1** WoS search query

| Search syntax |
|---|
| Visitor OR visit OR engagement (All Fields)<br>AND digitali* OR digital (All Fields)<br>AND museum OR museums OR exhibition OR exhibitions (All Fields)<br>AND NOT "machine learning" OR "deep learning" OR "artificial intelligence" (All Fields)<br>AND NOT archive (All Fields)<br>AND 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 or 2014 or 2013 or 2012 or 2011 or 2010 or 2009 or 2008 or 2007 or 2006 or 2005 or 2004 or 2003 or 2002 or 2001 or 2000 (Publication Years) |

updated to April 22nd. We have included all articles published in the last 22 years, considering that 2022 is represented only for the first four months of the year and will have limited relevance in certain aspects of the result section. A total of 1257 results were obtained with the syntax shown in Table 1.

After removing duplicates, 1240 articles were left. Then a close reading of titles and abstracts reduced the number to 1109, considering articles whose content is not covering any issue related to museums, visitor engagement, or virtual reality. We reported that some research published in journals of environmental sciences, ecology, and zoology, contain the same key terms but address very different research fields. Finally, after discarding reviews, editorials, data papers, and meeting abstracts, the pool of items reached the final number of 1082.

## 3 Results and Discussion

**Overview**. Articles are spread across 675 sources (books, journals, proceedings) with an average number of citations per document of 4.43, and 0.72 average citations per year per document. Items are mainly journal articles (54%) and conference papers (42%), and only 4% are published as book chapters. The total of authors involved is 2886, meaning 0.38 documents per author and 2.67 authors per document. Multi-authored items are 850 (79%), with 3.2 co-authors per document and a Collaboration Index (CI) of 3.13. The latter measures the mean number of authors of multi-authored papers per joint paper [32, 33], while co-authors per document measures authors' appearances per total number of documents. This suggests that the research team is generally formed of three authors. In terms of annual scientific production (Fig. 1), starting from 2016, publications constantly total 100 or more. The graph shows a considerable jump in 2018, maybe because the hardware for immersive reality started to become affordable and adopted by major entertainment companies [34]. Another spike is positioned between 2020 and 2021, when COVID-19 restrictions have amplified the debate on digitalization of cultural institutions. Compound Annual Growth Rate returns a constant rate of 14.59% over the examined period. Considering the average article citation per year (Fig. 2), articles that collect the highest number of yearly citations were published in 2000 and 2008.

It should be noted that we will differentiate between global citations, those that are provided by WoS metrics gauging the impact of an article in the whole database and across all disciplines, and local citations, those that are received from documents that are present in the analyzed collection as is formed through the search query in Table 1. Hence, the latter measure the impact in the field of museum digitalization.

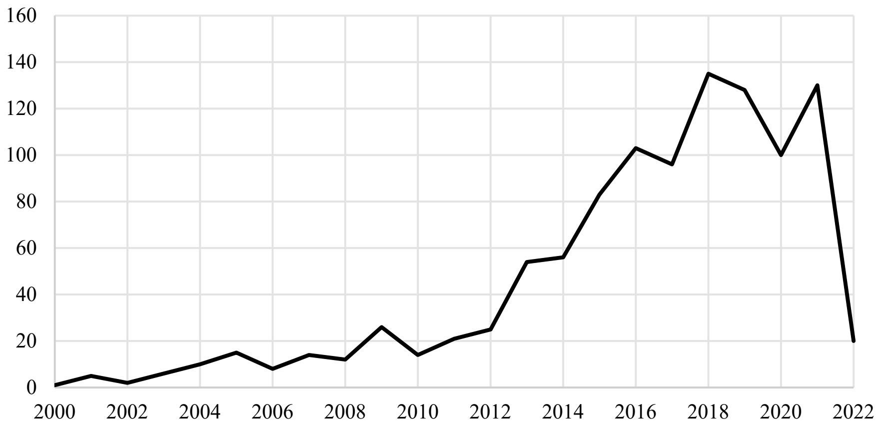


**Fig. 1** Annual Scientific production. Y: Articles, X: year

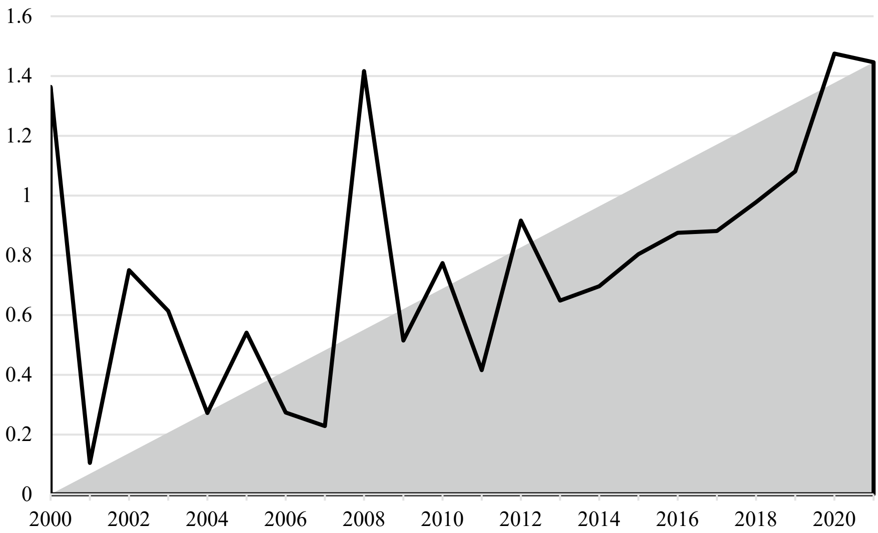


**Fig. 2** Average Article Citation per Year. Y: Citations, X: year

**Analytics and graphs**. The analysis covers statistics on sources, authors, and documents. First, we examine the relationship between topics and geographies by looking at the keywords of the academic works.

Examination of keywords (Fig. 3) shows that the authors' countries are mainly the United Kingdom (237), Italy (229), Greece (101), Spain (101), and the USA (90). The keyword "cultural heritage" is mostly used by Italian authors. British scholars prevail in the use of "digital heritage". Keywords "virtual reality" and "augmented reality" have a similar distribution; the former is used by most of the Austrian and Chinese authors that were considered in this research; British authors mostly address "engagement"; "social media" and "virtual museum" are frequently cited by Italian authors; "education" is the second most used keyword by Spanish scholars. If we look at the authors' affiliations (Fig. 4), "cultural heritage" is mainly used by authors from Sheffield Hallam University and Università Politecnica delle Marche. The former prevails in the use of "virtual reality", the second in the use of "augmented reality". Some keywords are almost exclusively linked to one university: "social media" to Politecnico di Milano, "engagement" to King's College London, and "heritage" to Newcastle University. Vice versa, certain universities are very much focused on specific topics: the University of Peloponnese on "cultural heritage" and the University of Patras more generally on "museums", which is part of the search query, and is not linked to any of the top 20 keywords. The University of the Aegean and the University of Nottingham distribute their contributions in most of the top 20 keywords.

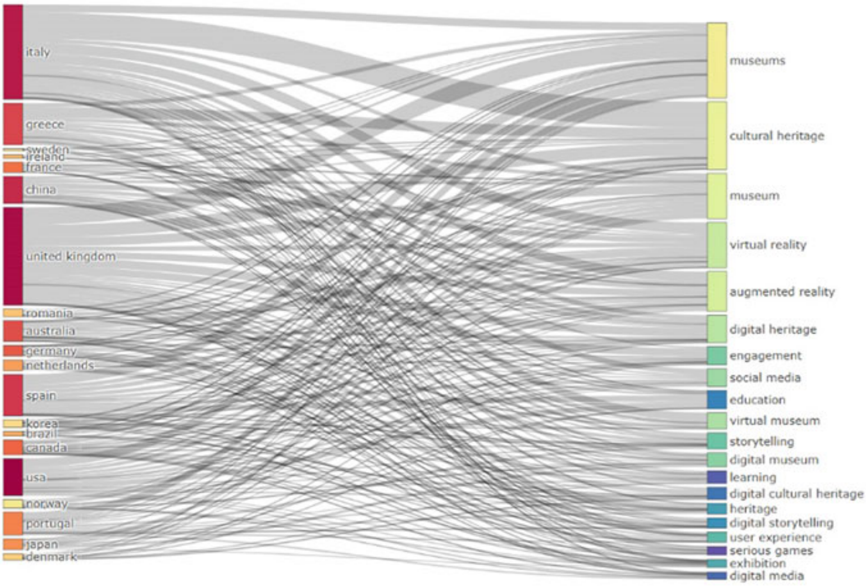


**Fig. 3** Fields plot elaborated by Bibliometrix. Left column: author's country, right column: keywords

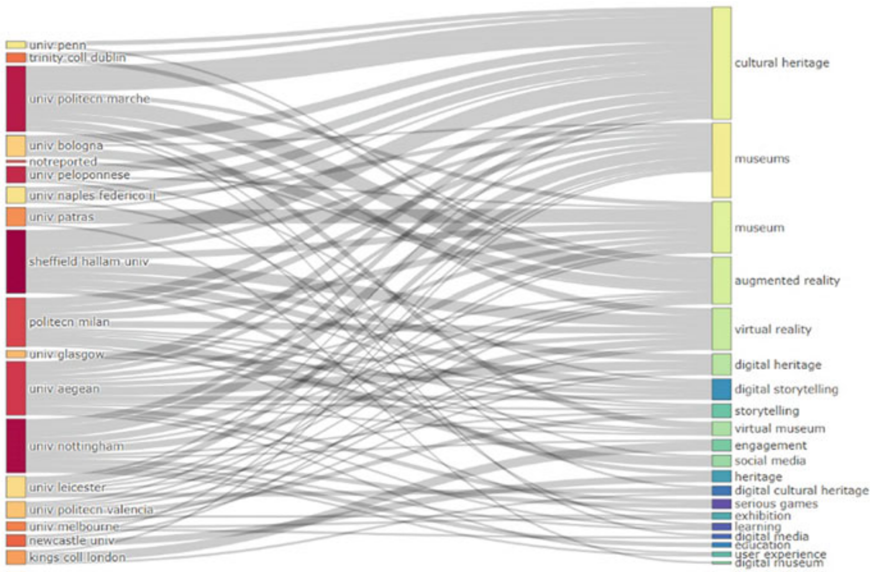


**Fig. 4** Fields plot elaborated by Bibliometrix. Left column: author's affiliation, right column: keywords

It should be considered that the keywords mentioned above are the author's keywords. Although many publications suggest a preference for using Keywords Plus [35, 36], which are index terms generated by an algorithm that scans the titles of an article's bibliography [37], they are usually more generic and linked to methodological aspects [38]. For this reason, we will employ Keywords Plus to better understand the structure of scientific production on museum digitalization, while author keywords are considered better descriptors of the content of the articles [20, 38].

The journal Museum Management and Curatorship (Humanities, AHCI), providing 31 documents, is the most relevant source in terms of published articles. Second is the ACM Journal on Computing and Cultural Heritage (Computer Science and Humanities, SCIE, and AHCI), with 25 articles. The journal of Museum Education (Education & Educational Research, ESCI) with 14 articles, and Curator – The Museum Journal (Humanities, AHCI) follow. Particularly relevant are the two volumes of the 2015 Digital Heritage International Congress, with a total of 34 contributions pertinent to the subject. The congress held in Granada, Spain, is then the venue where museum digitalization has been more organically discussed in the last 22 years. The following 2018 Digital Heritage International Congress held in San Francisco, California, is well represented with 12 papers. Source clustering through Bradford's law [39, 40] shows that the core area that represents the nucleus of journals that cover the examined issue is quite broad. Bradford's model suggests that the core literature is scattered across 41 periodicals, confirming that the issue of museum digitalization is highly interdisciplinary and is present in sources of different scientific fields.

To evaluate sources' impact, we have considered the *g-index* developed by Egghe, which is the "unique largest number such that the top g articles received (together) at least $g^2$ citations" [41]. It has been demonstrated that this index, compared to the *h-index*, is not influenced by the total number of publications [42]. Hence, in our case is preferable because the initial publication year varies considerably. Museum Management and Curatorship has the highest *g-index* (17), and ACM Journal on Computing and Cultural Heritage is second with 12. Considering the number of examined articles, those published in Digital Creativity ($g = 8$) and in Visitor Studies ($g = 6$) have had a significant impact. Of the 12 top journals with a *g-index* of 5 or above, 5 are published in England, 3 in the USA, 1 in Greece, 1 in Italy, 1 in Poland, and 1 in the Netherlands. The category of humanities is the most represented with 6 periodicals, then computer science and archaeology with 3, art with 1, tourism with 1, and social sciences with 1. Most are indexed in AHCI collection (8), SCIE (3), ESCI (2), and SSCI (1). Source dynamics performed on these journals (Fig. 5) shows that periodicals concerned with museum studies have constantly investigated museum digitalization starting from the period 2004–2008, while periodicals more centered on computer science have considerably increased their interest only in the last years.

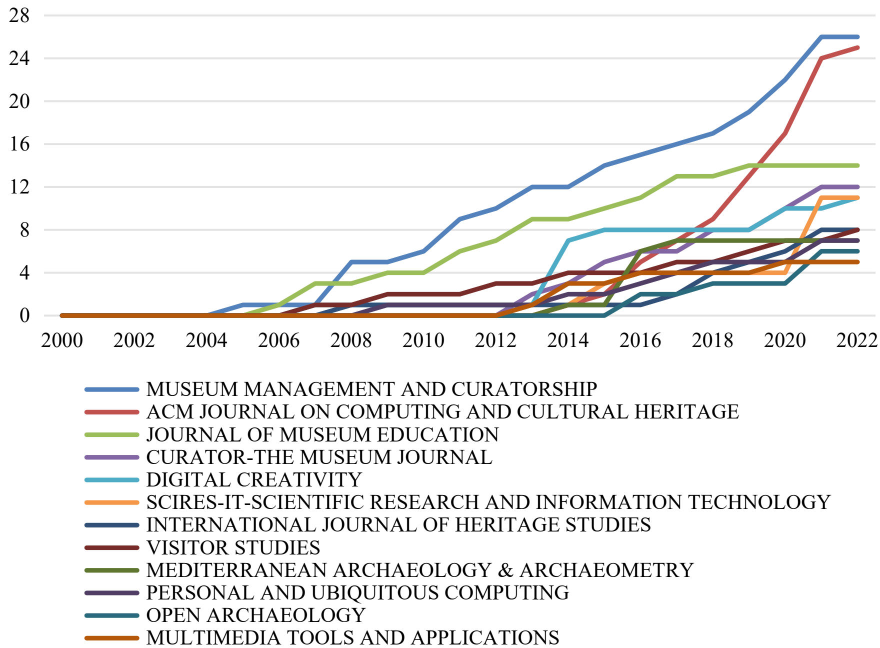


**Fig. 5** Source dynamics. Y: Cumulate publications, X: year

Focusing data analysis on authors, we observe that the top-ten most relevant authors per fractionalized number of documents [43] range from 0.8 to 4.4 documents. Top-ten authors per fully counted documents, ranging from 6 to 11 papers, are the same as the fractionalized count with slight differences in terms of rank. Benford has the most extended production on the subject over time, while Antoniou has the most protracted timeline if we consider active authors that have already published an article in 2022. Petrelli has constantly published every year 1 to 4 articles from 2016 to 2020, and Lepouras has continuously published 1 to 4 articles from 2016 to 2019. COVID-19 is having a remarkable impact on authors' production on museum digitalization: the two most cited articles were published only in 2020 and 2021 by Arnaboldi and Agostino (joined by different co-authors) with the titles "New development: COVID-19 as an accelerator of digital transformation in public service delivery" [44] and "Italian state museums during the COVID-19 crisis: from onsite closure to online openness" [7]. Both look at how Italian state museums implemented strategies of engagement during the lockdown. This element confirms that researchers have shifted their focus in the last three years. Another interesting aspect is that most of top authors' timelines start in 2013–14 and end in 2020, suggesting that 2021 imposed a halt in terms of production. Top authors published the majority of their articles in 2017–18.

Frequency distribution of scientific productivity studied with Lotka's Law [45] shows that 88% of items are authored by occasional contributors, while core authors have published at least 5 articles on the topic. The 0.2%, 19 researchers, can be considered core contributors in the field. Rounding this number to the 20 top authors, their *g-index* ranges from 4 to 9, with Petrelli and Pierdicca that record the best local impact.

The most relevant affiliations per number of articles are Sheffield Hallam University (25), University of Nottingham (21), Università Politecnica delle Marche (20), University of Peloponnese (16), University of the Aegean (13), Politecnico di Milano (12).

In Fig. 6, we can see the corresponding author's geographical distribution. Almost the same number of articles have Italian or UK corresponding authors, followed by USA, Chinese, and Spanish researchers. The total is then split into Single Country Publications (SCP), which are co-authored by researchers of the same country, and Multiple Countries Publications (MCP), with at least one co-author from a different country. Hence, the MCP ratio measures the intensity of international collaboration of a country. In this regard, the Netherlands (44%), Sweden (33%), and Denmark (29%), have the best ratio of international collaboration. Low international collaboration is measured with Brazilian, Romanian, Japanese, and French authors.

Counting instead the number of documents per country (Fig. 7), namely the affiliation countries' frequency distribution, the USA is represented in 518 documents, the UK in 366, Italy in 285, and China in 144. Large parts of Africa and central Asia are not present in any affiliation. Though, in terms of total citations per country, UK authors collect a total of 936, prevailing on the USA with 759, Italy with 672, and after that is a considerable gap to the fourth, China, with 347 citations.

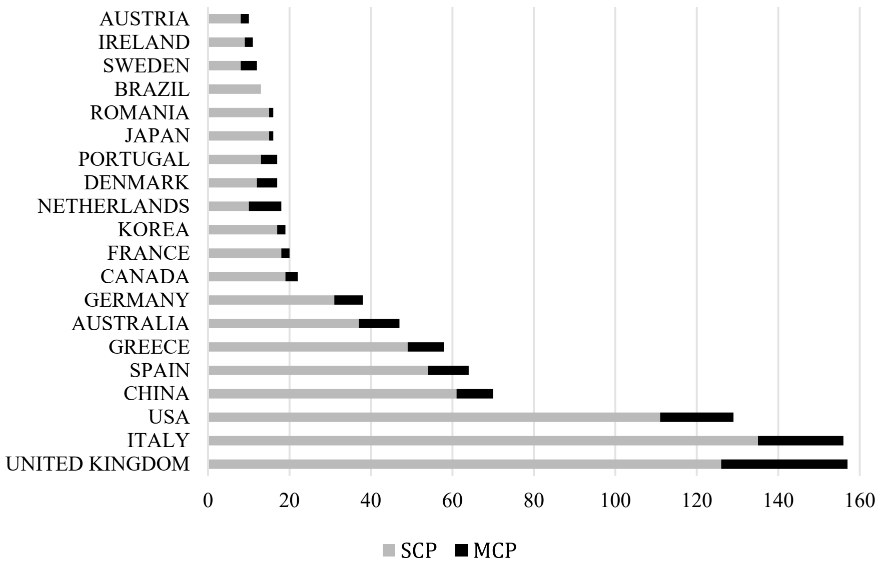


**Fig. 6** Corresponding Author's Country. Y: number of publications (SCP = Single Country Publications; MCP = Multiple Countries Publications), X: country


**Fig. 7** Country scientific production. Scale: white (unrepresented countries) to dark grey (USA = 518)

The last aspect of our analysis is related to the 1082 items retrieved with the search syntax mentioned above. We will call "documents" all items that are included in the bibliographic collection; "references" all articles that are cited in the bibliography of each document; "cited documents" all articles that are included in the bibliographic collection and at the same time cited as references.

Within the examined bibliographic collection, the most locally cited source is the book series Lecture Notes in Computer Science, published by Springer with 340 citations. Curator (247), Museum Management and Curatorship (234), and Journal of Cultural Heritage (215) score a similar number of citations. Thesis works are also quite present, with 185 citations. The most cited author in museum digitalization is Petrelli (25 local citations), which is not surprising as her works are all centered on the relationship between museums and digital platforms. Marty has 18 local citations, Not has 13 local citations (she co-authored three works with Petrelli), Agostino and Arnaboldi both have 12 local citations, having also co-authored three works together.

Most globally cited documents are published in computer science journals: "Using augmented reality and knowledge-building scaffolds to improve learning in a science museum" [46] 108 citations, "Effects of the inquiry-based mobile learning model on the cognitive load and learning achievement of students" [47] 78 citations, "Leveraging explicitly disclosed location information to understand tourist dynamics: a case study" [48] 75 citations. All three address museum issues only partially. This is demonstrated by the fact that top cited local documents are instead all published by Museum Management and Curatorship and are centered on museum issues: "Museum websites and museum visitors: digital museum resources and their use" [49] has 16 local citations, "The presence of Web 2.0 tools on museum websites: a comparative study between England, France, Spain, Italy, and the USA" [50] has 9 local citations, "Heritage in lockdown: digital provision of memory institutions in the UK and US of America during the COVID-19 pandemic" has 7 local citations. Their local/global citation ratio is 25% to 28%, meaning that more than one-fourth of their citations fall into the examined topic-specific bibliographic collection.

Concerning the most locally cited references, it is interesting to observe that although the majority of sources are journal articles, among the first 8 documents, only two are articles. The most cited source is Nina Simon's "The Participatory Museum" (53 local citations), which tackles the issue of community engagement through the design and practice of participatory projects. In fact, the author looks at the institution of the museum from a social point of view, examining the hiatus that the audience feels in terms of authority and relevance to their life [25]. John Howard Falk's books are second ("Learning from museums: visitor experiences and the making of meaning", 43 local citations), fourth ("Identity and the Museum Visitor Experience", 33 local citations), and eighth ("The Museum Experience", 20 local citations). The former [16] interprets museums as learning environments proposing a model underpinned by theories from psychology, education, anthropology, and neuroscience. The second [51] has a similar approach, focusing on the construct of visitors' motivations influenced by their identity. And suggests that some of these motivations occur even before a visitor enters the museum. The third [52] can be considered as the starting point of Falks' research, in collaboration with Lynn Diane Dierking, where the framework of the interactive experience is studied in its physical, personal, and social dimensions. All three books combine accessible language with broad multidisciplinary contributions. Similarly, the book "Learning in the Museum" [53], published by George E. Hein in 1998 (23 local citations), has a foundational role in laying out how the educational theories of John Dewey, Jean Piaget, and

Lev Vygotsky can be adapted to museum contexts. Tallon and Walker's edited book "Digital technologies and the museum experience: handheld guides and other media" [5] is the most cited document (25) that explicitly addresses the digital in its title.

The most cited articles are "Beyond virtual museums: Experiencing immersive virtual reality in real museums" (35 local citations), which examines the positive and negative aspects of immersive VR [54], and "Virtual museums, a survey and some issues for consideration" (26 local citations), on preservation and dissemination of cultural heritage through Web3D, VR, AR, MR, haptics and handheld devices, in a virtual museum environment [55]. Both are published in the Journal of Cultural Heritage.

In terms of the year of publication, references range from 1709 to 2022. Reference Year Publication Spectroscopy (RYPS) is a quantitative method that identifies the temporal roots of research fields, and is based on the analysis of the distribution of frequencies with which references are cited [56]. The RYPS of the studied bibliographic collection (Fig. 8) shows that the historical papers relevant to the field are quite recent, mainly published in 2012–14. The deviation curve shows only one distinct peak in 2010, when Simon [25] and Parry (ed.) [57] published their books, while Carrozzino [54] and Bruno [58] published their articles on virtual reality in the Journal of Cultural Heritage. Particularly relevant is 2012–13, when the personalization of visitor's experience has been widely discussed for the first time in separate articles by Ardissono [59], Lombardo [60], Capriotti [61], Charitonos [62], and Fletcher [63]. Also, Petrelli [64] and Coenen [65] discussed tools and applications for interactive visits. Additionally, the proceedings of the SIGCHI Conference on Human Factors in Computing Systems (2013) and the updated version of Falk and Dierking's book [66] contributed significantly. Other relevant historical references are published in 2004–5 and 2000–1.

The most relevant word in the bibliographic collection (Fig. 9), after having excluded the words used in the search query, is "heritage" among Keywords Plus occurrences (44) and "cultural heritage" among author's keywords (96). Both with

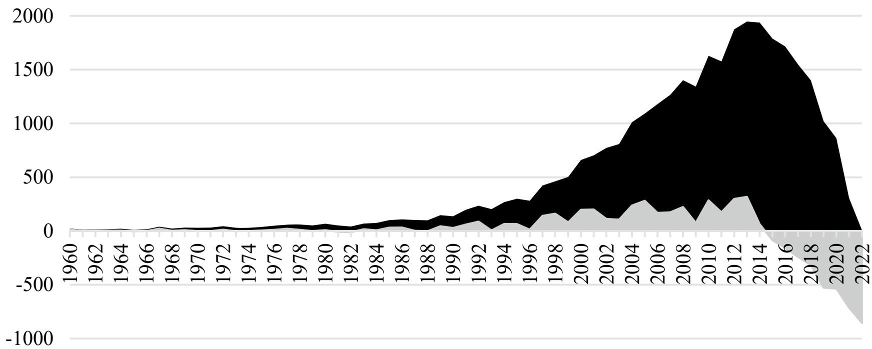


**Fig. 8** Reference Year Publication Spectroscopy. Black: Number of cited references per year, Grey: Deviation from the 5-year median

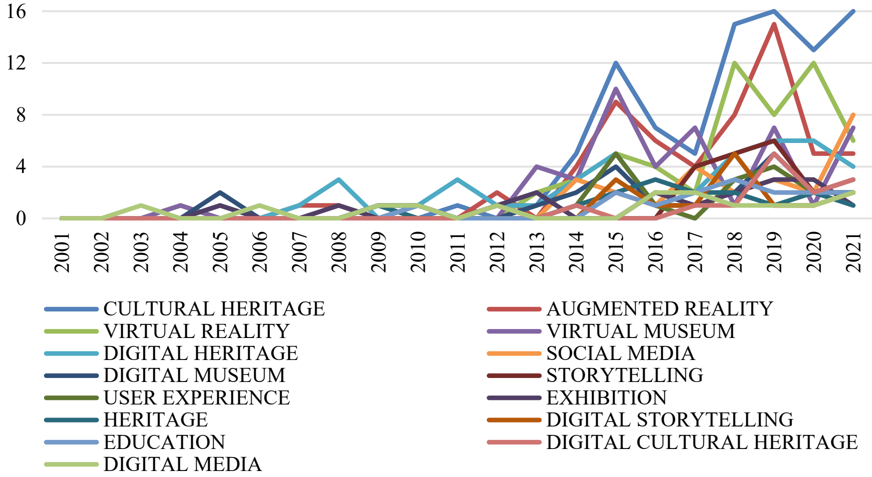


**Fig. 9** Word dynamics. Y: Annual occurrence of author's keyword, X: year

a considerable gap on the second most used keyword. The frequency of "design" and "model" in Keyword Plus suggests recurrent works on methodological aspects. Author's keywords are very much referred to immersive reality ("augmented reality" and "virtual reality"). Abstract's words confirm the use of bigrams "cultural heritage" (297), "social media" (134), and "augmented reality" (126).

Over the years, starting from 2015, "cultural heritage" has been the most used keyword by authors (Fig. 9). Words that contain "virtual" ("virtual reality, "augmented reality", "virtual museum") also started to be used consistently in 2015. While words like "digital media" are being used from 2000, "storytelling" in association with the museum has been used only from 2017. The term "social media" shows the highest growth in 2021.

If we group frequencies of $n$ words year by year, it is possible to know how trend topics vary within the examined collection. Searching the $n = 5$ most frequent author's keywords, "new media" and "website" were used until 2012. Then in 2012–16 gamification was introduced in several articles ("game-based learning", "3D modeling" and "usability") together with the concepts of "virtual heritage" and "participation". In 2016–19, "virtual reality" and "augmented reality" are the most studied topics together with the concept of "digital heritage". In 2019, there is a meaningful shift towards "storytelling" and "social media" until 2020–21, which shows another significant linguistic shift in terms of processes ("digitization", "digital culture" and "digital transformation"), tools ("3D printing"), social engagement ("museum education"), and events ("Covid-19"). The word "guide", which records frequent usage in many articles until 2014, is not frequently employed after 2016.

The words used in abstracts have similar dynamics, with an evident prevalence in the last three years of the words "eco museum", "HBIM", and "olfactory".

Trends essentially confirm a growing interest in visitor engagement in both social and technological acceptation, together with studies on social media. COVID-19 dramatically impacted titles and keywords, though it should be considered what will be the long-lasting effect of this event over time. The increasing use of "touch" and "olfactory" suggests that the visitor's experience is being studied beyond its visual dimension.

**Structure of knowledge**. The analysis outlines a conceptual, intellectual, and social structure of the research field. The visualization of this knowledge domain is expected to reveal the main themes and trends of the bibliographic collection, how certain authors influence the overall scientific production, and the geography of the research network [67].

Cluster map by documents coupling divides the items into subsets that are internally homogeneous and externally homogeneous. Figure 10 represents the five clusters positioned according to their impact and centrality (relevance to the field). This cluster analysis selects the top 250 documents with a minimum of 10% cluster frequency. Coupling is measured by references and the articles' impact through local citation score. The figure shows 5 clusters labeled with the main Keywords Plus terms: orange, blue, red, purple, and green.

The largest cluster (purple) is in the upper-right quadrant, with impactful and relevant documents. It has an impact of 2.62, a centrality of 0.42, and 82 documents. Marty [49] and Lopez [50] are the main contributors with research documents on museum websites and the use of web 2.0 tools. In general, articles in the purple cluster discuss how internet enhances the experience of a museum visit.

The green cluster is across the two right quadrants, with the highest centrality (0.43), average impact (2.28), and 57 documents. Smith [68] and King [69] are prominent authors in this cluster centered on social engagement with virtual environments and social media. Smith combines principles from participatory design with

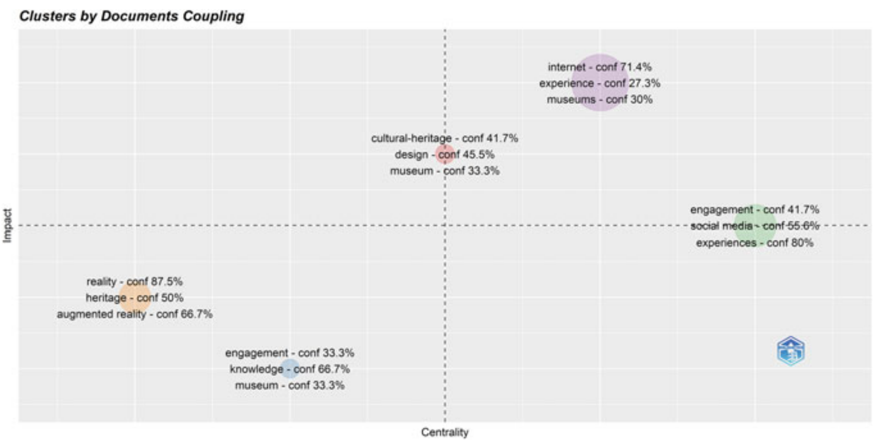


**Fig. 10** Clusters by documents coupling positioned by impact and centrality. For color interpretation, refer to the text

themes of contemporary digital culture to create heritage innovation; King analyzes literature on digital engagement, interactivity, and participation in combination with a survey of heritage professionals.

The red cluster is across upper quadrants, with average centrality (0.41), relevant impact (2.45), and 33 documents. Most contributions are published in computer science journals and provide case studies of interactive exhibitions for cultural heritage. Among authors, Pierdicca [70] suggests the implementation of the Internet of Things framework to study visit patterns for a personalized museum experience, while Petrelli [71] explores the design, implementation, use, and evaluation of tangible data souvenirs for interactive museum exhibitions.

The lower-left quadrat has two clusters with lower impact and lower centrality, suggesting topics that might be emerging or ending in the context of museum digitalization. The orange cluster is mainly represented with the keywords "reality" and "augmented reality", suggesting a focus on interaction interfaces: Augmented Reality (AR), Virtual Reality (VR), Augmented Virtuality (AV), and Mixed Reality (MxR). Orange has a centrality of 0.31, an impact of 2.1, and 45 documents. Barsanti [72] discusses the optimization of 3D models of artifacts for virtual reality, Yoon [46] studies informal learning in a science museum using augmented reality, and Caggianese [73] analyzes interaction design focusing on a holographic projection system equipped with a gesture-based interface. The blue cluster has a similar focus on interaction interfaces but is more directed toward the learning impact rather than the design implications addressed in the orange cluster. Blue cluster has a centrality of 0.39, impact of 1.90, and 33 documents. One representative article is the study by Damala [74] with a qualitative and quantitative analysis of an augmented reality prototype to achieve an interactive learning experience in museums.

Moving to the visualization of the conceptual structure, Fig. 11 represents the co-occurrence network of authors' keywords. The network is based on simple similarities between words that are hierarchically grouped in clusters. After removing the words of the search query, we can see the core cluster, in red, which is formed around the concept of digital heritage and the use of VR and AR. Associated with these, we see other tools such as 3D printing and mobile applications, forms of visit augmentation such as storytelling and gamification, and hybrid approaches such as mixed reality.

Most of the terms are strongly connected with the center of the blue cluster that revolves around the virtual museum as a setting for the exhibition. Satellite words refer to 3D reconstruction, virtual heritage, and the issue of digitization itself.

The green cluster is isolated but internally coherent with the topic of social media. The terms "communication", "participation", "education", and "digital culture" complete the cluster together with "covid-19". The latter is also the only connection of this cluster with "virtual museum". This result confirms that the impact of the pandemic has been primarily studied in connection with the social media activity of museums.

The purple cluster is centered on the user experience and has stronger ties with the red and blue clusters. The words refer to the visitor's perspective, and especially to interaction design and personalization. Finally, the isolated yellow cluster suggests an interest in informal learning through games.


**Fig. 11** Co-occurrence network of author's keywords. Elaborated by Bibliometrix

The thematic map of authors' keywords (Fig. 12) visualizes four types of themes based on two dimensions: centrality (importance of the topic in the given research field) and density (level of development of the theme). The motor themes of the discipline are based on aspects of communication, education, and visitor experience. Basic and transversal themes relate to cultural heritage on the one hand, and virtual museum (with augmented reality) on the other. Blue cluster on social media and COVID-19 is being consistently developed together with another cluster that contains digital humanities and technology. Two clusters are in the quadrant of niche themes, namely highly developed and isolated topics. One is virtual archaeology; the other refers to informal learning through gaming applications.

Two clusters collect themes that are less developed. The orange cluster with "digital storytelling" and learning scenarios is also in the field of basic themes. Instead, the purple cluster containing "survey", "co-design", and "community engagement" is peripheral to the research field, suggesting that it is possibly emerging or declining.

When the thematic map is evaluated over time, it draws a trajectory of the evolution of the topics, and how they are developed and connected together. In order to set the time span of each period, Fig. 1 shows that 2012 and 2017 are two crucial turning points in scientific production. Hence, time slices are set accordingly, weighting occurrences of 250 words year by year.

Figure 13 shows that in the first sub-period, museum digitalization is dominated by discussions around the virtual museum and digital media, mainly supported by research on augmented reality and interaction design. Starting in 2013, the virtual museum concept grows and assimilates issues related to digital media and digital heritage. In the second sub-period, topics are much more specialized and introduce a social aspect in the field: social media, education, children, and storytelling. The last period is short but characterized by massive scientific production. Most of the technological issues investigated in 2013–17 (augmented reality, 3D printing, gamification, user experience), converge to redefine a new understanding of cultural heritage. Social media also collects various research strands, especially those related

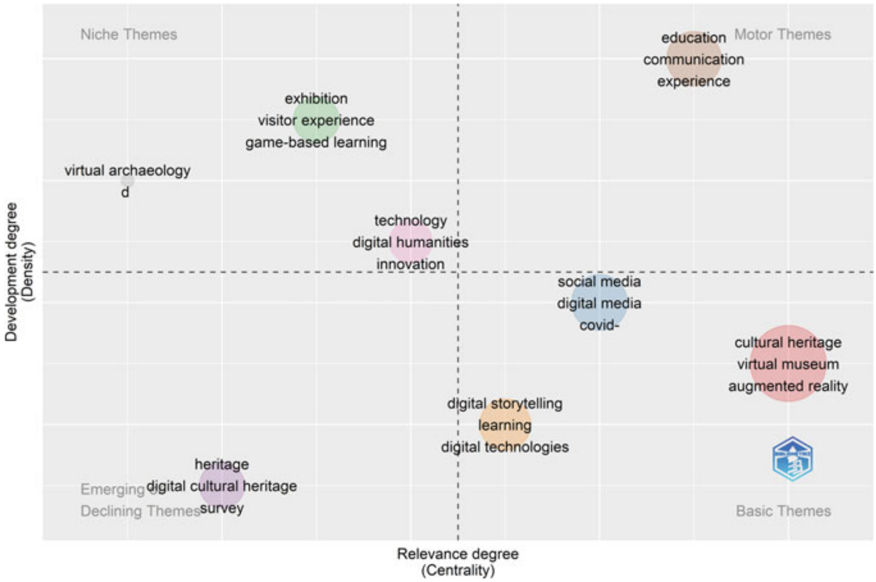


**Fig. 12** Thematic map of author's keywords. Elaborated by Bibliometrix

to younger generations. In turn, learning and education are now underpinned by social media and augmented reality. Digital storytelling started as a personalized visit experience to become now a separate research issue.

The intellectual structure is based on a co-citation network of articles that are both cited in another article. In other words, it is "the degree of relationship or association between papers as perceived by the population of citing authors" [75]. The co-citation network visualizes 50 papers on museum digitalization clustered

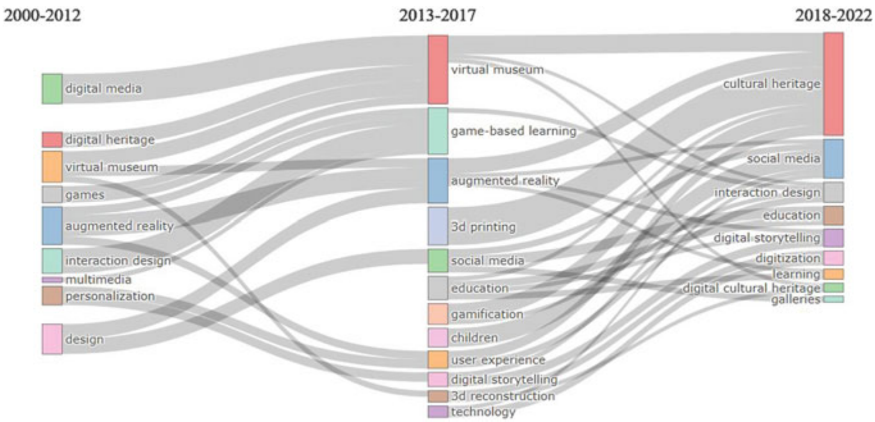


**Fig. 13** Thematic evolution map of author's keywords. Elaborated by Bibliometrix

with the Louvain algorithm (Fig. 14). The analysis confirms the existence of 4 main streams of literature: the dimension represents the normalized number of citations received by the paper, and the thickness is the strength of co-citation bonds. Their position indicates centrality in the research field, and their proximity shows the density of the stream of literature.

The red cluster contains the core publications of the bibliographic collection and overlaps with the documents with the most locally cited references we have previously discussed. It is not surprising that red nodes are grouped in the center of gravity of the network. These citations can be summarized with "learning in/at the museum" and are used to build the theoretical framework that aims at educational goals through technologies, experiments, and social engagement. Some are co-cited only internally in the cluster, such as Hein [53], Tallon [5], Capriotti [61], and Parry [57], while others have strong connections with different clusters, such as Simon [25] and Falk [16]. The red sub-set of articles is generally transversal and very well connected with

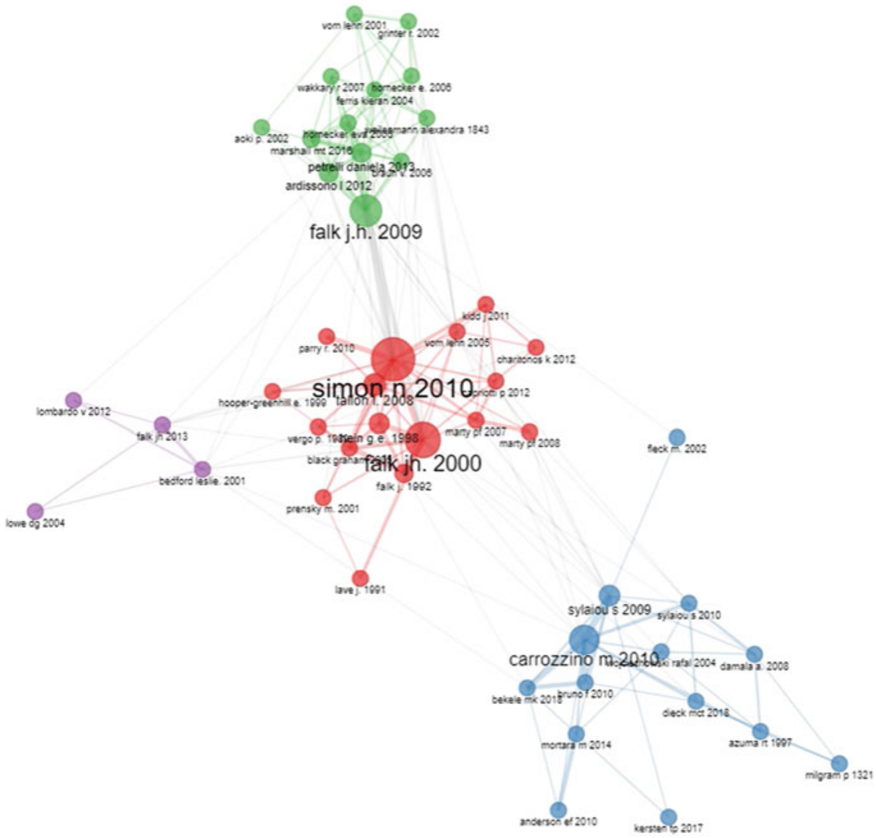


**Fig. 14** Co-citation network of articles. Elaborated by Bibliometrix

the green cluster. The latter discusses how to integrate virtual and physical experiences. Falk [51], Petrelli [64], Ardissono [59], and Ferris [76] are the main nodes of this stream of literature that can be labeled as "personalization". The blue cluster is densely populated and more peripheral to the center. We label this stream of literature that covers all issues of immersive reality applied to cultural heritage as "virtual museum", also referring to one of the most used keywords analyzed in this study. Carrozzino [54], Bekele [15], Sylaiou [55], Damala [74], and Mortara [77], represent the main co-cited articles of the cluster.

The small purple cluster that is close to the center of gravity contains the stream of literature that falls under "storytelling", based on Bedford [78], Falk [66], and Lombardo [60]. It confirms the existence of a residual and possibly growing interest in this direction, as shown in our previous analyses.

Finally, we analyze the social structure of the research field by looking at the collaboration network among authors, institutions, and countries.

Co-authorship network identifies research groups working in the same sub-field in order to cluster groups of regular authors and the most influential figures within the analyzed research field [79]. Museum digitalization shows a fragmented collaborative network (Fig. 15).

Most are biunivocal collaborations, such as the three publications in which Benford and Bedwell have worked on ways to augment museum visits with visual markers, hidden objects, or card games. Among three-author research groups, Nisi-Cesario-Coelho shows a robust collaboration around the relationship between museums and teenagers through games and interactive stories. Vayanou-Katifori-Ioannidis have collaborated in 5 publications on personalized storytelling and human-led hybrid guides. A four-author group is composed of Petrelli-Ciolfi-Marshall-Not with significant contributions by the first author and separated collaboration with other authors. These collaborations are generally positioned on the relationship between museum and information, spanning from the Internet of Things to advanced storytelling techniques. Web of Science categorizes their contribution under "computer science". Another solid research group is formed at Università Politecnica delle Marche with Pierdicca-Malinverni-Frontoni-Angeloni-Clini. Their work on digital platforms is especially aimed at archaeological sites. Antoniou-Lepouras-Wallace-Vassilakis-Poulopoulos form the most consistent research group, and the first author also has strong connections with Vayanou-Katifori-Ioannidis, resulting the focus in the wider collaborative network in museum digitalization. Antoniou et al. work on games, guides, and social media engagement for museum visits.

Figure 16 shows the collaboration network of institutions. One populated cluster is formed by Northern American universities and American national academies, having the University of Pennsylvania as the most contributing affiliation with publications concentrated in the period 2015–18. Another populated cluster is led by Greek universities such as the University of Peloponnese and the University of the Aegean, but extended to Universidade de Vigo, Università di Napoli Federico II, University of Glasgow, and the University of York. Among small clusters, Università Politecnica delle Marche has strong collaborations with the Italian National Research Council.

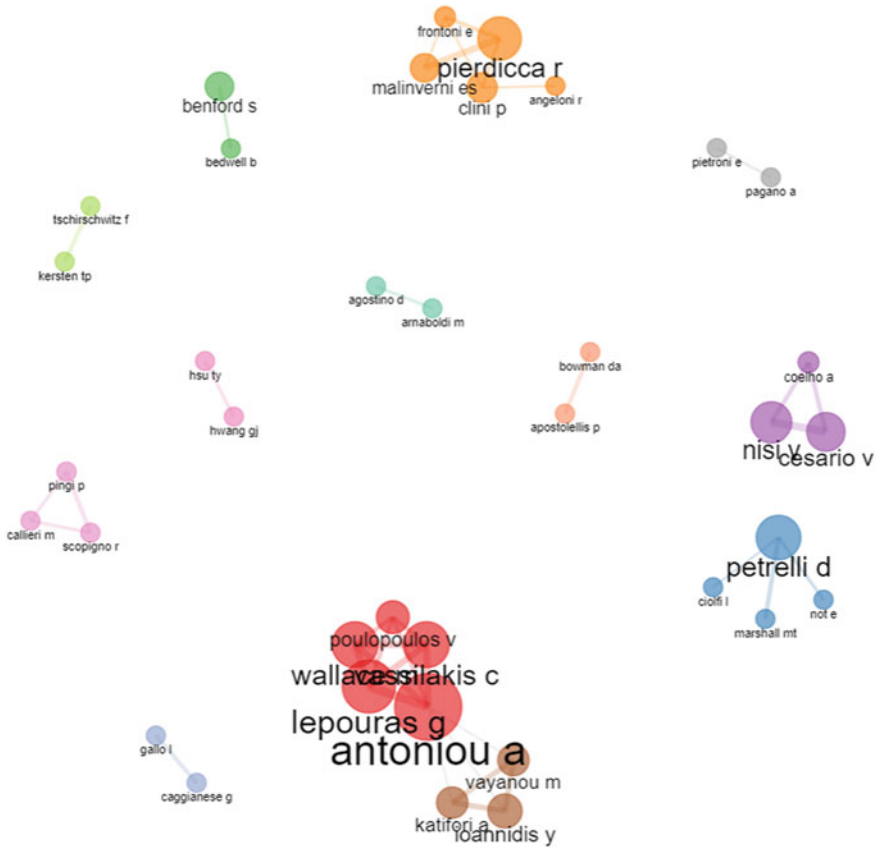


**Fig. 15** Co-author network. Elaborated by Bibliometrix

Country-wise, the collaboration network confirms that the main clusters are led by the UK, Italy, and the USA (Fig. 17). The latter is mainly related to Canada and eastern countries; the UK collaborates with all European countries and has the largest reaching network, Italy has a smaller cluster but many collaborations with European countries and American countries. Interestingly, while the UK has very strong collaborations with both USA and Italy, ties are relatively weak between USA and Italy. The clusters mentioned above are very much polarized towards one country; however, a fourth collaborative cluster (purple) is formed by Greece, France, Germany, Spain, and Austria with multiple connections among nodes (distributed network) and central to the analyzed topic of the bibliographic collection. This purple cluster is at the intersection of the other three main clusters. Biunivocal relations are observed between Brazil and Portugal, and Germany and Turkey. It should be mentioned that China is usually among the top contributors in bibliographic analyses [80–82], but in museum digitalization is still not a major contributor and is relatively isolated. Russia, central Asia, and Africa have residual or null impact on the collaboration network.

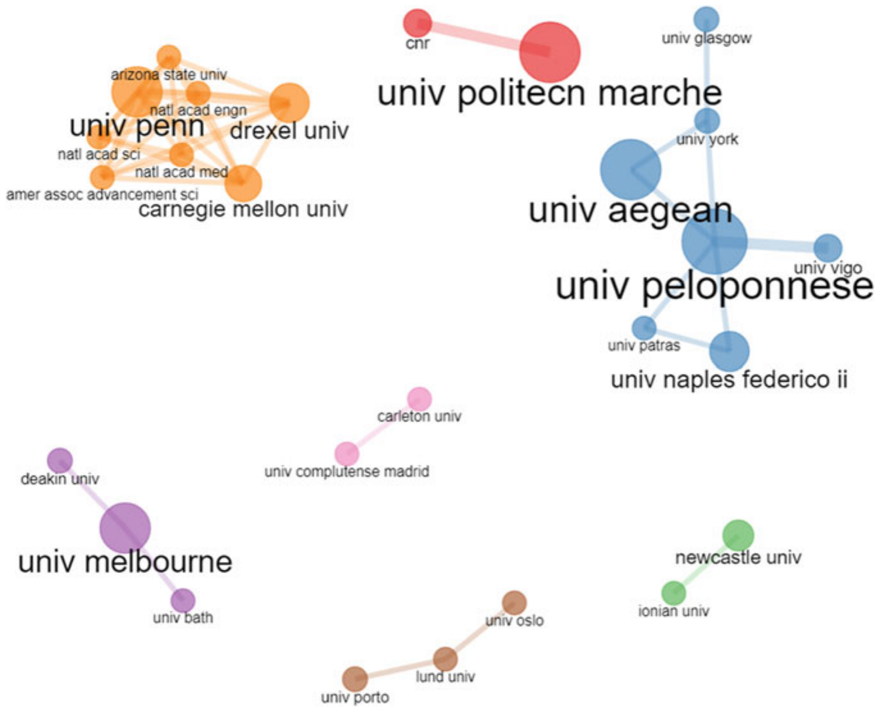


**Fig. 16** Collaboration network of institutions. Elaborated by Bibliometrix

## *3.1 Limitations*

This literature review has some limitations. First, the WoS database is one of the main databases and is generally regarded as the source with the highest quality of entries [82]. However, other databases, such as Scopus, might have partially different entries according to the typology of the document [83]. Hence, articles not indexed in WoS have not been analyzed. Second, publications whose abstract language differs from English have not been included as well. Some essential publications in French, Spanish, and Chinese have been excluded. Third, some analyses imply the use of mathematical models that simplify a large amount of data to allow interpretations and visualizations. This process may omit perspectives that are relevant to the study.

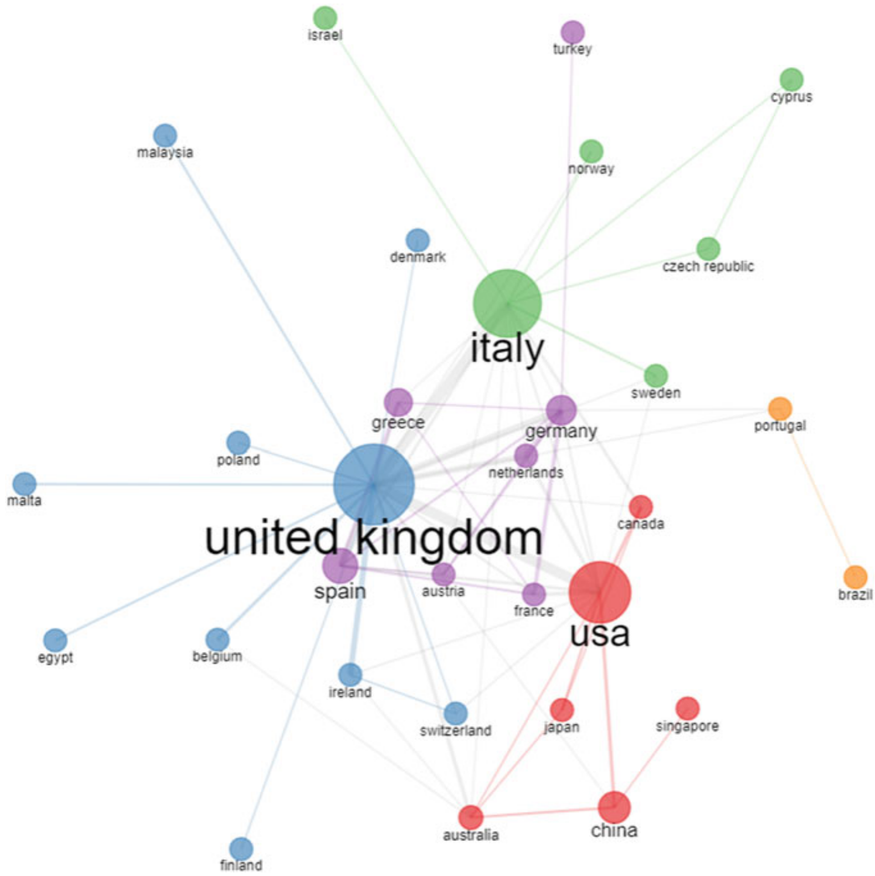


**Fig. 17** Collaboration network of countries. Elaborated by Bibliometrix

# 4 Survey

## *4.1 Methodology*

The survey aims at completing the descriptive quantitative analysis performed in the literature review with a qualitative evaluation of the issue of museum digitalization through interviews with museum professionals. This critical review with a group of experts will highlight similarities and differences with the research strands that we have identified in the literature review. Additionally, we decided to source participants among curators and directors of museums to measure the distance between academic publishing and practice. This will allow us to see if emerging topics in literature align with professionals' opinions.

To achieve maximum exploration of the topic, the questionnaire is composed of open-ended questions so that interviewees can introduce new concepts on museum digitalization. The survey follows a qualitative design through in-depth, semi-structured interviews with ten professionals (Table 2). This group includes seven directors, one curator, one expert in historical heritage conservation, and one expert in digital storytelling. All experts are well-known and affiliated with one of the institutions listed in Table 2. Answers have not been associated with the corresponding institution to guarantee their anonymity.

**Table 2** Interviewee affiliation

| Museum | Location | Nr of inhabitants | typology | Nr of visitors (2018)* | Nr of visitors (2019)* |
|---|---|---|---|---|---|
| Museo Sigismondo Castromediano | Lecce | 795.134 | Provincial | 8000 | 4000 |
| Museo dell'Ara Pacis | Roma | 2.848.084 | Civic | 216,806 | 203,586 |
| Museo Archeologico Nazionale di Taranto—MArTA | Taranto | 576.756 | National-autonomous | 73,237 | 71,032 |
| Museo Archeologico Regionale Paolo Orsi | Siracusa | 399.224 | Regional | 63,239 | 42,290 |
| Museo internazionale delle marionette Antonio Pasqualino | Palermo | 1.253.000 | Private | 40,000 | 29,374 |
| Museo archeologico nazionale di Napoli—MANN | Napoli | 3.085.000 | National | 616,878 | 670,594 |
| Museo Egizio | Torino | 2.260.000 | National | 848,923 | 853,320 |
| Civico Museo Archeologico | Milano | 3.250.000 | Civic | 70,200 | 44,930 |
| Museo di Storia Naturale di Venezia Giancarlo Ligabue | Venezia | 853.338 | Civic | 79,870 | 70,660 |
| Museo Archeologico e d'Arte della Maremma | Grosseto | 221.629 | Civic | 15,033 | 16,030 |

*Sources* *(microdati Istat, Visitatori nei musei del Sistema Musei Civici, Annuario Statistico Roma Capitale, MIBACT, www.museodellemarionette.it, Annuario del Turismo—Città di Venezia, Rapporto Musei 2019 e 2020 Regione Toscana)

To get more homogeneous answers, we have sourced only institutions from one country. Hence, these museums operate under the same regulatory framework. Italy has been chosen for the following reasons:

- As demonstrated in the literature review, Italy is the second most frequent country of origin of authors
- As demonstrated in the literature review, Italy is the second most frequent country of authors' affiliation
- As demonstrated in the literature review, Italy is one of the core clusters of scientific production
- As demonstrated in the literature review, Italian museums have been widely studied with reference to COVID-19 impact [7, 44, 84, 85].

Museums are spread over nine different regions, from north to south. Their typology and size have been differentiated into four civic museums, three national museums, two regional museums, and one private museum. All are positioned in cities of different sizes and administrative statuses: Lecce, Roma, Taranto, Siracusa, Palermo, Napoli, Torino, Milano, Venezia, and Grosseto. Certain centers are more subject to tourism; others have local relevance.

Interviews took place through individual online meetings in April–May 2022, recorded and transcribed by the authors. All participants have been contacted by email or phone and asked to participate in the study. They have been provided with a privacy statement signed by the authors and had the chance to request and review the recorded meetings. The duration of the interview was 45 min up to 60 min.

With the transcripts, we first analyzed the text using the software Voyant to find recurrent words and concepts. Then we performed a qualitative assessment of the answers. Finally, we compared these answers and key concepts with those that emerged in the literature review.

The survey of museum professionals is structured on four key areas that have been highlighted in literature: (1) Digitalization in museums; (2) Engagement; (3) Interaction; (4) Virtual Environments. Each key area is explored with four open-ended questions.

**Digitalization in museums**. This set of questions generally enquires about the expert's view on the topic. Question 1a asks about the main challenges for a museum in relation to digitalization. Question 2a asks how experts feel about the migration of museums to online platforms (i.e., websites, virtual tours, web galleries, Instagram, etc.) as new forms of engagement. Question 1c asks about the existence and consistency, in their museum, of a department dedicated to the development of digital content and platforms. Question 1d asks about initiatives adopted during COVID-19 restrictions and whether such strategies were further developed after the re-opening to visitors.

**Engagement**. This set of questions enquires about engagement through digital platforms. Question 2a asks how important is the image and presence of their institution on social media. Question 2b asks whether the target audience of digital programs is the same audience as their in-person programs. Question 2c asks if they have evidence that social media presence increases the museum's engagement with the public. Question 2d asks what target audience they would like to attract more in the future.

**Interaction**. This set of questions enquires about interactive experiences during the museum visit. Question 3a asks to list the interactive platforms/systems adopted. Question 3b asks what part of these systems is digital and when they were designed. Question 3c asks to elaborate on the weaknesses of interactive platforms/systems. Question 3d asks if interaction is an essential component of the visitor's experience.

**Virtual Environments**. This set of questions enquires particularly about interactive interfaces and their development besides the physical visit to the museum. Question 4a asks if they think that regular employment of virtual tours can engage new visitors in the long term. Question 4b asks what experts think about the contribution of virtual tours to the visitor experience in museums and if the virtual tour can replace the physical visit. Question 4c asks if they provide a virtual tour of the museum. Question 4d asks about their strategy to implement digital content from a distance other than the virtual tour.

## 5 Results and Discussion

The cities where the ten museums are located range from 220.000 to 3.200.000 inhabitants, while the number of visitors measured as an average of the two-year period before COVID-19 restrictions (2018–19) is between 6000 and 850,000 (Table 2). Most used words during the interview were "audience" and "social", 36 times. The term "virtual" has been mentioned 32 times, and "communication" 27 times. It should be noted that the word "game", although never introduced by the interviewer in any question, has been used 14 times (Table 3). This confirms the rising attention on gamification of the visitor's experience that is evidenced in literature.

Moving to the first key area of the questionnaire, digitalization, for question 1a on main challenges, interviewees affirm the following in order of relevance and process:

**Table 3** List of 10 most cited keywords

| Word | Frequency (number of times) |
|---|---|
| Audience | 36 |
| Social | 36 |
| Virtual | 32 |
| Communication | 27 |
| Contents | 25 |
| Tour | 21 |
| Experience | 17 |
| Heritage | 16 |
| Video | 15 |
| Game | 14 |

(1) re-organization of the collection in new catalogues and displays to create a more rational digitalization workflow (30%). (2) make the digitalization functional to: (a) research, (b) communication to the public, and (c) conservation of perishable material (40%). (3) make digitalization more inclusive and accessible to the different target and social strata (40%). While smaller museums express the primary need to digitalize their collection, large museums have already achieved this step and are already focused on the next stage, that of content accessibility. One expert said:

"The challenge is to reach a point of balance between the materiality of the objects and immateriality of digital data". Another expert focused on the inclusivity issue:

> To guarantee the utmost inclusion, access should be oriented to all targets and designed through research and digitalization programs. At the same time, differentiated communication channels will adequately reach various types of visitors.

Answers to question 1b on online platforms favor migration to such realms in as much as the message and content of a cultural institution can be communicated to multiple audiences. A specific point of view comes from one expert who considers the transition unnecessary if it is just for the sake of doing it. The online transition becomes substantial when technological innovation goes together with social innovation. One respondent said:

> We are working on some hypotheses to be present in the metaverse. I consider the metaverse a chance to fulfill the dream of perfect worlds. These solutions should be supplementary and not alternatives for those with limited time or who visit the museum in groups with a predetermined schedule.

Question 1c on the presence of dedicated digital departments collected 7 "no". Two of the remaining respondents are part of a network of museums in which the communication/digital department is centralized within a broader institutional framework. One expert said:

"The team is transversal. Archeologists work with external experts (videogame, digital, anthropologists, and sociologists). The digital product creates bonds with certain audiences (kids, elderly people, but also visitors from Eastern countries)". They all agree that the job of a digital expert must be continuously coordinated with specialized consultants such as archeologists, historians, art historians, and other professionals. Technicians are not expected to give their contribution independently. Additionally, these services are often performed by external companies because of the lack of specialized staff, making the integration with museum strategies very problematic.

Regarding question 1d on the long-term effect of Covid-restriction, in most cases the work during the pandemic was an implementation phase of strategies that were already active. Initiatives: intensive use of the website and social media; development of digital content and ad hoc virtual programs, detailed studies of specific artworks, 3D videos, conferences, contests, games, online laboratories, live performance in streaming, and digital classrooms. Most of the activities are still operational on digital platforms. Instead, COVID-19 helped to strengthen their presence on social media. Most of the traditional cultural activities (conferences, seminars, performances, and guided tours) resumed their in-person format. All other activities are still offered online. Only one expert said that they are aiming to return to pre-Covid strategies. Another expert said:

> This forced closure allowed us to become very resilient to changes and to strategize a new way of communicating with the visitors. This communication goes on and must evolve; we should never look back.

In the key area of engagement, question 2a asks about museums' curation of social media image (Table 5). It is seen as a fundamental component. All experts agree on its relevance, although specifying the following caveats: have a strong visual identity, coordinate communication across all different activities, and customize their social media presence on different social media. Facebook is considered by one expert a mere repository of information. For another expert, it's essential to be friendly in order to attract people and create a community. One expert said:

> We use a program called 'travel appeal', created for hotels, that allows us to understand visitor's appreciation. It monitors the digital reputation of the museum. This generates a ranking of satisfaction. It is monitored carefully but retains some problems since performances are measured with keywords related to the hotel sector.

Question 2b on the possible overlapping of targets of digital platforms and physical visit received various responses. Two experts agreed on this correspondence. Five experts did not agree, especially considering age differences and respective education to the use of interactive devices. Serious games are mainly used by adults (40–50 years old). In terms of nationality, non-Italian visitors interact more on digital platforms. Two experts affirm that it's not possible to make a difference between the physical and digital public: they are all part of the same community of the museum, and considered at the same level. One expert didn't elaborate specifically on the issue. Noticeable feedbacks are:

> No. [touristic city] is a reality unto itself in the sense that the museum attracts a variable percentage of tourists that pass by and visit the exhibition. Therefore, it is very popular among children and grandparents or families.
>
> No. There is a group of users who follow the web and social pages with interest but do not necessarily become physical visitors. It might happen. The community is transformed into a physical community if there is social awareness. The museum must regain possession of its social centrality; it must be an expression of a community to have a consistent audience.
>
> We must not consider the digital visit inferior and secondary to the physical visit. We must consider all as a single community.

To question 2c on proof of public engagement with digital platforms, two experts answered that it is not possible to give an evaluation on this question because of the COVID-19 restrictions. Eight experts confirm that they have proof that digital platforms increase public engagement. They need to be complementary to the rest of the visit and functional in order to be coherent with the identity of the museum. Two of them said that the number of visits or likes reveals the engagement, but it is not proof of the real impact of the content that has been delivered. One expert pointed out:

> Communication with visitors is much easier on social media, but the goal is also to create a physical agora (in gardens, bar, restaurant) to build new spaces for social engagement.

Question 2d on the typology of target that they believe their museum should aim at in the future, over 60 and young people (15–30) are indicated as the preferred targets to be engaged in the next strategies. Two experts mentioned the local community because with them they have the potential to build a long-term relationship. Two experts refer to accessibility as one of the main factors to consider: people with different kinds of disabilities, people who cannot afford technological devices (social disparity), and non-native digital people (older adults). One said:

> We will continue to involve the community as much as possible. The 'threshold' effect still blocks the visitor at the entrance. Young people are very hard to attract outside school environments (school visits). We are trying with a dedicated language in communication and with games.

In the key area of interaction, Tabb. 4–5 show a classification of the systems used in museums. Question 3a, asking about interactive activities to be experienced during the visit, received the following list of items, ordered from the most mentioned to the least mentioned:

1. Museum guide
2. App
3. Audioguide
4. Video
5. Touch screen or tablet with database
6. Interactive games
7. Immersive experience for people with visual or hearing impairment
8. Interactive tour with museum guides or performer

One expert said:

> The museum is equipped with a visit system focused on artificial intelligence. We have digitized the visit path, and we have a google-centered ecosystem that can be programmed according to the tastes and position of the visitor. According to the target, the age, and the subject of interest, the AI adapts to whoever uses it. This system, however, needs many inputs; the pandemic did not allow its use and therefore the prototype in this period is being tested further.

Question 3b asked whether such interactive experiences are digital and when they were designed. Almost all are based on digital platforms. The guide is considered the first interactive method to create empathy and interest in the visitor. Dramas performed in the visited venue are regarded as an innovative device for one expert. Collateral activities such as performances and interactive visits through a virtual tour can be added to analog interactive methods. The oldest digital platforms date back to 2006, primarily to create digital twins of the collection. Others were designed in 2010 or 2015–2016. Most of them used funds from the European Commission, and the digitalization process in general is still ongoing. One expert mentioned that digitalization started in 2016 with European ERDF funds, "When the museum became autonomous in 2015, it was possible to create a strategic plan by choosing long-term orientations and guidelines. These kinds of projects need long-term planning".

Question 3c on weak spots of digital platforms was answered primarily with economic sustainability in the long term: maintenance and hiring of external technical experts because of the lack of existing personnel that can guarantee updates and curation of devices/technologies. This is connected to one of the most common weak points, the obsolescence due to continuous updates or shifts in operating systems (i.e., Android, Apple, Windows). Another negative factor is the lack of real interactivity, which can cause lower interest in the physical path in the museum, especially if digital systems are used during the visit. The accessibility of interactive scientific content needs to be improved and made available to people of different backgrounds and education. Concerning virtual tours, the quality of the digital product needs to be very high. Still, they usually present problems that are impossible to overcome, such as light refraction on displays. The alternation of exhibition layouts or display arrangements during the months or the years can be another weak point, especially for museums that cannot afford a different virtual tour every time the visit layout changes. One expert said:

> The visitor should be prepared before the visit. Usually, we assume minimum competence in this regard. In recent times, the level of reading concentration has decreased while the percentage of those who lack schooling is still high. So, we adapt to a zero degree of content to be experienced on digital devices. While the reconstruction of a statue in a temple is an arduous task, the technology that makes this content available to the public should be elementary.

All experts agreed on question 3d that interaction is essential for a visitor. Two experts specified that it is only a component of the visit, especially with digital interfaces. It needs to be customized to the individual experience (personalization) and can be extended before and after the visit.

In the key area of the virtual tour, question 4a asks whether this technology can create long-term engagement. One expert disagreed, six agreed with this statement, two agreed with reservations, and one couldn't say. Most experts confirmed that the regular use of virtual tours could attract more visitors in the long term if it enriches the visit in a process that extends "before, during, and after" the visit. Two of them considered essential the virtual tour only in a few cases in as much as the elements or the space represented no longer exists (virtual reconstruction of an archeological area, for example) or the virtual tour of the museum offers only a partial preview of the visiting experience in presence. One expert said:

> There are initial peaks of great interest, but then the use of the virtual tour reaches a stable level of a small number of users. There is no doubt, however, that in the case of archaeological sites, where what is no longer visible or difficult to reconstruct can be represented by the virtual tour, the virtual visit can be a standalone experience separated from the on-site visit.

On question 4b, on the degree of replaceability of the physical visit with the virtual tour, they all agreed that the virtual tour cannot replace the physical visit except for some cases related to the impossibility of reaching the museum (distance, political issues, disability, etc.) or for objects/areas that no longer exist. Two of them added that the virtual tour can support the visit as a preview and invitation to join the physical visit. It is crucial to find a balance between the physical and the virtual visit. One expert said:

> If the virtual tour is designed to provide a wide range of additional processed content, which can be transformed into an experience that integrates the material and immaterial, then it makes sense to undertake this path from the point of view of a museum.

Question 4c received eight affirmative responses on the presence of a virtual tour of their museum. Final question 4d, on the perspective of adopting digital experiences different from the virtual tour, received the following answers:

- No (10%)
- gaming (20%)
- digital platform dedicated to cultural heritage (20%)
- film, short film (20%)
- virtual reconstruction of the context in which the collection was based (not existing geographical contest of the past) or the museum is based (exterior and interior) (20%)
- augmented reality
- webGIS: interactive map
- digital storytelling
- 3D reconstruction of the cultural heritage
- podcast
- TikTok.

One expert explained:

> The aspect that is missing in an archaeological museum such as [museum name] is the context: the historical context, therefore the temporal distance that separates us from the time in which the objects in front of us were made, and the environmental context in which they were used. The digital environment can certainly help us to reconstruct both of these contexts.

## *5.1 Limitations*

The interview was conducted with a qualitative methodology on a restricted number of experts. A structured interview with a larger sample of experts, as well as parallel research on other countries, would improve the spectrum of the issue of digitalization from the experts' point of view.

## 6 Conclusions

The interview offered a starting point to verify keywords, concepts, and directions that emerged within the bibliographic collection. The experts portrayed the state of the art in museum digitalization from the viewpoints of directors and curators that manage cultural institutions on a daily basis. This mixed methodology shows that academic production and practice intersect in most of the topics that emerged through the bibliographic analysis. The stream of literature on "learning in/at the museum" is also present in the interview, but educational goals are not mentioned as primary motivations for the process of museum digitalization. The research topic of "personalization," which investigates the integration of virtual and physical experiences, has a very strong parallel with the topics that emerged from the experts' responses. This is often considered their main concern when adopting digital platforms. Another topic that parallels academic research covers issues of immersive reality applied to cultural heritage, as is tackled in the stream of literature "virtual museum." Both academic researchers and directors have minor but rising interest in digital "storytelling." Experts also confirmed a significant interest in gamification as a way to engage specific targets.

We have verified two primary domains of interest: knowledge and reality. The first involves teachers and students and gives a social aspect to the interaction with the museum. The second examines the different degrees of reality attached to the visitor's experience: the analysis spans from the development and optimization of the devices to the theoretical discussion on the relevance of digital twins for cultural heritage. This implies a question, often present in our analysis, around the existence of a virtual museum.

The educational aspect of museum digitalization shows a more independent development than studies interactive interfaces. This is due to the fact that museums can be the right venue to deliver informal education through immersive experiences or hands-on activities. A thematic museum can expose school-age students to important societal issues, both outside and in collaboration with schools [86]. For instance, such a hybrid cognitive model can be shaped as a mobile learning environment, allowing students to access physical and virtual resources [47]. Alternatively, mobile location-based systems used in the museum are being experimented on teenagers to perform serious games and create new learning scenarios [87].

Issues related to COVID-19 are researched and discussed in relation to social media presence and social media engagement as lessons learned from the 2020–21 period.

Finally, the ultimate goal of museum experts seems to be the personalization of the visit. A customized experience renders strong visitation motives and possible long-term affiliation. This effect can be established with digital and analog interactivity, social engagement, and maximum accessibility.

## Appendix

See Tables 4 and 5.

**Table 4** Interactive systems used during the physical museum visit

| Museum | Digital | Analog |
|---|---|---|
| Museo Sigismondo Castromediano | Artificial intelligence | Drama in the museum space, contemporary art show, performances |
| Museo dell'Ara Pacis | Audioguide, videoguide, video, Augmented Reality, app Sistema Musei Roma Capitale | Guided visit |
| Museo Archeologico Nazionale di Taranto—MArTA | App Past for Future (videogame), Augmented Reality, Artificial Intelligence | Guided visit |
| Museo Archeologico Regionale Paolo Orsi | Virtual tour | Guided visit |
| Museo internazionale delle marionette Antonio Pasqualino | Virtual tour | Interactive guided virtual visit |
| Museo archeologico nazionale di Napoli—MANN | Extramann app | Interactive virtual tour mediated by the guide |
| Museo Egizio | Audioguide | Guided visit, guided visit with the director |
| Civico Museo Archeologico | Tablet with data sheets | Guided visit |
| Museo di Storia Naturale di Venezia Giancarlo Ligabue | Touch screen, audioguide, interactive rooms, immersive game, audioguide | Tactile visit, tactile visit for the visually impaired, guided visit |
| Museo Archeologico e d'Arte della Maremma | Video, immersive itinerary for hearing impaired people, immersive itinerary for visually impaired, audioguide | Tactile 3D reconstructions, tactile tables, guided visit |

**Table 5** Digital systems/platforms disconnected from the physical visit

| Museum | Online digital system | platform |
|---|---|---|
| Museo Sigismondo Castromediano | Social network | YouTube, Facebook, Instagram |
| Museo dell'Ara Pacis | Google Arts & Culture | artsandculture.google.com |
| | Virtual tour | website |
| | Video-story telling for kids | website |
| | Video-story telling | website |
| | App MiC Roma Musei | playstore, app store |
| | Video on temporary shows | website |
| | Social network | YouTube, Facebook, Instagram, Twitter |
| Museo Archeologico Nazionale di Taranto MArTA | Virtual tour 3D | website |
| | Artsupp | Artsupp website |
| | Google Arts & Culture (ongoing) | artsandculture.google.com |
| | MArTA Lab—e-learning lab | website |
| | Gaming: Past for Future app | playstore, app store |
| | Social network | YouTube, Facebook, Instagram, TikTok, Twitter |
| Museo Archeologico Regionale Paolo Orsi | Virtual tour | website |
| | Podcast | .izi travel |
| | Google Arts & Culture | artsandculture.google.com |
| | Social | Facebook, Instagram, YouTube |
| Museo internazionale delle marionette Antonio Pasqualino | Podcast | .izi travel |
| | Visual and sound archive | website |
| | The human library | website |
| | Pupi archive | website |
| | Video virtual tour Italian/English/sign language | YouTube |
| | Social network | Facebook, Instagram, Twitter, YouTube |
| Museo archeologico nazionale di Napoli | Extramann app | playstore, app store |
| | Video | website |
| | Ppodcast | Ohmyguide tours |
| | Gaming: Father and Son1 | playstore, app store |
| | Gaming: Father and Son2 | playstore, app store |
| | Gaming: manncrafts | Minecraft for PC Java or mobile (Android e iOs) |
| | Google Arts & Culture | artsandculture.google.com |

(continued)

**Table 5** (continued)

| Museum | Online digital system | platform |
|---|---|---|
| | Open-data | website |
| | Social network | Facebook, Instagram, YouTube, Twitter |
| Museo Egizio | Virtual tour | website |
| | Virtual tour for kids | website |
| | Google Arts & Culture | artsandculture.google.com |
| | Social network | Facebook, Instagram, YouTube, Twitter, LinkedIn |
| Civico Museo Archeologico | Virtual tour | website |
| | Didactic datasheet | website |
| | Archive of collection | website |
| | Informative material | website |
| | Social network | Facebook, Instagram, YouTube |
| Museo di Storia Naturale di Venezia Giancarlo Ligabue | Google Arts & Culture | artsandculture.google.com |
| | Database | website |
| | Thematic datasheet | website |
| | Virtual tour | artsandculture.google.com |
| | Social network | Facebook, Instagram, YouTube, Twitter, LinkedIn |
| Museo Archeologico e d'Arte della Maremma | Didactic laboratories online | website |
| | Podcast | .izi travel |
| | Google Arts & Culture | artsandculture.google.com |
| | Social network | Facebook, Instagram, YouTube, Twitter |

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# Practice

# The Humanistic Basis of Digital Self-productions in Every-Day Architecture Practice

**Marco Verde**

**Abstract** The intersection of robotics and architecture supports the search for new spatial, structural and construction models useful to support the innovation in conception and making of spaces towards a more sustainable production, and to refine the "Industry 4.0" paradigm from a humanistic perspective to meet the needs of the socio-ecological transition. One of the major emerging challenges of technological innovation, in fact, is to accelerate the realization of a high quality architecture that is responsive and sensitive toward the environmental and social context within which is designed and implemented. This requires a holistic and transdisciplinary approach during the whole process, from conception to construction. In this regard, the self-production in every-day architecture practice (starting from small scale projects) represents an important field for theoretical and empirical investigations that calls for a smarter use of traditional and non-traditional building materials, and innovative computational ways of dealing with craftsmanship for more sustainable manufacturing methods along the whole factory life-cycle, suggesting a greater insight into the humanistic basis of architecture. This chapter will frame the design-research in contemporary strategies and processes for architecture undertaken at ALO, architecture and design studio based in the south Sardinia (Italy), and will showcase some of the computational design and robotic fabrication research carried out within the daily practice.

**Keywords** R&D and entrepreneurship · Digital theory · Design thinking and human–computer interaction · Computational and parametric design · Performance-based architecture and design · Digital twin

**United Nations'Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_35

# 1 Introduction

By reconnecting the design process to that of construction through a holistic and material driven approach, sustainability can emerge as a synthesis of different knowledge. Moreover, thanks to the contribution of a new computational thinking and processes to both moments, a more sustanible production can become actualised in a new tectonic and spatial conception of architecture that goes beyond utilitarian, decorative and mannerist paradigms and aims. The divergence from the conventional fragmented practice is becoming increasingly necessary.

However, recent developments show that this innovation tends to be relegated to elitist projects, landmarks, exotic canopies or sculptural pavilions [1]. The sustainable transfer of innovation in design and construction must aim at tailor-made strategies starting with small-scale interventions that, by sheer numbers, will have a greater impact on people's daily lives and the quality of urban development already from the micro-scale, while being oriented towards criteria of scalability and habitability.

At ALO we tackle this problem through a holistic applied research that focuses on investigating a novel conception and making of space by exploring innovative uses of traditional materials, like wood and concrete, and researching non-serial prefabrication as critical for a more sustainable production.

Our work is material-driven and supported by advanced computational design and fabrication strategies that help us to transfer into practice smart design criteria borrowed from nature.

To provide an overview of our design and fabrication research, the chapter is organized as follow: Sect. 1 introduces the research territory discussing then need for a humanistic approach to technology, some pivotal design criteria and key topics such as performative revamping, digital craft and the search for lightness.

The following sections present the structure of the ALO laboratories and provide a sample of three current holistic research strands unfolding through our practice: Innovate use of traditional materials (Sect. 2.1); Collaborative robotics for advanced building components (Sect. 2.2) and Computation in design and making for augmented human experience (Sect. 2.3). Finally, in conclusions, a trajectory for future developments will be introduced and a novel paradigm for collaborative robotics will be proposed.

## *1.1 The Humanistic Turn of Industry 4.0*

By the middle of the first 20 years of the digital turn in architecture [2] the need for closer relationships among the processes of design and making, as well as computation and matter emerged. The exploration of novel possible futures was especially fed by theorists and scholars [3–9] who provided the ground for a novel culture in architecture more focused on the "how" rather than the "why".

The renewed approach to architectural design, already passed through several, micro-phases, especially supported by the "democratization" of digital fabrication technologies, which starting from 2000s is bringing designers back in touch with the making. Fablabs [10], Arduino microcontroller or open source communities are only some of the expressions of a new culture bringing machines out from factories and closer to people. The concept of 3D printing, for example, is already mainstream. The vision for a procedural practice in architecture suggests the move from arbitrary top-down choices and empirically reconnects with matter through bottom-up strategies. Matter itself, and subsequently digital fabrication, started being regarded as active agents within the process of architecture itself, becoming generative, genetic and evolutionary.

To a part of the architectural domain already, design and making are conceived as a single non-linear data flow. This new paradigm is pushing architects and engineers to rethink their processes and strategies through computation. We are now bridging the gap that has emerged between the design and construction industries due to the mechanistic and fragmented view of complexity that has prevailed over the past two centuries.

Meanwhile, robotics landed inside architecture schools; and some research-oriented firms (among which ALO) are already prototyping their custom end-effectors to self-produce their own building components directly inside their proprietary laboratories, making research in matter and fabrication an actual instrument for design within their daily practice.

However, a technocratic race towards novelty seems also emerging driven by a fanatical attitude towards technology. Similarly this is also happening within the Industry 4.0 sphere. But technology per se doesn't suffice to generate content and to impact everyday practice. We need a humanistic theoretical framework within which to understand why emerging technologies may be valuable for the next generation of architectures, and how to develop such a strong thinking to overcome even the possible unavailability or non-immediate accessibility of certain technologies, especially those for digital fabrication.

In "Mechanization takes command" Giedion provides a transversal analysis of the influence of the total phenomenon of mechanization correlating among several symptoms the "*decaying sense of materials*" not so much to mechanization but to "*the manner in which mechanization was employed*" [11].

Giedion work is still surprisingly relevant. In this regard, possibly one of the biggest weaknesses of the Industry 4.0 project lies in the way it has been proposed and received by industry, i.e. mainly from a technocratic point of view. In Italy, it often turned into a digital upgrade of obsolete machinery and procedures, as obtaining important tax incentives was not directly linked to the innovation of the products themselves. In 2021, up to 95%[1] of the cost of new machinery could be converted into a tax credit without, however, the benefit being tied, as a necessary condition, to the innovation of the products themselves. At the same time actions in favour of

[1] https://www.mise.gov.it/index.php/it/incentivi/impresa.

R&D towards design innovation offered tax credits up to only 10% of the investments.[2] The diversity of the two incentive policies somehow shows that, the main concern is to boost the market by stimulating the blind acquisition of new machines, of course connected to the Internet, equipped with monitoring sensors and able to share production data. Returning to Giedion, is there a sufficient interest in what is being done (or could be done) with these machines such as robots, especially in the architecture and construction sectors?

This open question highlight one of the major missed opportunity to trigger a tangible effort toward a new approach to industrial production in the pursuit of a sustainable industrialization through: (1) product differentiation, (2) a true collaborative and inclusive ecosystem among humans and machines, (3) the extension of product life through upgradability of components, (4) the overcoming of the constraints of mass production leading to overproduction, and (5) the pursuit of lightness [12]. We should indeed be especially concerned about reducing the weight of simple and complex products, as it is directly related to the amount of raw materials required for their production, transport, use and disposal or recycling.

As for architecture, perhaps the slowest sector to embrace technological innovation, the utilitarian I4.0 mindset may need a major revision if our goal is to become seriously environmentally responsible. Despite the ease of access to advanced fabrication techniques, more and more architectures are appearing that promise disruptive innovations but often turn out to be almost theatrical stage sets, illusory shining architectures heedless of the cost to keep them up.

For these reasons, both Industry 4.0 and computation in architecture shall aim to expand human capabilities by designing collaborative processes in which human and machine efforts are ideally deployed simultaneously (and not sequentially) to make innovative products and spaces that are consistent with the objectives listed above and that otherwise, without the intersection of the contributions of the two parties, could not be produced.

### *1.2 Tight-Fit and Performative Revamping*

Invoking the concept of sustainability is already a cliché, a mandatory requirement, but in the end it is scarcely implemented in ordinary urban development. Deep down, nothing has changed in the way new residential buildings or shopping malls are designed and constructed. Sustainability has mostly turned into a list of qualities to be met and ingredients to be mixed, but at the scale of everyday life in general, interest in ordinary design and construction that does not disrupt established practices still seems to prevail. Just as sweeping the dust under the carpet is not a real solution, building greenish façades wrapping obsolete design concepts in the name of a certain biophilic luxury mood is also not a real answer.

[2] https://www.mise.gov.it/index.php/it/incentivi/impresa/credito-d-imposta-r-s.

The construction industry in large part, especially in small local communities, is not yet ready to dismiss older building systems, and this prevents the diffusion at daily practice of novel solutions for new buildings. For this reason, for a small research-oriented firm, bringing innovative concepts to the daily buildings practice can be still tricky. However, being equipped with a proprietary laboratory for the digital fabrication of complex building components offers great opportunities to explore an alternative path towards sustainability in architecture focusing on the advanced, high-quality revamping of existing, exhausted architectures.

In this context, small and old historical buildings, which often have complex and irregular spaces, are one of the most suggestive places to take an innovative approach in which technology becomes an instrument for finding new design opportunities that cannot be foreseen in advance, rather a tool for problem solving. In this sense, light-weight, tight-fit and performative interventions can be now carried out with a meticulous control of the liminal space between the old and the new.

Especially the search for light structural and construction models based on redundancy and differentiation becomes critical to preserve older buildings integrity and identity while exploring alternative models for a contemporary living through non-mimetic work.

Lightness, in a strict physical sense, is one of the greatest challenges for the contemporary culture that is widely educated to the idea that heavier is better while the lightest is ephemeral. Saving weight can have an exponential impact on the entire life cycle of a building, from its structural conception down to the furnishing and all the processes relating to its existence, including the industry that orbits around it.

Thomson discusses the concept of form in nature as the expression of the forces acting on a body [13]. Learning from nature, lightness is achieved by shape, by the differentiation of building components, by distributing forces across redundant adaptive systems made of small entities. In 1904 A.G.M. Michell presents a model for the minimization of material in frame-structures showing how their weight could be drastically reduced shifting from continuous elements to networks of multiple small building components [14]. His diagrams resemble the porous, organization pattern of the upper human femur bone tissue, which first exact mathematical analysis was originally published by John C. Kock [15]. In nature, lightness is a survival strategy indeed.

Next to these criteria of differentiation and distribution of forces, the integration of multiple functions into single building components, surpassing the segregation of functions into mono-purpose components, becomes as well critical towards the minimization of weight and matter consumption. Nature provides an infinite number of examples among which the eggshell, which performs as a protective envelope and a porous membrane that regulates the moisture level by allowing only water particles of a certain size to pass through, or sea sponges such as the Venus Basket sponge, whose structure allows the organism to resist the forces of sea currents but also to create low-speed interstitial micro-vortices that promote feeding and reproduction [16].

If we transfer the concepts of structural differentiation, lightness and polyfunctionality of building components to architecture, space becomes a differentiated body, whose components, from skin to furniture via structure, are no longer segregated to perform only single functions. Hereby, the figure of the architect, the engineer and the builder, as currently conceived, blur and embrace a new transdisciplinary approach, supported an active adoption of computational design and advanced manufacturing strategies. Hereby, the design process is no longer linear, but becomes performative as it produces knowledge by transgressing the boundaries of the disciplines through computation.

In this process, we need to be concerned about building a new responsible relationship with local artisans: it is necessary to breathe new life into a sector that suffers as much from the standardization and cost-cutting processes put in place by large retailers (offering increasingly low product quality well hidden behind more accurate finishes) as from the growing shortage of skilled labour. There is perhaps a need to refine the conception of digital craftsmanship, which has emerged over the past decade, recalibrating the concept not so much as an evolved expression of the individual, but as a collaborative virtuous process across disciplines.

## 1.3 Holistic Research-Driven Practice at ALO

ALO's roots back to 2005 and the firm was founded in 2012 in Cagliari, in the south of Sardinia (Italy). The context of a small island imposes many constraints that risk slowing down innovation processes. Architecture needs time to think and make mistakes, and making architecture the main activity of a small company could force one to accept too many compromises in order to survive. Moreover, in Italy, too many figures overlap and clash within a sector that is actually poorly regulated in terms of hierarchies and competences.

Despite our small company size, we push ourselves to be engaged in a significant production. We manage to keep architecture in a safe place; we feed the studio through complementary design-research and R&D services, and deeply dedicate ourselves to architecture only when there is the change to do something truly significant with open-minded clients.

Research has a pivotal role within our daily work. Every built, unbuilt or architectural competition project is taken as an opportunity to push further our agenda.

In order to make actual our thoughts through everyday studio life, we are developing an in-house laboratory for digital fabrication, and we are already able to strategically combine several techniques from laser cutting, to 3d printing and robotic processing within our projects. Exploring a strategic combination of different digital technologies and defining an ethical and meaningful role for robots in architecture is indeed one of the biggest questions we are addressing.

In this search, the idea that digital fabrication has become a broader transversal concept. It is a holistic synthesis of thought, design and realisation; a transformative entity that triggers new possible futures and fosters our agenda.

The hybrid studio setup, blurring from studio to advanced industry grade workshop, supports a cost-effective research towards the cross-pollination of architecture, engineering and a performative manipulation of traditional materials.

At ALO we took such a challenge, and we work to merge advanced design and fabrication protocols with traditional craftsmanship so that all parties within the process contribute to the achievement of unique final result that are an expression of the intersection of the best of their abilities.

Having embarked on a path of constant innovation and research has helped us to trigger a virtuous activity of high-quality sartorial and performative architectures.

## *1.4 The Project of Villa Vi. A Study Case on the Innovate Use of Traditional Materials*

Villa Vi is a villa located on the coast of Golfo Degli Angeli in Quartu Sant'Elena (Cagliari). It was built in the'60 s and the aim was to transform the building into an experiential, fine guest house. Villa Vi project embodies some of our thoughts about the intersection of contemporary living and hospitality with matter, digital fabrication and the aim of providing an immersive architectural experience for guests. For this purpose, architecture and matter have a pivotal role; the search for innovative applications of traditional materials like wood and concrete was central (Fig. 1a, b).

The entire work was triggered by the original traits of the existing structure of the villa featuring uncommon triangular arches surrounding two porches on the main facades. Their polygonal topology became the generative seed for the entire design which aim was to blur the boundaries between exterior and interior spaces across scales. Beside the full renovation of the façades, interiors spaces and exteriors, including the design of the performative landscape surrounding the villa, we designed and robotically fabricated a collection of bespoke wooden, faceted furniture, POLYHEDR.a, the new concrete main entrance portal POLYHEDR.a/r and several parts and jigs to facilitate an high-precision and fast construction (Fig. 2).

### 1.4.1 Innovation of Traditional Materials Through Computation in Design and Making

POLIHEDR.a are irregular polyhedral pieces of furniture that, by shape, integrate several functional accessories typical of a guest room. A desk, a bookcase, and the luggage rack find their place in a compact but articulated hybrid wall system that wraps around a stand-alone shower space. These are the main elements organizing the layout of Villa Vi guest rooms. From the very beginning, the pieces were intended for self-production. Therefore, we developed a sophisticated parametric system that served both to digitally adapt the topology of the layout of each guest room to the

**Fig. 1** **a, b** View of Villa Vi's main garden and building. A computational environmental analysis informed the differential organization of the landscape so to provide a beneficial microclimate for outdoor living during the hot summer season

different dimensions of the floor surface and to achieve state-of-the-art finishing qualities as a unique expression of the synthesis of design and fabrication.

From the very beginning, we decided to use birch plywood as building material. This material is characterized by exceptional structural performance and CNC machinability. This was important to achieve well-refined, self-supporting structures

**Fig. 2** Digital wood: the architectural furniture is made of self-supporting sub-modules. All facets are designed through a computational procedure that generates all geometrical features necessary for the six-axis circular-saw robotic-cut carried out directly at ALO laboratory

even while using panels of reduced thickness. However, processing birch plywood requires special attention. This is because, for example, the colour one perceives can change from honey to chocolate depending on his/her point of observation. In this regard, our goal was to achieve a final monolithic appearance, with continuous grain flowing in one sole direction as well as a homogeneous colour between the faces while moving around the piece.

From this initial brief, we decided to start the design-research looking at the "Quartabuono" joint to assembly all faces without showing the thickness of the panels. This type of joint is used in carpentry to join wooden elements that must form a right angle with the section of the material not visible to give continuity to the grain.

However, when it comes to irregular polyhedral, both concave and convex, with thick faces and more than three faces converging to one vertex, exactly the collision of the thicknesses of the facets at the vertexes would require an empirical trial and error assembly procedure making impossible a precise fabrication of the parts by traditional means. Therefore, due to the complexity of the parts and over all assembly, the design-research aimed to develop e fully digital design and fabrication protocol to avoid any kind of manual intervention and achieve a high quality finishing.

Given the amount of aspects to intersect as a whole, the project required clearly a computational design approach (Fig. 3). A first software module allows to work on a simplified parametric figure, a "skin without thickness", in order to facilitate the adaptation of each piece to rooms size while minimizing calculation time and the real time verification of the compliance with all manufacturing constraints, among which, for example, the minimum acceptable values for the angles between adjacent faces (set to 20°). Then, once the morphology is set up, a second module independently processes the digital twin by transforming all simple faces into 3D panels with a given thickness, calculating the bisector of the shared faces and eliminating excess material in the joints, the number and position of connecting dowels, part numbering, and all the data needed to drive the six-axis circular saw cutting and multi-tool robotic manufacturing as a whole. The entire system is parametric, so changes can still be applied and reflected in new digital manufacturing layouts.

POLYHEDR.a parametrics delivers further sophisticated design features. It recognizes the spatial orientation of each face of the polyhedral figure with respect to a given observation vector and then, getting ready for their digital fabrication, it unfolds all parts flat on a plane and carry out the nesting negotiating among (1) the initial reference vector for grain, (2) the direction of the grain of the raw board to be machined (3) the minimization of residual waste material. As a result, once facets are assembled back in real world, the grain wraps the figure as a continuous flow, enhancing the global monolithic appearance of the furniture still reducing the amount of raw matter necessary for the construction (Fig. 4).

In addition to this, in order to facilitate the assembly, every part is numbered according to a specific protocol that provides for each face (1) a unique tag identifying the part itself, and for every edge, (2) the tag of the adjacent part. Artisans taking

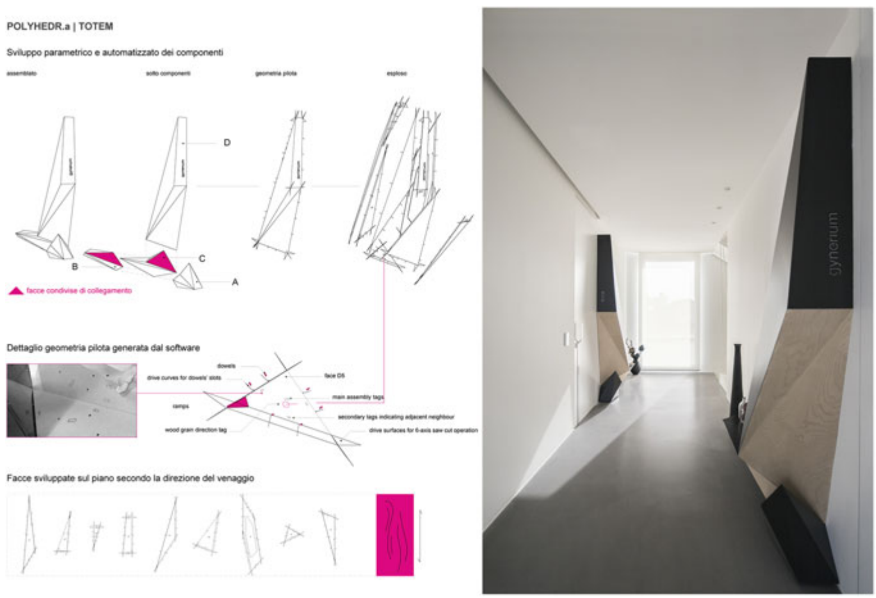


**Fig. 3** The diagram illustrates the phases of recursive computation for the generation of the executive 3D digital twin of the guestrooms' totems

**Fig. 4** Detail of the grain flowing along the body of the furniture along one consistent direction

care of the assembly could then assembly all parts just following the tagging system and a few 3D representations of the final piece.

Starting from this research we derived the POLYHEDR.a/r formwork system to robotically fabricate the scaffoldings system for the production of the concrete structural components of the entrance (Fig. 5).

**Fig. 5** Digital Concrete: a view of the FRC portal

This reverse version of the parametric system, as the name suggests, builds the thickness of the scaffolding and all production drive data calculating the thickness of the material outside the initial 3D reference geometry of the part.

In addition, POLYHEDR.a/r parametrically generates all components of the inner steel reinforcements as well.

### *1.5 The RCC Project. A Study Case on Collaborative Robotics for Advanced Building Components*

The concept of collaborative robotics is spreading across industrial production; however, it is largely presented from a reductive perspective of problem-solving.

Differently, human–robot collaboration should go beyond the idea of simply replacing human labour in repetitive or heavy tasks in order to become instrumental to deep product innovation.

To tackle such utilitarian approach, in 2018 ALO initiated the research project originally named "Robotic Collaborative Construction" (RCC) focusing on designing products and processes where humans would work in unison with machines summing both best skills to achieve complex productions not otherwise possible.

Our agenda is to effectively transfer the research on robotic fabrication in architecture into daily architecture practice, with a focus on the scalability of the results to small-scale projects with limited budgets too. For this purpose, RCC addresses a further architectural elaboration of some of the criteria enunciated by Pearce (1980) and, specifically, that of "*Minimum Inventory/Maximum Diversity"* [17] from a holistic and computational perspective to the advantage of a greater flexibility with respect to the possible architectural conception and making of space.

In this sense, RCC explores the idea of a non-standardised digital prefabrication that is efficient in terms of cost, processing energy consumption and the architectural quality of the results in terms of their completeness, structural integrity and refinement.

Imagining such a scenario, perhaps starting from the architectural domain, we could enunciate a new model of industry, the *"Industry X",* where "X" is not a letter but a symbol representing the symbiotic interaction between man and robot.

### 1.5.1 RCC Hardware and Software Design-Research

The project stems from the idea of combining to our advantage, on the one hand, the capability of robots as spatial positioners for building components and, on the other hand, the ability of a skilled worker, such as a welder, to complete complex assembly operations that need human awareness ore solve unexpected faults in real time in a viable manner.

For this purpose we designed a double-curved membrane consisting of steel rings to by assemble without the use of any kind of scaffolding or jigs. The rings had to be welded in place by an operator while the robot was employed to recursively load and position each component, piece by piece, directly according to a dynamically linked 3D parametric model (Fig. 6). Some might argue that welding could also be automated. But in the event that an artificial-intelligence robotic system could be adapted for this application to handle unforeseen complexities in real time by autonomously adjusting processing paths, what would be the cost of such a total automation development in terms of research, necessary infrastructure, and long-term flexibility? Would such total automation be a reasonable option to make the process sustainable even for a small firm or for application to small-scale projects? Even with an access to infinite resources, we believe these questions should be given more consideration.

For this reason, the RCC project departs from some of the totalitarian and technocratic positions that are emerging in the field that seem to increasingly distance research from viability in everyday practice in the name of novelty itself. On the contrary, RCC aims to enhance the skill, versatility and intuition of human operators towards greater architectural quality, flexibility and agility in a lean digital production.

The overall objective of the basic research was to develop a set of proprietary hardware and software tools to prove the concept, evaluate potential issues to be addressed and possible future research directions and application in daily practice.

On the hardware side, we designed and 3D printed a custom self-centring gripper (Fig. 7) to perform parametrically controlled pick-and-place-and-weld operations driving the robot directly from the design interface of the digital-twin.

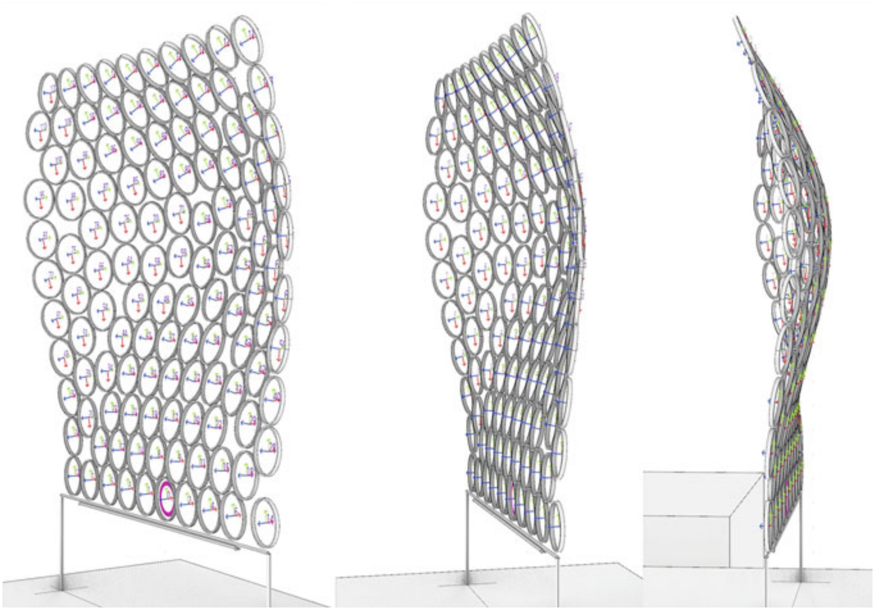

**Fig. 6** Details of the 3D double-curved membrane parametrically generated as to preserve the tangency between building components and manufacturing tolerances

The gripper is electrically isolated to allow welding operations while the robot still holds the part in place. In common practice, the part to be welded is fixed on an external positioner (1 or 2 axis) while the robot performs the welding; we inverted the roles, living the welding to a skilled worker and using the freedom of six-axis positioning to facilitate complex assemblies (Fig. 7). Moreover, the gripper has a certain level of autonomous intelligence. Through embedded sensors, it can detect when the part has been picked and then control the force applied to hold it firmly without overloading motors. It has also an embedded LED lighting system to communicate its state with the operator. All building parts and mechanisms have been designed to be 3d in-house printed in the perspective of a sustainable research economy and further developments.

On the software side, we have expanded the control and simulation capabilities of existing methods based on the Kuka PRC plug-in [18], the parametric programming environment for robots that since 2016 has made robot programming easily accessible to designers. We developed a series of customized codes to facilitate simulation control, to trigger specific actions along the process based on factors of time, distance and Boolean operations. We also developed a system to check the state of the end-effector and provide feedback consents during the process. The control engineering of the gripper was realized in-house too connecting the parametric digital-twin to our kuka robot via Arduino micro controller to carry out online simulations and off-line programming too.

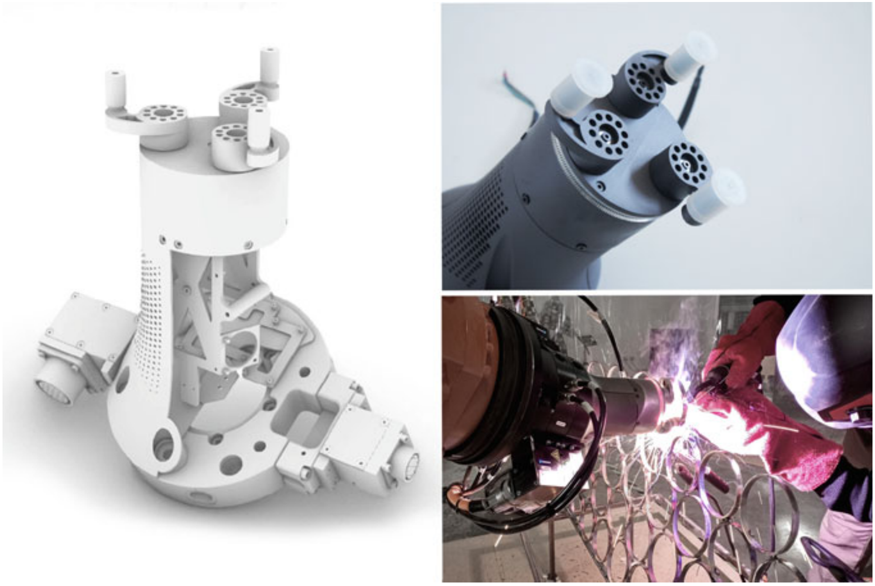

**Fig. 7** Digital assembly of the self-centering gripper (left). In-house 3d printed functional end-effector (top-right). Testing the collaborative construction protocol (bottom-right) with the robot positioning building components and the welder fixing parts in place

Finally, we developed a general parametric digital environment that accurately simulates complex end-effector actions to be verified for both safety and assembly accuracy purposes. In the perspective of future architectural applications, the system has proved suggestive for hypothesizing complex assemblies (even of non-standardized building components) to more accurately fit complex design contexts with clean prefabricated solutions, potentially useful in the case of an intervention in a historic building.

The research work was supported by the "Microincentivi per l'Innovazione" grant program awarded to ALO by Sardegna Ricerche (2019) (Fig. 7).

## *1.6 The APTICA Project. A Study Case of Computation in Design and Making for Augmented Human Experience*

The need for accessibility of spaces and culture is finally spreading; architecture has first and foremost a responsibility towards people who, for whatever reason, have a disability. The accessibility of museums is one of the critical issues with respect to which this renewed attention is beginning to be prolific and translates into an innovation of methods and processes to facilitate the enjoyment of museum

**Fig. 8** The figure shows the APTICA interfaces with the 3D miniature of the artwork. The dark top surfaces are the touch feelers, sensing surfaces that enable the multimedia contents navigation

content. In this context, starting from the small scale of museum devices and installations, new digital fabrication technologies and advanced multimedia strategies are gaining ground in the research and development of new methods to engage visitors in inclusive, immersive and rewarding experiences.

Our research work on this subject started in 2019, thanks to the collaboration with CRS4 (Sardinia's Centre for Research, Development and Advanced Studies) that commissioned ALO to design and prototype a functional device for the multimedia and tactile exploration of pictorial works. Our work stemmed from the initial studies developed by researchers at CRS4 on the transformation of pictorial works into scaled 3D representations, equipped with sensors to enable the multimedia content. From here, we developed a new complete and functional interface named APTICA.

Beyond the utilitarian aspects, which were particularly relevant to this project, the brief immediately showed the possibility of opening a new chapter within philosophical, historical and semiological discussions about the frame, an object that has so far assumed the status of a theoretical object as observed by Pinotti [19].

The frame, which appeared in a context that intended art as a reality detached from the one we live in, was a boundary between the representation and real space. Its purpose was intended to intensify the perception of the depth of the field or to project the movement outwards.

The historical evolution of its role went through various phases until its denial. However, the whole debate starts from the assumption of a visual fruition of the artworks; therefore for people with severe visual impairment, the frame in its traditional conception loses its value. This consideration raised a new question: Can we reformulate the role of the frame and envision a new type that encourages alternative cognitive processes and facilitates the tactile exploration of pictorial artworks? Indeed, the challenge of this project was to move from the concept of the frame as a boundary for the eye to that of an intensifier of the senses.

### 1.6.1 Accessibility by Design

A complex tactile experience requires training and preparation. A strategy is needed to see objects with the hand, and from the perspective of a designer there are specific criteria that must observed in order to achieve effective results [20]. APTICA is ultimately designed to prepare the hands for the tactile experience.

The device is a table-top physical object with part of its body that seems floating over the supporting surface with the aim of isolating it from the surrounding world and stimulating the perception of a suspended object on which to focus one's senses.

The first part that user comes into contact with is the perimeter of the frame: a fragmented body made up of a sequence of blades, all different and oriented like rays towards the centre of the subject. The fragmentation aims to provide an initial intense tactile transition from the surrounding solid objects to the sensorial space.

Then the hands encounter a second element, the skin: a smooth surface surrounding the tactile subject at its centre. The skin is a neutral transition zone to reset the touch. The concave shape of the skin then guides the hands towards its deepest part suggesting a tactile immersion in the sensory space of the 3D tactile miniature. To achieve a smooth and robust surface, the skin is made of glass fibre moulded on a mould made by robotic milling.

Finally, at the centre of the membrane is a platform to accommodate the interchangeable tactile cards that are automatically recognised by the system to enable the respective audio and video descriptions. The tactile surfaces on the top layer of the 3D miniatures feature a sophisticated design that takes advantage of a computational design strategy to fill the area with a single line pattern necessary to build conductive tracks with a minimum amount of electrical connections.

### 1.6.2 The Computational Design of Single Line Touch Feelers

The subjects of the paintings are simplified and transformed into small-scale three-dimensional figures, each with a different height according to the different degrees of depth in the artwork. The upper part of each figure has been developed as a tactile surface, the touch feeler, which perceives visitor's touch and allows multimedia content stored on the integrated PC to be activated.

Next to Aptica body, the development of the touch feelers was the second major research topic we carried out. We were asked, for technical and usability reasons, to design a new sensor working based on two electrical connections (positive and ground) that would work without bracelets or additional connections. Accordingly, the work focused on finding a computational strategy to generate the conductive traces while minimizing the number of electrical connections and ensuring in-house feasibility of the prototypes.

Various geometrical approaches were explored (Fig. 9), however, in the case of non-compact figures, many failed to produce a single curve occupation. But this was very important to avoid overly complex wiring and an excessive number of electrical connections. Moreover a non-directional pattern would have been beneficial to avoid confusing the tactile perception of the figures. Hence, we searched for a computational strategy to generate an occupation pattern consisting of a single curve capable of filling any kind geometric figure, compact or non-compact.

Various geometrical approaches were explored (Fig. 9), however, in the case of non-compact figures, many failed to produce a single curve occupation. However, this was very important to avoid overly complex wiring and an excessive number of electrical connections. Moreover a non-directional pattern would have been beneficial to avoid confusing the tactile perception of the figures.

Finally, hooking back to the studies of D. Hilbert or W.Sierpinski [21] on space-filling curves such as those, we developed a computational protocol that, starting from a given boundary condition (the edge of the figure) and a set of genotypic parameters and constraints, modulates and folds back the edge on itself up to fully occupy the figure with a single complex curve. The single curve folds on itself according to a set of guide parameters that define: (1) the distance of the folds from the boundary of the figure, (2) the distance between the end and start point, (3) the minimum interstitial space between folds, (4) the minimum radius of curvature of the folds. The complex figure generated becomes then a geometrical skeleton for the construction of the conductive traces of the Touch-Feeler (Fig. 10).

Through this procedure, which combines physical-computing methodologies and parametric-associative design strategies, we obtained a generative system that occupies the space of the figure with a single continuous trace, while still matching production and functional constraints. The graphite based touch feelers were then prototyped in our laboratory by fine-tuning a reliable fabrication protocol combining painting, cutting and laser engraving as to achieve repeatable and precise results.

For this project, various digital fabrication techniques were strategically combined to address both the performative needs and budget economy; from this intersection, we could successfully develop a new type of interface that, by its shape and materiality, offers new opportunities to answer the demand for the accessibility of pictorial artwork. A new design iteration has been already undertaken for the development of a still more stable and durable version of the touch feelers. Nevertheless, APTICA is an expression of a novel design culture where computation, matter and fabrication actively combine to make avant-garde innovation possible inside small scale design studios too.

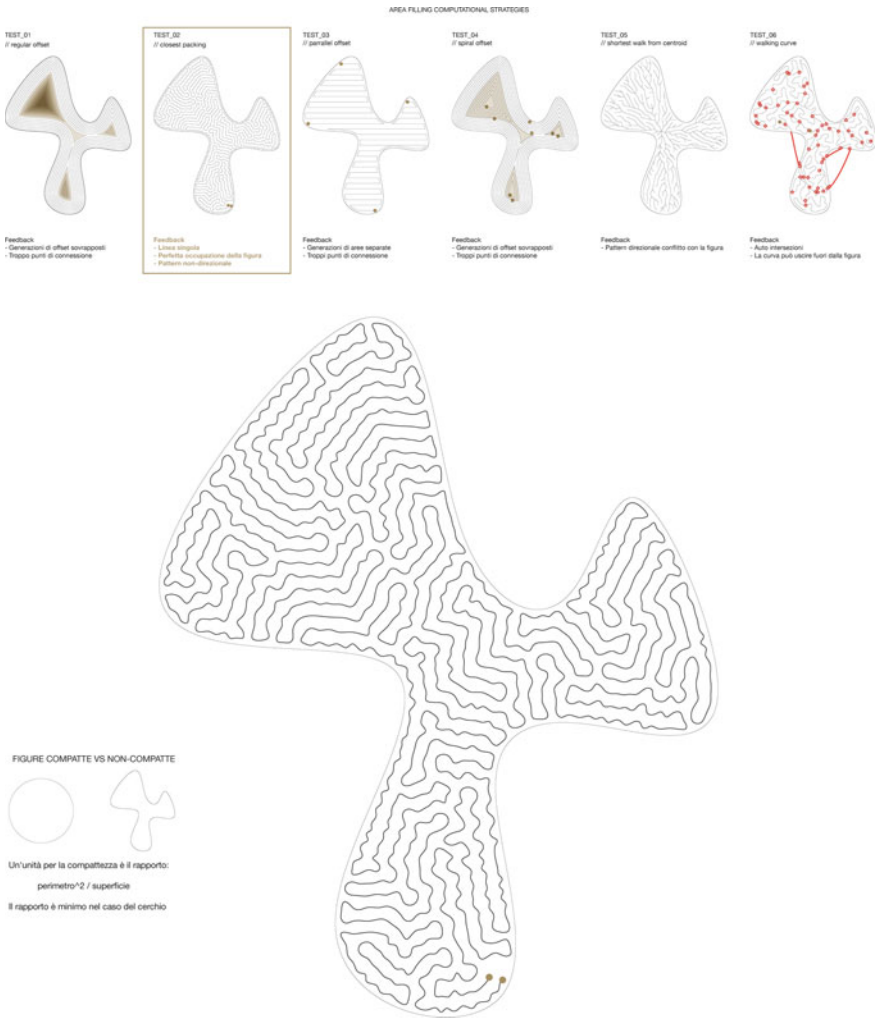


**Fig. 9** The diagrams illustrate the different geometrical and computational approaches tested in order to find a single line filling procedure adaptable to both compact and non compact figures

## 2 Conclusions

The chapter outlined some of the criteria supporting ALO's design research in the field of contemporary strategies and processes for architecture. The projects sampled are the expression, at different scales, of an effort made in the course of everyday practice towards the formulation and acceptance of new concepts of space, structure and furniture, as well as of making strategies and human experience.

**Fig. 10** Detail of the conductive graphite pattern of the touch feelers prototype

In this framework, digital fabrication and robotics become instrumental towards a novel material culture focusing on the achievement of a performative materiality. The search for new spatial repertoires and construction models according to the criteria illustrated aims to reduce the consumption of resources through a novel logic of differentiation and polyfunctionality. The concept of architectural composition is surpassed by the concept of formation; the design process is no longer linear and becomes performative as well; non-standardized prefabrication provides novel opportunities for a more responsible and higher quality production even for everyday small projects; matter and fabrication themselves become active agents within the conception and making of space and designs for human experience.

To date, dealing with small-scale interventions has certainly facilitated the implementation of some of the key aspects of our research. As also noted by Colarevich [22], certainly the scale factor is significant, especially since the behaviour of materials changes precisely in relation to the size of the parts. But we are aware that the performance of a material is as much an expression of its intrinsic capacity as of its form. We therefore believe that, although the shift to larger scale in general cannot be straightforward, the construction criteria highlighted and derived from a holistic and biomimetic approach to architecture pave the way for a new generation of smart and intrinsically more sustainable and smart architecture. Certainly, the smartness we pursue goes far beyond the widespread idea of smartness, which often focuses on the mere integration of digital technologies that can make architectures almost alive, capable of informing us about their state of operation and their relationship to their surroundings.

Rather, as a primary and unavoidable condition, smartness should be a matter of the materiality itself of architecture, both spatial and constructive. We should look for a type of intelligence which could provide the ability to passively contribute to the microclimatic well-being as much as to the programmatic and energy needs of both the occupants and the surrounding environment. The new architectures will possibly be interactive constituents of an augmented urban and territorial ecosystem.

### *2.1 Toward the Industry "X"*

Like many other digital technologies that were initially confined to factories, robotics is undergoing a phase of democratisation. However, while the potential of robotic applications in production and human life is increasingly arousing enthusiasm, a sense of scepticism is also emerging because these technologies are often seen as a substitute for human labour. While it is true that machines are often used only to maximize production to meet the needs of mass production at the expense of certain labours, the digitization of production, if aimed at mass customization, can foster the specialization of existing figures and the emergence of new figures and markets. In fact, this is already happening.

In this context, we have the opportunity to embark on a virtuous path in which robotics is not a mere substitute for humans, but an instrument to enhance their skills and capabilities. By overcoming mistrust through a humanistic education in technology and developing critical thinking regarding certain fetishist approaches, we could develop a true deontology to elaborate strategies that privilege human–machine interaction and lead to collaborative productions that would not be possible without such interaction. Industry X, would be a new model of production based on a symbiotic and ethical interaction between man and robot; the X would just represent such a powerful convergence.

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# Digital Twins: Accelerating Digital Transformation in the Real Estate Industry

**Mattia Santi**

**Abstract** Digital twins have been introduced in 2002 at the University of Michigan by Michael Grieves. Digital twins are part of the Industry 4.0 revolution and are a strategic technology that, after being implemented in numerous industries such as aerospace and automotive, is now becoming important in the real estate sector. This chapter will introduce the concept of digital twins and their current applications, exploring different types of digital twins and their characteristics. The analysis will then focus on the existing issues facing the real estate sector, with an appreciation of how digital twins could significantly impact this industry. Digital twins will be explained covering the basic principles behind the technology. The chapter will continue analysing some contemporary applications of digital twins in the real estate industry developed by leading companies in the sector.

**Keywords** Digital twins · Building automation · AI and machine learning · BIM

**United Nations' Sustainable Development Goals** 9. Industry Innovation and Infrastructure · 11. Sustainable Cities and Communities

## 1 Introduction to Digital Twins

In recent years, digital twins have become increasingly popular and their use cases are spreading across all industries, from aviation to marketing, from automotive to real estate. Dr. Michael Grieves first introduced the concept of the digital twin in 2002 at the University of Michigan [1]. The concept presented was based on the idea of generating a digital clone of a physical entity and linking them together. Based on this concept, a digital twin can be defined as a digital clone of a physical system that covers its entire life cycle and is connected to it via real-time data exchange.

These data are analysed and visualized thanks to digital simulations and machine learning providing a real-time interconnection between the physical element and the

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_36

digital element. This real-time connection makes it possible to analyse and understand the behaviour of the physical asset and provides useful insights to enable a predictive maintenance strategy (Fig. 1).

Dr. Michael Grieves, in his original formulation of the digital twin concept, describes a digital twin as a system consisting of two elements, the physical asset and the digital replica. In the model proposed by Dr. Grieves, these two elements are connected during the entire lifecycle of the physical asset, from creation to production, operation, and disposal. According to this model, the physical asset and its digital clone exchange data in real time providing feedback to each other in a sort of mirroring effect. The name of this conceptual model was the "Mirrored Space Model" [1].

A digital twin can describe a physical asset at different scales. To achieve a digital twin, it is necessary to have a physical asset, a system of sensors connected to this asset that collects data, a system that analyses this data in real-time and a system that helps visualise it. Therefore, the concept of a digital twin goes beyond the traditional notion of a visual model, if we consider for example a BIM model, the primary distinction between a BIM model and a digital twin is the connection between the physical item and the digital model via a feedback loop. The main scope of a digital twin is to monitor and manage an asset during its lifecycle, supporting the decision-making process and predictive maintenance.

Digital twins can be applied at different scales, for instance, there are digital twins representing individual assets or digital twins representing systems of multiple assets, therefore the level of detail adopted for the representation of the physical reality can vary based on the purpose of the digital twin. Digital twins can be used for different types of reasons and this affects the level of detail that needs to be achieved and the quality of data required to make sure that the information collected and analysed is suitable for the scope of the project. Considering that digital twins can collect and process large amounts of data in real-time, it is essential to use the appropriate level of detail required to achieve efficient and reliable digital twins.

A digital twin is characterized by three main elements: the data exchanged with the physical asset, the model and the visual representation of the model. Considering that the central idea is to establish a real-time connection between the physical and

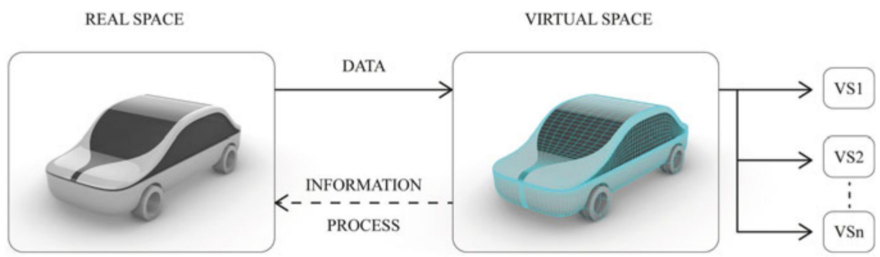


**Fig. 1** Diagram reproducing the "Conceptual Ideal for PLM" introduced in 2002 by Dr. Michael Grieves

virtual realms, the data exchanged are defined as dynamic data, meaning data that can change asynchronously over time as soon as updated information is available.

Depending on the purpose of the digital twin, the model can be interpreted in a variety of ways. For instance, the models could be physics-based models to simulate the real context of the digital twin, agent-based models to simulate specific behaviours and interactions, or a combination of the two.

The other element to consider is the visualization of the digital twin model, the visualization strategy depends on the purpose of the digital twin but also the target users of the digital twin. For example, in some cases, a 2D visualisation may be sufficient, while in other cases a more immersive experience may be preferable. The correct visualization strategy is essential to allow the digital twin to absolve its main function of helping to make informed decisions.

Considering a wind turbine as an example, to build a digital twin to monitor this energy production infrastructure it is necessary to have sensors capable to measure in real-time the physical conditions of the turbine and its surrounding environment, such as temperature, wind speed, weather conditions, etc. In parallel, there should also be a digital model of the physical asset that contains the information needed to monitor the physical condition of the asset and its performance. In addition, there could be a 3D visualisation of the wind turbine that can help engineers observe its physical characteristics, its context and combine this information with the data received from the sensor to gain a multidimensional understanding of the asset and its performance, for example by measuring how much energy is produced and under what specific environmental conditions. More advanced models may also allow for simulation to test emergency scenarios and identify predictive maintenance strategies.

Digital twins should not be identified with simulation models. These are typically focused on simulating specific phenomena or processes. Although digital twins can also be used for simulation, digital twin models should be able, within their scope, to give a complete representation of an asset, allowing to run of multiple simulations in multiple scenarios. Another difference is that a digital twin establishes a two-way connection with a physical asset, allowing it to inform the simulation with real-time data collected by the interaction with the physical asset [2].

## 2 Origins of Digital Twins

Digital twins are a key technology in the context of Industry 4.0, although they are not a new technology. In fact, the idea of using digital twins was originally introduced by NASA in the 1960s and the Apollo 13 rescue mission in 1970 could be considered the first application of the idea of the digital twin, more than 30 years before the term “digital twin” was coined [2]. Each spacecraft was replicated in an earthbound version used to simulate and study the operation that the crew had to perform in space and to train the crew. The Apollo 13 simulators used the most advanced equipment in the entire space programme: only the crew and mission control consoles were real, while the rest was a simulation developed with advanced computers, complex calculations and expert engineers.

After the launch of the Apollo 13 spacecraft, there were technical problems and the mission changed from an exploration mission to a rescue mission. This became the first application of digital twins. NASA had a copy of Apollo 13 on the ground which enabled the engineers to carry out the necessary tests and make informed decisions to help the crew manoeuvre the damaged spacecraft to safety [3].

Contemporary digital twins are connected to physical assets through the use of the Internet and can exchange data in real time between the physical asset and the digital model. Apollo 13 did not have the "Internet of Things", but NASA was using state-of-the-art technology to achieve a near real-time connection with the crew 200,000 miles away. Considering this, Apollo 13 simulators could be considered early-stage instances of digital twins since they were connected to the actual asset in near real-time and could respond to changes in the physical asset [3] (Fig. 2).

This was the first application of digital twins before the term digital twin existed. Although Dr. Michael Grieves formally introduced the concept of a digital twin in 2002 under the name "Mirrored Space Model", it was actually in 1991 that the idea of a digital twin first appeared in the publication "Mirror Worlds: or the Day Software Puts the Universe in a Shoebox…How It Will Happen and What It Will Mean" by David Gelernter. The term "Digital Twin" (DT) first appeared in the draft version of NASA's technology roadmap in 2010. In this publication, NASA first introduces a formal definition of Digital Twin, describing it as "*an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best*

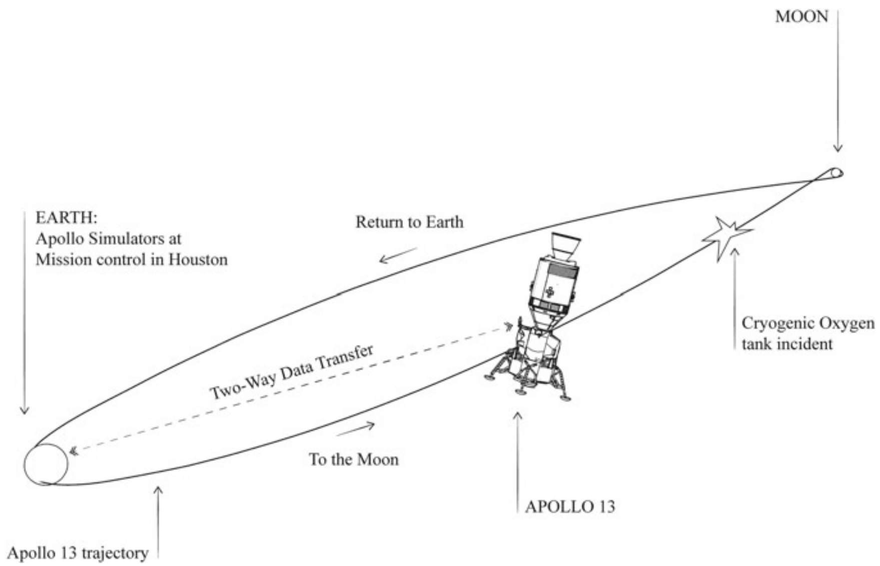


**Fig. 2** Diagram describing the trajectory of the Apollo 13 mission

*available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin*" [4].

A few years later, leading industry media such as Gartner, Lockheed Martin and Forbes recognised digital twins as a strategic technology trend. Until a few years ago, limitations in processing power, data scarcity, storage constraints, bandwidth costs, and technological hurdles slowed company adoption of digital twins, but we are now seeing digital twins expand across different industries. Digital twins are now within reach of many companies, supported by the quick integration of IoT devices.

Digital twins became a key technology part of the Industry 4.0 revolution, a new evolution of industry characterized by revolutionary technologies such as Quantum Computing, Spatial Computing, the Internet of Things (IoT), Artificial Intelligence (AI), Genetic Engineering, 3D printing and more. Digital twins can play an essential role in the Industry 4.0 landscape, helping to bridge the gap between the physical and digital worlds. Digital twins, depending on their implementation, may enable a completely new way of interacting with physical reality thanks to spatial computing and could open the way to a completely new range of services and business applications.

## 3 Different Types of Digital Twins

In several sectors, digital twins have been widely applied, helping to digitise different types of products. According to the type and the scale of their application, digital twins can be categorized into 4 different types: Component Twins, Asset Twins, System Twins, and Process Twins [2].

Starting from the smallest units that define a system, Component Twins are digital twins used to mirror the basic components of a product. The component twins allow monitoring of these individual system components, considering their operational status and performance.

Combining multiple components, a more complex digital twin can be obtained to simulate the overall behaviour of an asset, considering the interactions between individual components. This digital twin is focused on analysing the system at the product level and can provide a considerable amount of data considering complex interactions happening between multiple components.

Multiple assets create a system that can be identified as a System Twin. System Twins are useful for representing complex elements characterised by the interaction of multiple asset twins. They can be helpful when it is necessary to control a group of assets and study their interactions at a system level.

Lastly, process twins are used to study the interaction between multiple system twins. These are large-scale digital twins that operate at the macro level and focus on understanding how multiple complex systems interact with each other. For example, they can represent large industrial plants or entire cities [2].

## 4 Current Applications of Digital Twins

Digital twins aim to provide a real-time copy of a physical asset and require a combination of IoT sensors and software development to build a reliable digital twin.

Therefore, digital twins still require a considerable investment that currently limits the range of applications of digital twins. Despite this, digital twins are currently applied in several industries, for example, in power-generating equipment, which includes large-scale engines such as jet engines, locomotive engines and turbines for power generation, where digital twins are applied in the management of maintenance requirements. Buildings, infrastructures, and their systems are other important examples to consider, as they can all benefit from digital twin technologies from the design to the operational stages, allowing for the management of these assets while considering their spatial characteristics and the way users interact with them. Digital twins play an essential role in manufacturing processes, and they have a natural application in product life cycle management. Digital twins are also used in the healthcare business to assist in the creation of digital profiles for patients receiving healthcare services. Another possible application in this industry is the employment of digital twins by pharmaceutical firms to model genomic codes, physiological parameters, and patient lifestyles [2] (Fig. 3).

As previously mentioned, digital twins also find applications in the automotive industry.

Cars are complex assets with several interdependent systems, therefore digital twins play a crucial role in their coordination, maintenance, and customer care.

In the automobile industry, digital twins are also utilized in product testing, where the digital twin of a product aids in evaluating its quality and performance by conducting digital experiments with different compounds and raw materials to improve the design and maximize the product's performance.

Another important application in this industry is the development of self-driving cars, which requires the use of several sensors to comprehend the interaction between the vehicle and its surrounding environment. Digital twins are necessary to test numerous scenarios and imitate the behaviour of these vehicles in the digital world [2].

Digital twins also find wide applications in the aerospace industry. As previously mentioned, one of the first applications of digital twins was in the aerospace field with Apollo 13 and all subsequent applications developed by NASA. Today, digital twins are essential for monitoring and simulating the behaviour of mechanical components, complex systems, entire vehicles or vehicle systems. They are very important when predictive maintenance is required and in complex projects that require complex simulations and monitoring. For example, they are used to monitor jet engines to check the level of degradation and simulate engine behaviour under different conditions, informing maintenance and design strategies.

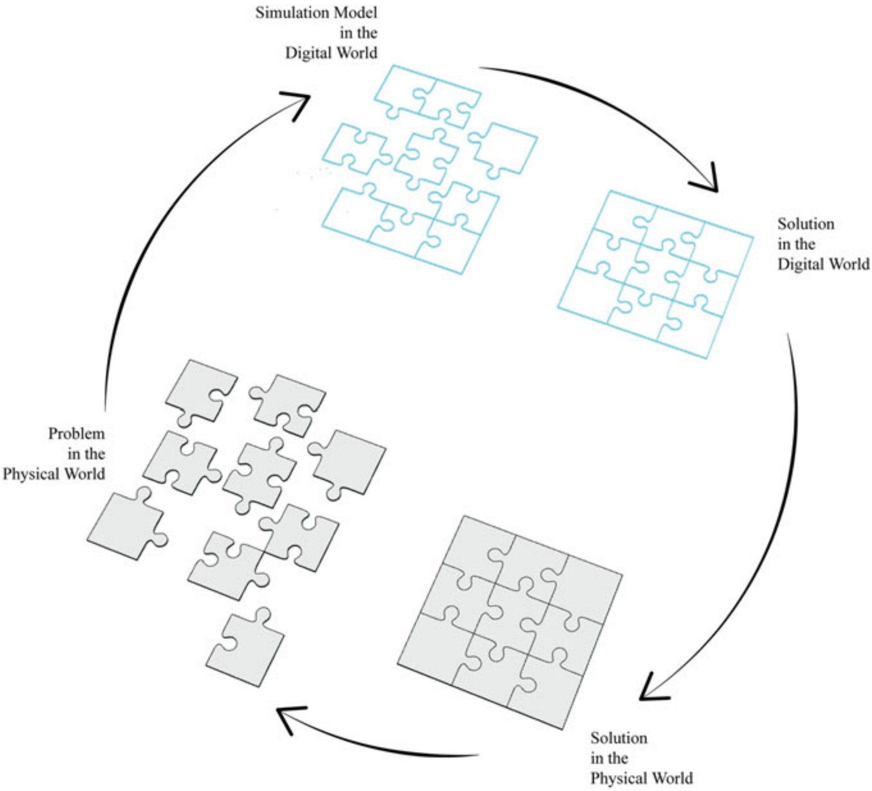


**Fig. 3** Digital twins provide a risk-free environment to test new solutions

Digital twins can also play an important role in smart cities, where urban planning efforts can be guided by actual data to make better design decisions and simulate numerous scenarios to meet the needs of multiple stakeholders.

Digital twins are currently being applied at the urban level to simulate entire urban areas and to monitor traffic by extracting statistical information on public transport, pollution levels, traffic intensity, etc. Many of these projects are still in the initial stages and it is possible to imagine that the number of such applications will increase and that these projects will be further developed in the coming years [2].

## *4.1 Case Study: The Flying Catamarans*

Digital twins are having an impact in several sectors and the sports industry is one of them. In 2012 the Emirates Team New Zealand (ETNZ) introduced new 72-foot hydrofoiling catamarans, which were subsequently adopted in the 36th America's Cup. In 2018, the America's Cup 75 Class Rule was published, defining the design rules for boats eligible to participate in the 36th America's Cup. No physical testing was authorized during the 36th America's Cup, therefore simulation-driven digital twins proved to be an essential design and testing tool. These racing yachts, rather than having a keel, have foil cant arms which can move outside or under the boat to provide stability and make these catamarans fly on top of the water [5] (Fig. 4).

These innovative racing yachts are 7.6-tonne boats with the crew, sailing at maximum speeds that can reach 50 knots, flying on the water, propelled by a double-sail skin mainsail, combined with a D-shaped mast to form a wing [5]. Since physical testing in wind tunnels or towing tanks was prohibited by AC75 class rules and teams could only build two racing boats, simulation-based digital twins became the solution for designing these racing yachts. The design team needed to create a comprehensive digital model that could be used by the entire team, from designers to boatbuilders and sailors, to create these high-performance products. To do this, they had to combine CAD tools with computational fluid dynamics (CFD), structural analysis and simulation, as well as product lifecycle management tools. The team's Velocity Prediction Program (VPP), which predicts boat speed under various conditions, is fed with CFD (Computational Fluid Dynamics) data from the simulation of many unique boat configurations characterised by different parameters, such as hull position or foil angles. This allows different design options to be evaluated against different scenarios and optimisation strategies to be defined. Another challenge in which digital simulation models have been important is the study of the interaction between aerodynamic and hydrodynamic forces operating on these vehicles. With the limitation of building only two physical models, having a digital twin of the vessel was essential to the entire design process, allowing for a high-fidelity copy of the physical asset on the one hand, and simulating the physical conditions in which the vehicle will operate on the other [6].

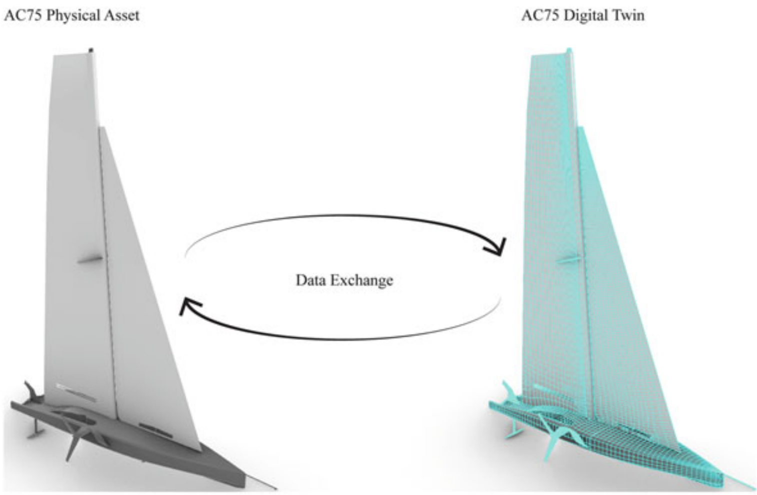


**Fig. 4** Digital twins were adopted in the design of the AC75 racing yachts

### 4.2 Case Study: Digital Clones of the Earth

The function of digital twins as a predictive tool can be widely scaled, creating digital clones of complex systems like an entire planet. At the time of writing, there are multiple initiatives attempting to develop a digital twin of the Earth to monitor climate change using predictive models.

One of these projects is Nvidia's Earth-2 project, which aims to build a supercomputer to implement a digital twin of the Earth to study and predict climate change. The difficulty in predicting climate change is that, unlike weather forecasting, the period is too long and there are too many variables to consider. Designing the best strategies for reducing the effects of climate change and adapting to the changes requires climate models that can predict the climate in various places of the world over decades.

These models are "multidecade simulations" of multiple complex systems such as the atmosphere, oceans, land, human activities, etc. This level of simulation requires ultra-high-resolution climate modelling therefore this was not possible until a few years ago [7] (Fig. 5).

Another project that aims to create a digital twin of our planet is Destination Earth (DestinE), a project promoted by the European Commission in collaboration with partner organisations, which aims to develop an accurate digital model of the Earth that can collect real-time data and investigate how natural events and human behaviour interact.

The DestinE project is a complex system composed of three main elements, the "Core Service Platform", "the Data Lake", and the "Digital Twins". The "Core

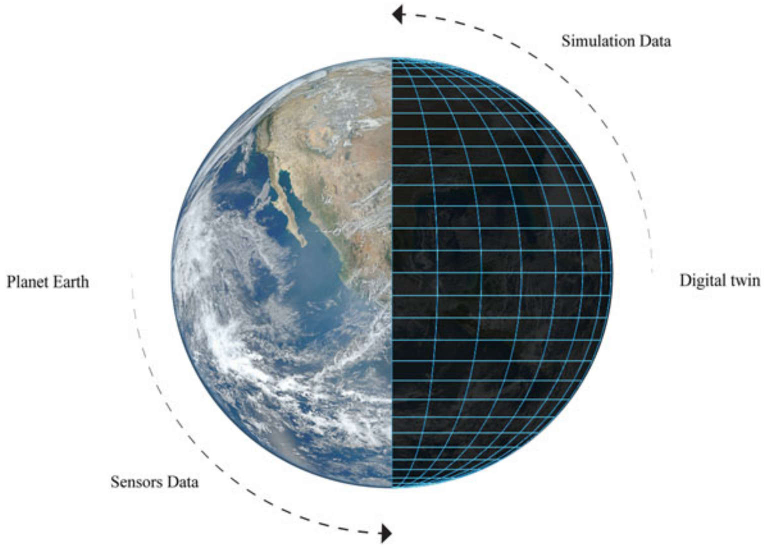


**Fig. 5** The Destination Earth project intends to create a digital replica of the planet Earth

Service Platform" will be the platform and the interface for the users to access DestinE model. The "Data Lake" will be the pool of data collected by the data holdings provided by Copernicus the European Union's Earth observation programme, data holdings from ESA (European Space Agency), EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) and ECMWF (European Centre for Medium-Range Weather Forecasts) and additional data provided by various sources. Then the "Digital Twins" will be implemented to create digital clones of complex systems (e.g. oceans, lands, etc.) that will all be connected to the main model.

Through DestinE, users will have access to theme-related data, services, models, scenarios, simulations, forecasts, and visualisations. In order to produce accurate and useful scenario predictions, the underlying models and data will be regularly evaluated. DestinE initially will be accessible mainly by public authorities but in the future will be accessible also by a wider spectrum of users [8].

These case studies are some examples of how digital twin technology is currently being applied in different sectors. The implementation of this technology has advantages and disadvantages. Analysing the benefits first, the digital twins facilitate a more effective research and design process for product development and design. Indeed, because of the volume of data generated, they enable the prediction of an asset's performance and the potential of making essential changes prior to initiating the manufacturing process. This enables enterprises to obtain more accurate information and hence make more informed decisions more quickly. On the other hand, digital twins enable continuous monitoring of products and systems, resulting in a more effective product life cycle management process. Thus, digital twins can aid in addressing the difficulties of material resource scarcity, pollution, climate change consequences, and the transformation towards a net-zero greenhouse gas emissions economy.

The United Nations Sustainable Development Goals (SDG) serve as a framework for identifying objectives to address real-world problems that impact society and the environment. Regarding these goals, digital twins, especially when deployed as a large-scale digital twin network, can contribute to the achievement of several goals. For instance, regarding SDG 09 "Industry, Innovation and Infrastructure", digital twins can contribute to the development of robust systems to monitor infrastructure or production processes to maximize their resilience and efficiency. Regarding SDG 11 "Sustainable Cities and Communities", digital twins can help develop connected settlements with transparent access to information, facilitating participatory democracy through the inclusion of citizens in planning and policymaking, and promoting decarbonisation and resilience. Digital twins can help monitor and control energy use and its interaction with the distribution network in real-time, enabling the optimisation of resources, from individual products to buildings and cities.

On the other hand, deploying digital twins has some challenges, such as requiring the integration of several technologies, such as 3D models, sensors, data analysis, and machine learning, which need specialized knowledge and a significant initial financial investment. Several challenges are inexorably linked to technology: data privacy is one of them; sensors capture incredibly valuable data that must be managed and processed according to increasingly stringent cybersecurity standards. In addition, network partitioning and latency must be considered when designing these systems. Indeed, more processing power and bandwidth are required to maintain the service's real-time effectiveness as the system gathers more data and as more users interact with it. These are all aspects to be considered about this technology, regardless of the specific industrial applications.

The importance of digital twins in architecture and how they could change the real estate sector will be explored in the following paragraphs.

## 5 Current Challenges in Real Estate Industry

Digital twins can contribute to bringing innovation in Architecture providing solutions for some of the pain points currently affecting the real estate industry.

The digitisation of operations and data continues to be a significant challenge in the real estate industry. Existing buildings often have a history that spans several decades; thus, part of the information associated with these buildings is not available in digital format, and in other cases, is unavailable at all. Often, gathering data about buildings needs access to the facility's physical assets and human activities to extract data about the building. This makes it challenging to collect and maintain information on existing real estate assets [9].

The emergence of hybrid workspace models that blend remote and in-office employment is a prominent trend in the present real estate market. This necessitates the construction of more resilient working spaces that can adapt to a variety of usage circumstances and the provision of digital interaction with the physical area. For instance, it becomes crucial to provide a seamless experience that creates the same working conditions for remote and in-office workers and to ensure that all workers may access meetings even if they are not physically present in the office. On the other hand, it is essential to have digital and automated processes to maximize the use of space depending on user requirements, therefore creating spaces that can adapt to user demand [9].

Another challenge in the construction world is the need to innovate construction processes to reduce carbon emissions, improve health and safety, optimise the construction pipeline, and reduce costs and delays. The construction industry is currently characterised by the rising cost of raw materials, labour shortages and a decrease in the number of craftsmen available on the market [9].

Sustainability is a crucial challenge for the real estate industry; in 2021, 37% of global $CO_2$ emissions were due to the buildings and construction sector, which accounts for 34% of global energy demand [10]. Buildings are characterised by embodied carbon generated during the construction process and operational carbon emitted during the operational life of the building. It is difficult to monitor energy consumption, especially in existing assets, so it is important to incorporate IoT devices to monitor consumption and integrate circular models to reduce the carbon footprint of the building sector and develop optimisation strategies to improve building performance.

On the other hand, another challenge is the integration of IoT technologies in existing and new buildings. Implementing this technology would give the possibility to access building information remotely, an important element that becomes crucial when physical access to the asset is not possible. In this sense, Internet of Things (IoT) technologies, whether sensors or data systems, are essential to be able to gather information about the building in real time [9].

## 6 Digital Twins in Real Estate and Architecture, Engineering and Construction (AEC) Industry

Design, construction and management operations can be facilitated by the use of digital twins, as buildings are high-value assets with complex life cycles. Besides being physical assets, buildings are also environments where people live and work, building social relationships and forming communities. To further evaluate the possible uses of digital twins in the real estate sector, it is important to reflect on the profiles of users who may be interested in using this technology.

One of the first user profiles to be considered are professionals involved in the design of buildings, such as architects and engineers involved in the design process and in the decision-making. Architects and engineers could benefit from accessing data on the performance of the assets designed, to provide better ongoing support to clients and learn how to improve design services.

Social workers, for example, may be interested in determining the social impact of specific policies and may need to discover resources and solutions to give effective assistance to individuals. Asset owners are also user profiles to be considered. Digital twins could provide them with greater control over their assets and lower management expenses. Another profile is elected officials who determine and vote on how public funds are distributed and invested and who, thanks to the implementation of city-wide digital twins, can analyse and understand the real needs of citizens.

The policymaker profile should also be considered as they are in charge of recommending and establishing laws and norms. This user profile would unquestionably benefit from having access to structured facts to comprehend the impact of past actions and make educated decisions for the future. A crucial profile is that of an emergency service planner since they are responsible for gathering data and simulating the effects of emergencies. In addition, tourists can benefit from a connected ecosystem of digital twins, as they would be able to locate the information they want more easily thanks to the interaction and exchange of information with the built environment. Finally, numerous forms of digital twins might help small company owners to identify local patterns and make key choices about the services they supply.

Citizens, in general, could benefit from accessing digital twins of public spaces to learn more about their neighbourhoods and how they can contribute to improving their community and environment [11].

Reflecting now on the potential applications of digital twins in the real estate sector, one interesting application is to model and anticipate how tenants would use and interact with the property, gaining insights into users' comfort and productivity. In order to increase the user's comfort, a digital twin might monitor the environment and provide recommendations and adjustments. This ability to foresee allows more informed project choices and favours the development of successful management strategies. Digital twins, for instance, may be used to examine complex utilization scenarios for commercial and public buildings, enabling flexible day-to-day space and function configurations.

Another important area of application for the digital twin is the design process. In fact, with this technology, designers can create more than just a 3D model, they can create a sandbox environment for a project, an interactive game in which design ideas, products and user scenarios can be tested against multiple design iterations, different environmental conditions and environmental data. The construction process can be replicated and visualised using digital twins. Computational analysis is already widely used to improve the design and many organisations now have access to sophisticated methodologies that link different disciplines, but with digital twins, designers have more reliable information to test design ideas in different scenarios, using environmental data to make their studies context-specific (Fig. 6).

Considering that digital twins are able to store maintenance information and can enable the automation of part of the building maintenance process, they can also enable better maintenance strategies. Given the need to move towards a more sustainable use of energy, buildings will no longer rely solely on programmed responses but will be required to provide autonomous responses to different user behaviour and different environmental conditions to optimise system behaviour and the use of resources in real time.

Digital twins could become an important tool for studying strategies to improve the sustainability of buildings. It is possible to analyse a building's performance and calculate its carbon footprint in real time by collecting environmental data. This allows the implementation of methods to optimise a building's energy use and make it more energy efficient. Digital twins could be useful to identify waste streams and their potential as resources, increase operational efficiency and resource utilisation through waste reduction, quantify environmental expenditures to encourage a circular economy, and help achieve zero-emission targets.

Another interesting application of this technology is at the urban scale, where it is possible to create virtual clones of entire cities and neighbourhoods, allowing large amounts of data to be recorded and studied at the community level, providing crucial information for making informed decisions at the urban level. According to a study conducted by the C40 Cities Climate Leadership Group, urban policy decisions made before 2020 might affect up to one-third of the global carbon budget that has not yet been determined by past decisions [12]. Therefore, political decisions and public administrations play an important role in creating the conditions to achieve

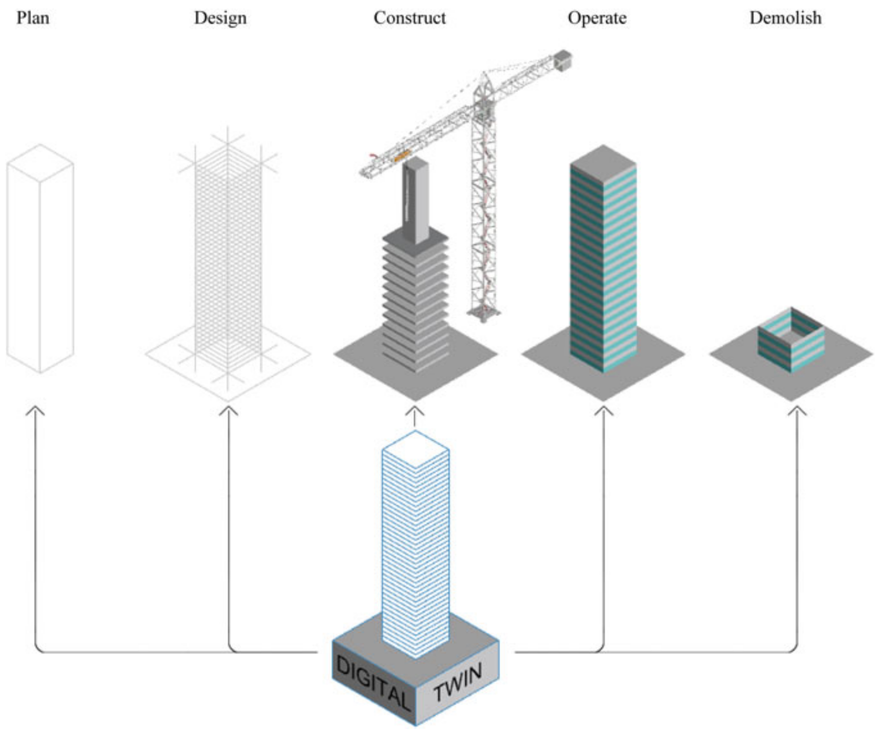


**Fig. 6** Digital twins help to manage buildings during their entire lifecycle

a low-carbon economy. Digital twins can provide a simulation and monitoring tool, enabling the testing of policy decisions, identifying dependencies and enabling cooperation between policy sectors, all while improving the participation of citizens and communities.

## 7 Current Challenges in the Implementation of Digital Twins

To comprehend the present challenges in the adoption of digital twins in the Real Estate and Architecture, Engineering, and Construction (AEC) industries, it is necessary to examine the many types of user profiles that may be identified.

Tenants are one of the first user profiles to be considered because some of the data collected by the sensors may put their privacy at risk, but on the other hand, this data could be used to improve their living experience. Landlords, on the other hand, might benefit from having well-organised data on the digital assets they own and manage. Investors are another type of user profile who might be interested in learning more about the performance and management of a particular asset.

Vendors, technologists and start-ups are also important actors to consider, as they might be interested in receiving information on certain assets to advertise their services or adapt their business models to market demands. Nevertheless, it is vital to consider how local councils and governmental organizations might benefit from direct access to current information about assets and operations, enabling them to be more visible on the ground and providing citizens with better services. Research organizations and academic institutions are other interesting user profiles. They could use digital twins as virtual labs to collect field data for research and experimentation as well as to give students the chance to gain experience working with information that is typically challenging to obtain. Furthermore, government authorities, suppliers, insurance companies and similar businesses can benefit from having real-time data on the buildings for which they provide services [11].

Another important challenge to drive the adoption of this technology is the definition of standards. Standards are essential to establish definitions, concepts and processes such as data management and interchange, as well as technical requirements such as interoperability and data security.

In this sense several institutions are currently working to develop standards and frameworks to facilitate the implementation of Digital Twin technologies, an example is the National Digital Twin programme (NDTp) run by the Centre for Digital Built Britain, a partnership between the University of Cambridge and the Department for Business, Energy and Industrial Strategy [13]. Other examples are standards developed by the International Organization for Standardization (ISO) specific for the Digital Twin technology, such as ISO/IEC AWI 30173 "Digital Twin—Concepts And Terminology", ISO/IEC WD 30172 "Digital Twin—Use Cases" and ISO/TR 24464:2020 "Automation systems and integration—Industrial data—Visualization elements of digital twins". Also, important to consider are standards like ISO 10303 "Industrial automation systems and integration—Product data representation and exchange" and ISO 19650 "Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)—Information management using building information modelling" [11].

Despite the increased use of digital twins in other industries over the past few years, which has made them more accessible, these technologies need a great deal of knowledge, and digital twins are challenging to implement in AEC processes, especially for small and medium-sized companies. Given the current state of technology, it is necessary to form multidisciplinary teams comprised of experts in fields such as software development, building information modelling (BIM), virtual reality, user interface design, interaction design, artificial intelligence and data science to connect IoT systems and create a system capable of streaming real-time data and allow users to interact with the system. Consequently, this technology requires considerable investment and requires the collaboration of multidisciplinary teams with different types of expertise. Therefore, it is important to consider the development of competency and skills frameworks to identify relevant roles within industry and organisations, as well as the key competencies needed to effectively implement these technologies. As a result, knowledge providers in this area can become important key players, because, without an adequate skill set, organisations risk employing staff with insufficient skills to develop their digital twin projects, with the risk of poorly designed results that do not work as intended [14].

## 8 Defining Building Ontologies

Real estate is one of the world's largest asset classes. Digital twins have the potential to significantly increase the value of real estate assets, from individual units to buildings and entire cities and facilitate the digitization of information relative to the physical assets. To achieve this and facilitate the implementation of digital twins it is necessary to define and set standards for digital twins [15].

The digital twin market is attracting tech giants like Microsoft, IBM, Siemens, Dassault Systems, Autodesk and others. These firms supply the digital infrastructure for IoT standards and protocols for data collection and analysis, enabling third-party companies to develop digital twins using the technology needed. The construction industry has been slower than other industries to embrace digital transformation. These companies are developing standards and integrations to support the acceleration of digital transformation in real estate. The software infrastructure that some of these companies are developing is important for the wider adoption of digital twins in the real estate sector (Fig. 7).

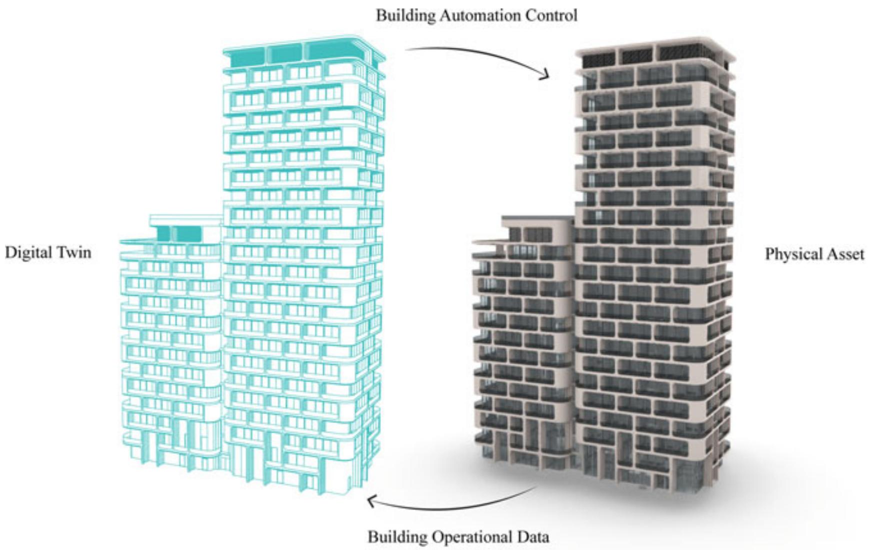


**Fig. 7** The digital twin of a building allows for the digitisation of information about the physical asset through real-time data exchange

For example, if we consider a building element like a door, which is a common and essential item to have in a building, it involves several stakeholders to be specified, to be built and to be installed. Just to describe the characteristic of a basic item like a door it is required a considerable data structure, that nowadays is generally managed in BIM environment and requires specialized professionals and organizations to handle these building information models. To digitise real estate assets beyond the design and construction phases, it is important to simplify the way buildings can be described. This is why some of the tech giants interested in the digital twin market are developing new building ontologies that can be used to facilitate the implementation of digital twins.

An ontology in computer science is a formal representation of the concepts and interactions inside a certain domain. It is utilized to model and arrange the domain's knowledge in a machine-comprehensible format. Ontologies are frequently used in artificial intelligence, natural language processing, and the Semantic Web because they provide a standardized vocabulary for the comprehension and interpretation of data. An ontology consists of a collection of concepts, their attributes, and the links between them. It is used to describe knowledge so that it may be shared and reused across several systems and applications. In practical terms, a building ontology serves to conceptualize the type of data that are necessary to describe a building in all its constituent parts, describing the building elements, their properties and the relations between them. An ontology can be seen as a set of models for a specific domain. These models are developed through the use of a Digital Twins Definition Language (DTDL). A Digital Twin Definition Language (DTDL) is a standardized language or set of rules that can be used to describe the structure and behaviour of a digital twin. It enables developers to create a digital twin by defining the various components, their relationships, and the rules that govern their interactions [16]. For example, a digital twin definition language allows to define the various rooms in the building as components, specify the relationships between them (e.g., one room is adjacent to another), and define the rules that govern their behaviour (e.g., temperature control). The built environment is characterized by a high level of complexity, and a building ontology needs to express this reality in a manner that is simple for digital twin developers to use in order for this technology to achieve wide adoption.

By optimizing data categorization, integration, and accuracy, creators of digital twins may produce more accurate digital representations of buildings and their components. Therefore, the development of platforms that link data generated by IoT devices to the building topology is a necessary first step in setting standards for digital twins and facilitating the wider adoption of digital twins in the real estate sector [15].

## 9 Game Engines

Visual representation is an essential element that enables digital twins, allowing the user to understand the link between data and physical assets and to interact with them.

Game engines are playing an important role in facilitating the implementation of digital twins. Game engines offer technologies for handling the 3D data required to create a realistic representation of a physical asset. Most innovative manufacturers have started using game engines to simulate production processes and test their products with different usage scenarios before manufacturing them [17].

Game engines, such as Unity or Unreal Engine, include sophisticated 2D or 3D physics-based development environments that allow the development of photorealistic simulation while also providing an environment defined by physical forces and effects that can depict how the asset will interact with the real environment. This technology is important for the implementation of Digital Twins because, in addition to real-time data, the model may be simulated against physical circumstances that the user can adjust in real time. Game engines are used by innovative car manufacturers to simulate the creation of new cars and provide more immersive experiences by allowing users to try out a vehicle before it is built. Considering this example, digital twins are important for a wide range of people, including CEOs, marketing, sales teams and customers. Thanks to the visualisation and simulation capabilities provided by game engines, digital twins become more accessible: individuals no longer need a significant level of technical knowledge to understand or decode the simulation in front of them.

For example, non-technical people may experience how a new building will appear and work in a real-world scenario thanks to the strong visualisation capabilities of game engines [17].

## 10 Implementing a Digital Twin of a Building

The technology stack required to implement a digital twin of a building would depend on the specific requirements and goals of the project, but generally, it will include some essential components.

One of these components is the 3D modelling software, which is used to develop a virtual clone of the physical asset, including its geometry, spatial relationships, and materials.

The Internet of Things (IoT) system, which consists of sensors and devices, is another important element. It is used to gather information from the actual building, such as temperature, humidity, occupancy, and energy use. These sensors then feed the digital twin with the data they have acquired.

Another crucial element is the cloud infrastructure, which is utilized to store and handle the data gathered from IoT sensors and devices as well as any other data that is important to the digital twin.

Tools for analytics and data visualization are additional components required for creating a digital twin. These are used to analyse the data gathered from IoT sensors and devices and to present the findings in a form that is clear and useful to all stakeholders.

Other important elements are machine learning algorithms, which are used to identify patterns and trends in the data collected from the IoT sensors and devices and to make predictions about future behaviour or performance.

Application programming interfaces (APIs) are also important elements of a digital twin, these are used to connect the various components of the technology stack, and to enable integration with other systems or applications that may be relevant to the digital twin.

The user interface is another crucial element of a digital twin. This is the interface that stakeholders use to engage with the digital twin, and it may consist of web applications, mobile applications, or other types of user interfaces.

Developing the digital twin of a building requires a software architecture that can handle the various data sources, processing requirements, and user requirements involved in such a project. We can summarize the basic software architecture necessary for a digital twin in three main elements: the data management layer, the processing layer, and the user interface layer.

The data management layer is responsible for gathering and organizing the diverse data sources that will be utilized to create the digital twin. This data can include information about the building's physical characteristics, such as its 3D geometry and construction materials, as well as data on its systems and operations, such as energy usage and occupancy patterns. The information collected will be interpreted based on a building ontology specific to the type of building that thanks to the digital twin definition language (DTDL) will define the data model for the digital twin, which serves as a blueprint for how the data should be structured and organized. Once the data model has been defined using the digital twin definition language (DTDL), the data management layer can use this model to integrate data from a variety of sources and ensure that the data is organized and stored in a consistent and meaningful way [16]. This data can be collected by the data management layer from a variety of sources, including sensors, building management systems, and manual inputs. The data management layer should be able to obtain building-specific data updates in real time.

Another important component of the software architecture is the processing layer, which is responsible for analysing and interpreting the data collected by the data management layer. This can include tasks such as identifying trends and patterns in the data, predicting future behaviours and identifying potential issues or inefficiencies. The processing layer is not directly concerned with the structure or organization of the data but rather focuses on the meaning and significance of the data. The output generated by the processing layer can be used by users or other systems to make decisions or take actions. The processing layer should be able to handle large volumes of data in real time and should be able to scale up or down as needed to meet the needs of the digital twin.

Moreover, the software architecture should include a user interface layer, which allows users to interact with the digital twin and access the data and insights generated by the processing layer. This can include features such as dashboards, alerts, and visualization tools that help users understand and monitor the building's performance. The user interface should be intuitive and easy to use and should be accessible from a variety of devices, including desktop computers, tablets, and smartphones.

Overall, the software architecture for a digital twin of a building should be able to accommodate the project's complex and diversified data sources, processing requirements, and user expectations. The system of a digital twin must be designed with a scalable and reliable architecture to accommodate additional traffic and data volume.

## 11 Reference Projects

Having discussed the potential applications of digital twins and explored some of the challenges in implementing this technology, it is useful to discuss a couple of projects that provide a good example of how digital twins can be applied on the architectural and urban scale.

### *11.1 MX3D Bridge*

The MX3D bridge, developed by the Joris Laarman Lab, is an innovative 12-m-long bridge 3D printed in stainless steel by the Dutch 3D printing company MX3D. The bridge is equipped with an innovative sensor system that will collect data about the bridge's structural behaviour and the environment. The data collected from the bridge is fed into a digital twin of the bridge, a virtual clone of the physical asset that analyses the condition of the bridge in real time, acquiring important information to understand how this innovative 3D-printed structure behaves from a structural point of view but also to understand how it interacts with its surroundings [18]. Funded by the Lloyd's Register Foundation, the project was developed in collaboration with several companies, including Arup, Imperial College London, Autodesk, University of Twente, Force Technology and the Alan Turing Institute. The sensors positioned on the bridge will measure real-time data like strain, displacement, vibration, and environmental elements like air quality and temperature acquired from the bridge while it is in use [19] (Fig. 8).

This data is used by research teams in the data-centric engineering program at the Alan Turing Institute to analyse material behaviour in diverse contexts and develop novel statistical methods to deepen understanding of advanced materials. The real

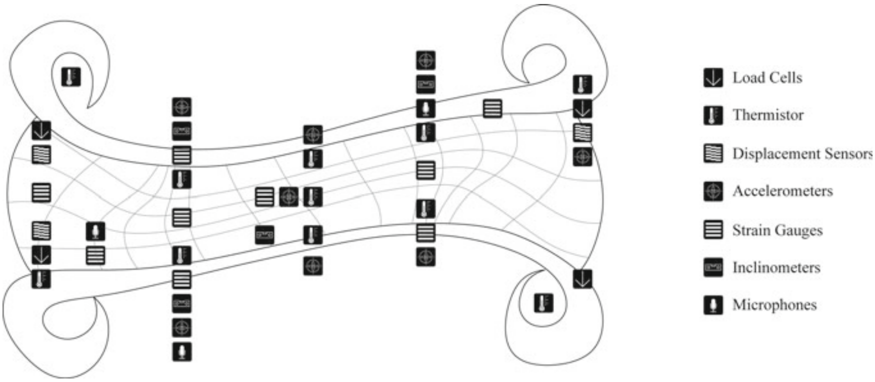


**Fig. 8** Diagram representing IoT sensors embedded in and around the MX3D Bridge. (MX3D 2021)

bridge's performance is compared to that of its digital counterpart to provide relevant data for the design of future 3D printed structures and any upcoming certification requirements for 3D printed structures.

The University of Twente is collaborating on this project with its BRIDE program, which uses the bridge's data to study how people interact with it, provide feedback on the design, and assess the project's impact on the community by examining the interactions between people, place, activities, and technology [19].

## *11.2 Wellington Digital Twin by Buildmedia*

Another interesting case study that implements digital twins at the urban level is the Wellington Digital Twin in New Zealand developed by Buildmedia in collaboration with the Wellington City Council. The project offers a new place for interaction powered by real-time city data. This digital twin makes use of smart city technology and real-time data to provide transportation statistics for buses, trains, ferries, bicycles, and vehicles, as well as visualisations of air traffic, cycle sensor data, traffic load, and available parking spaces. Considering that human beings typically process information through visual means, this model integrates data visualisation with a simulated real-world metropolitan context to achieve a strong visual appeal. To create an urban-scale Digital Twin with this level of complexity, it was necessary to combine data from different agencies [20] (Fig. 9).

The project started with the building of the 3D landscape using heightmaps derived from geographical data made available by Land Information New Zealand. More than 18,000 structures with 3D models and textures were built using a photogrammetry model of the Wellington Central Business District provided by the Wellington City Council. In this project, it is possible to understand the importance of adopting

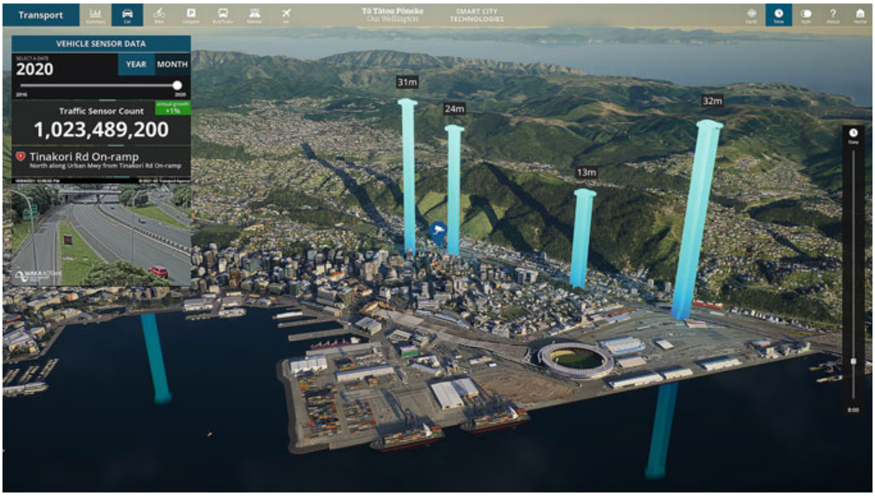


**Fig. 9** Image of the Wellington Digital Twin developed by Buildmedia (Reproduced from Buildmedia 2021)

appropriate visualization technologies to construct Digital Twins, where the adoption of game engines allows the management of large quantities of data. The model was detailed using a variety of animation and 3D components, and the entire scene was handled within a physics engine capable of producing the atmosphere system that gives the scene a feeling of realism and enables the simulation of various environmental conditions. Then, this realistic replica of a real city was connected to a network of IoT sensors spread around the city. These data on traffic, pollution, and temperature are communicated using a custom REST API that can manage a variety of data formats, including JSON, XML, and HTTP [20].

Although the Wellington Digital Twin will continue to evolve, it is already being used to show a range of citywide initiatives for public consultations and meetings with stakeholders. Having all the information in one model simplifies and enhances interactions with local businesses and public stakeholders. The capacity to trace decision-making is also crucial; it is possible to start collecting a history of proposals and choices that will affect the city, enabling more participation and transparency with local inhabitants.

## 12 Potential Impact of Digital Twins in the Real Estate and AEC Industry

The impact that digital twins will have over the years in the Real Estate and Architecture, Engineering and Construction (AEC) Industry depends on several factors and it is difficult the predict since the technology will evolve and adapt over the years.

On the other side, it is possible to identify some specific areas in which Digital Twin could have a considerable impact.

One of the first aspects to consider is the impact that this technology may have on our society especially if digital twins are deployed on an urban or even national scale, which could lead to new ways of interacting with the built environment. For example, one of the goals of the National Digital Twin programme in the United Kingdom is to create a network of digital twins connected through shared data [21]. The establishment of such a building ecosystem might enable new services for citizens and could open new market opportunities related to real estate assets. Thanks to this technology in the near future buildings and structures could be augmented beyond their physical nature, becoming accessible online and providing new ways of experiencing them in the digital realm. This could also affect the value of physical buildings, introducing new digital economies linked to physical buildings.

The influence of digital twins on building sustainability and life cycle management is another essential scenario to consider. Thanks to their monitoring capabilities, digital twins can help reduce energy consumption and carbon dioxide emissions related to building assets. On the other hand, thanks to the data collected by digital twins during the life cycle of a building, they can become very useful to inform and activate recycling strategies at the end of a building's life cycle, promoting a circular economy and sustainable use of resources. Even small improvements gained via data-driven decision-making that can be enabled by digital twins might have substantial social, environmental, and economic consequences in a sector like real estate which represents a considerable percentage of the total carbon footprint of an entire country and a considerable portion of a country's gross domestic product (GDP).

Another field where we can expect digital twins to have a considerable impact is the field of software used to design and manage the construction processes. As the industry has evolved from CAD to BIM, we can expect to see new software becoming necessary to implement and manage digital twins in professional practice. Understanding the difference between BIM and digital twins is important to understand what the impact of digital twins could be in this field. The fundamental distinction between a BIM model and a digital twin is that the latter exchanges data in real time with the physical asset. A digital twin is an interactive platform that collects and visualises data, a living model that visualises information in real time and can be used to simulate user scenarios and environmental conditions based on the acquired data. While a BIM model transfers information primarily in one direction based on user input and the amount of information remains constant over time if users do not add new information to the model, a digital twin is a two-way information model that aims to generate feedback loops between the physical and virtual worlds to optimise the system performance. The accuracy of the digital twin should increase over time based on feedback loops between digital and physical assets. Due to the difference in purpose, a digital twin focuses more on dynamic data, whereas a BIM model focuses more on static data. This is not due to a technological constraint, in fact it would be possible to build a digital twin from a detailed BIM model. A digital twin during its life cycle should be able to provide more information than initially entered by the user. Digital twins should provide information on an asset's performance, as well as relevant feedback for improving the asset's design depending on the data collected. As more data is collected and comparable assets are deployed with their own digital twins, the accuracy of the representation of the digital twin improves.

Finally, it is important to consider how public and private organizations may develop or acquire the wide range of skills that digital twins necessitate in order to create a successful digital twin ecosystem. The skills required to build a digital twin range from data science to IoT, AI, BIM, and data visualization. This may require interdisciplinary partnerships, but also highlights the need for competence frameworks to assist governmental and commercial institutions in exploiting the full potential of digital twins. As a result, another potential effect of digital twins is that they can necessitate the establishment of new specialities and skill sets tailored to digital twin projects.

In conclusion, the application of digital twins is not yet widespread enough to disrupt the real estate industry, but as full digital twins of buildings become more common and standardised, companies will be able to optimise entire buildings, asset portfolios and lifecycles through a constant flow of data and information.

New business models and market opportunities will then emerge, as well as a change in the way places are conceived and created. Buildings could become more dynamic and responsive to human behaviour and the natural environment. In the future, it may be necessary to design not just the physical space of a building, but also its cyberspace.

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# The Right Algorithm for the Right Shape

## An Algorithmic Framework for Efficient Design and Conception of Building Facades

**Inês Caetano, António Leitão, and Francisco Bastos**

**Abstract** Buildings are a critical element of civilization, within which we spend over around 70% of our lifetime, but also one of the main contributors to the greenhouse effect. It is therefore important to ensure their design guarantees good indoor conditions, while minimizing the environmental footprint. Among the different building elements, the facade is one that most influences these two requisites and thus its design requires, in addition to the traditional aesthetic and functional requirements, the integration of performance criteria from early design stages. However, there are still some barriers to this integration, such as the limited flexibility of design tools, the need for multiple analysis and optimization tools, and their high computational cost. Recent computational design approaches, such as Algorithmic Design (AD), have been facilitating the combination of creative processes with the search for better performing and more sustainable design solutions. However, these approaches require programming skills, which most architects do not have. To maximize its potential for architectural design, efforts should be made to reduce the complexity of AD and approximate it to the architects' design practice. We address this by proposing an AD methodology and algorithmic framework for facade design that encompasses its different stages, from conceptual design to manufacturing, and requirements, such as aesthetics, environmental performance, comfort, and costs, among others, while supporting the variability and diversity typical of architectural design problems. By combining the framework's ready-to-use algorithms, multiple design scenarios can be considered, and various design requirements addressed, helping to achieve the goals established by both the 2030 Agenda and Industry 4.0.

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_37

**Keywords** Computational and parametric design · Performance-based architecture · Algorithmic workflow · Computational design analysis · Digital fabrication

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns

## Abbreviations

| | |
|---|---|
| AD | Algorithmic Design |
| ADO | Architectural Design Optimization |
| AEC | Architecture, Engineering, and Construction |
| CNC | Computerized Numerical Control |
| DF | Digital Fabrication |
| GUI | Graphical User Interface |
| IEQ | Indoor Environmental Quality |
| SDGs | Sustainable Development Goals |

## 1 Introduction

Buildings are one of the main $CO_2$ emitters and spenders of energy resources [1–3] but also a critical element of civilization, within which we spend over around 70% of our lifetime [4]. Half of these emissions results from the operational costs of buildings, such as heating, cooling, lighting, and ventilation; and the other half from the construction processes, namely the production, transport, and manufacture of building elements, and material disposal [2]. To meet the United Nation's Sustainable Development Goals (SDGs) [5] building design must provide good indoor conditions while minimizing the environmental footprint.

Among the different building elements, the facade is one that most influences the buildings' Indoor Environmental Quality (IEQ) and environmental performance [4, 6–10]. Therefore, in addition to aesthetic and functional requirements, facade design requires the integration of performance criteria from early design stages, as well as manufacturing-related strategies assessing the construction viability of the developed solutions.

Unfortunately, there are still barriers to such integration. One is the limited flexibility of design tools, hampering the application of iterative design changes in the search for improved solutions. Another is the large computational resources and specialized knowledge needed by analysis and optimization tools [11, 12], resulting in time-consuming and computationally-expensive processes whose results are difficult to interpret. A third barrier emerges when it becomes necessary to use multiple tools that hardly interoperate with each other, increasing the propensity for information loss and error accumulation [12]. A last critical barrier is the time and effort needed to address manufacturing and cost-related constraints [13], especially when dealing with unconventional design solutions. All these obstacles make the integration of performance and manufacturing-related design variables incompatible with project deadlines and resources, hindering the development of more ambitious facade designs whose performance goes beyond minimum regulatory requirements.

Advancements in computational design approaches have improved the integration of performance criteria within the design practice, making it easier for architects to combine creative processes with the search for better solutions in terms of environmental performance, IEQ, production costs, among others [14–16]. Algorithmic Design (AD), a design process based on algorithms [17], is one such approach that allows for (1) greater design flexibility, (2) the automation of repetitive and error-prone tasks, (3) the integration of different types of data in a single model, (4) the coordination of different design tools, such as modelling, analysis, and fabrication tools, and (5) the automatic extraction of technical information. AD has large potential for reducing the environmental footprint and meeting the 2030 SDGs Agenda for a more sustainable built environment [5].

Nevertheless, AD is an abstract approach that requires programming experience, which most architects do not have. To maximize AD's potential for architectural design and motivate the search for more sustainable design solutions, efforts should be made to reduce the technical complexity of AD strategies and make them more accessible to a wider audience. Considering the current state of the art, it is therefore important to systematize and structure the algorithmic generation of design solutions in an architectural-oriented methodology that considers the diversity of architectural design problems and their different aesthetic, performance, and construction requirements. To successfully deal with the variability and context-specificity typical of architectural practice, the proposed methodology must have enough flexibility to adapt to multiple design briefs and workflows, while providing control over the coordination of different types of information and over the translation of digital designs into actual constructions [18–20].

This chapter addresses this goal by placing particular emphasis on the field of facade design due to the aesthetic and performance relevance of this building element, as well as due to its design complexity and impact on the projects' feasibility. Given the universality and problem-solving capabilities of mathematics, this research uses its language to address the above-mentioned goal, adopting a strategy that encompasses:

- The architects' creative process, by systematizing the design complexity of current facade design strategies, while helping with the algorithmic development of new facade design solutions.

- The coordination of different conceptual and performance requirements, by automating analysis and optimization processes from early design stages, providing reliable feedback on the solutions' performance and aesthetical quality.
- The context specificity of architectural design problems, by guiding the selection of geometry- and performance-related algorithms based on the type, scale, and complexity of the problem addressed.
- The materialization of the resulting solutions, informing about their viability in terms of cost, waste, and resources, while automating the production of technical documentation for the selected fabrication strategy.

To that end, an extensive investigation on contemporary architectural processes is first presented, which discusses the impact of the growing environmental awareness and new computational design means on both facade design strategies and the increased complexity of construction processes. A mathematics-based methodology is then proposed, together with its implementation in an AD framework containing different algorithms embracing the complexity of procedural modelling, performance simulation, design optimization, and fabrication techniques. To evaluate the potential of the proposal to support design workflows encompassing creative intents, performance requirements, and fabrication constraints, from conceptual design to manufacturing stages, a set of case studies is then presented and discussed. Finally, the chapter concludes with considerations on the case studies' results, elaborating on the proposal's suitability to meet the 2030 SDGs Agenda and approximate the Architecture, Engineering, and Construction (AEC) field to the Industry 4.0 paradigm.

## 2 Facing New Challenges

The need to successfully respond to the growing concern with the buildings' ecological footprint motivated the increasing integration of design performance in architecture, triggering new design approaches that go beyond aesthetic and functional levels [21, 22]. As a result, design practices that are more environmentally-aware emerged [23]. Under the names of performance-based, performance-driven, performance-oriented, or even performative design, this design paradigm has been gaining ground in the literature [24–27] as well as in architectural practice, particularly in the design of facades due to the aesthetic and environmental relevance of this building element [7].

### *2.1 Environmental Concerns*

We are currently facing an environmental problem and the AEC sector is one of the main contributors. According to the literature, buildings are responsible for 50% of natural resources consumption, 42% of the total energy consumption, and 35% of greenhouse gas emissions [2], which are among the main contributors for climate change and global warming [28]. Half of these emissions result from the operational costs of buildings, such as heating, cooling, lighting, and ventilation, and the other half from construction processes, namely the production, transport, and manufacture of building elements and the disposal of building materials [2]. In 2012, for instance, buildings were responsible for around 75% of Europe's energy consumption, and almost 70% of it was for space heating [3].

Given the urgent need to minimize the buildings' ecological footprint [3, 4] and stop the growing trend of $CO_2$ emissions [3], several regulations and incentives were established worldwide [29]. The Building Research Establishment Environmental Assessment Method (BREEAM), first published in 1990, is the oldest method for assessing, rating, and certifying the buildings' sustainability regarding a wide range of environmental issues. This method was followed by several other regulations, including the Kyoto protocol signed in 1997, one of the first initiatives to limit $CO_2$ emissions; the European Union's Energy Performance of Buildings Directive (2002/91/EC, 2010/31/EU, and COM/2016/0765) targeting the improvement of buildings' energy performance; the U.S. Green Building Council's certification Leadership in Energy and Environmental Design (LEED); and the Japanese Comprehensive Assessment System for Built Environment Efficiency (CASBEE).

The existing legislation, however, requires architects to evaluate the performance of their designs regarding different criteria [11] to ensure the proposed metrics are met [12]. As a result, building design has become an even more demanding task, since it must simultaneously respond to the already existing aesthetic, structural, and IEQ requirements, plus the increasing number of performance metrics established worldwide.

## 2.2 *The Role of Performance Analysis*

In the last decades, several analysis tools were released to help architects evaluate the performance of their designs regarding different criteria. Examples of analysis tools include EnergyPlus and TRNSYS for whole-building energy simulations, Radiance for (day)lighting analysis, and DAYSIM for climate-based daylight simulations. Using these tools, architects become more aware of their designs' ecological footprint, as well as the impact of design changes on the solutions' environmental performance [4].

Unfortunately, many practitioners still do not use any kind of digital analysis tool in their design processes and those who do rarely benefit from these tools to support their creative process, using them instead to validate the performance of already well-defined solutions [12, 28, 30]. Moreover, obtaining accurate analysis results remains a challenging task due to the wide variety of factors that affect building performance

[4], including external ones (e.g., climate, geographic location, site conditions, etc.) and internal ones (e.g., occupants' behavior [31], spatial orientation [32], envelope transmittance [33], etc.).

The need for specialized knowledge, the lack of intuitive Graphical User Interfaces (GUI), the long computation times, the poor interoperability with the architects' preferred tools, and the idea that analysis tools restrict creative processes are some of the barriers to their widespread adoption [4, 11, 12]. Furthermore, the performance evaluation of a building requires the laborious and time-consuming production of an analytical model containing only the data needed for the intended analysis. Additionally, most analysis tools are single domain, forcing the use of multiple tools to evaluate different criteria, each one requiring a specific analytical model [30], resulting in a process that is prone to information loss and error accumulation [12]. Since a performance-based design process needs to analyze multiple design instances, the number of analytical models required grows considerably. Given the constant pressure for short deadlines in the AEC industry, evaluating an acceptable sample of possible solutions is, usually, an impracticable scenario [11].

To address the need for a faster and more reliable data-flow process suiting the iterative nature of architectural practice and minimize the alternation between different analysis tools, some modelling tools started to integrate their own analysis strategies [34]. However, the proposed solutions present some limitations in terms of (1) modelling flexibility and accuracy, particularly in representing and analyzing less conventional solutions and construction schemes, and (2) information support, often making no suggestions about which design direction to follow and how to translate analysis results into design changes.

## *2.3 Searching for the Best Performance*

Architectural Design Optimization (ADO) was motivated by the need to more effectively explore the design space in the search for better-performing design solutions [11]. By minimizing the buildings' ecological footprint, ADO can contribute to reduce the negative impact of the AEC sector [5].

In addition to simplifying real-world complex problems, often dealing with multiple conflicting requirements [15], into mathematical ones, ADO requires the iterative remodeling of designs and their subsequent performance evaluation to check if the fitness goals are met [28]. As multiple conflicting goals often result in a set of possible solutions that are not optimal for all requirements [15], ADO does not ensure the global optimum is reached [11]. Nevertheless, it increases the chances of finding it or, at least, of getting close to it [29]. In any case, the probability of obtaining more sustainable solutions is still much higher than that of traditional practices where no optimization is applied [11, 35]. Moreover, these processes are important to remind architects of possible design solutions that might otherwise not occur to them [36].

To successfully reduce the environmental impact of buildings, architects need to adopt either passive or active design strategies that consider both the existing performance requirements and the design variables affecting these [28] from early design stages, where major performance improvements can be achieved [37]. Nevertheless, the strategies employed often do not affect the buildings' shape, let alone guide the exploration process in an environmentally driven way. Moreover, only a few requirements are usually considered at initial design stages, e.g., aesthetic and functional ones, the others being typically postponed to later stages, where the design idea is already well-established [28, 38]. However, at later stages, most design changes are quite complicated, or even impossible, due to the lack of flexibility of most design models [38]. As in most cases architects explore the design space by manually adapting the solutions according to a few analysis results [23], only a few and small design changes are often evaluated due to time and effort constraints [12, 14]. As a result, the efficacy of the ADO process often becomes compromised [38], potentially leading to unrealistic or low performance results [28].

## 3 Sketching Through Algorithms

The technological evolution of the last decades has provided architects with the means to explore unprecedented design solutions, facilitating the production of unconventional facade elements of different shapes, patterns, and materials [39]. In addition to enhancing the architects' creative process, emerging design technologies have been allowing the integration of building performance requirements in an environmentally aware perspective. Combined with the architects' innate desire to go beyond conventional geometries and the usually tight time and economic constraints of architectural projects [12], the process of designing building facades grew in complexity [40]. Fortunately, part of this complexity can be reduced through AD, which provides the flexibility needed to coordinate multiple design requirements and data in the search for more sustainable facade design solutions [3, 4, 6].

### *3.1 Extending Design Creativity*

AD is a design approach based on algorithms that has been gaining prominence in architecture [41–46] and that greatly contributes to the movement of the AEC sector towards both the Industry 4.0 and the United Nations' 2030 Agenda goals. The increased design efficiency, flexibility, accuracy, and automation of this design approach have been motivating a new generation of architects to increasingly adopt AD strategies in their design practice [43]. To do so, however, architects have to acquire new skills, such as learning programming techniques, which often ends up being a barrier to AD's widespread adoption [47].

Two main AD paradigms currently stand out, the main difference between them being the type of algorithmic representation used, which can be textual or visual.

Among the two, the visual paradigm is more popular within the architectural community but current practices have evidenced several shortcomings that hinder the development of large AD programs [45, 48, 49], making the long-term use of visual-based AD strategies difficult [50]. The absence of abstraction mechanisms addressing scalability issues [49, 51], the poor intelligibility and difficult manipulation of the resulting AD programs [48, 52–54], the accentuated drop in performance when executing large AD programs [55–57], and the lack of version control mechanisms supporting collaborative design practices [52, 58] are among the limitations of visual AD. All these shortcomings have motivated the transition from this paradigm to the textual paradigm to benefit from the expressiveness and scalability of textual programming strategies [49]. Accordingly, some of the existing visual-based AD tools were extended with textual programming mechanisms [49, 51], such as loop iterations, recursive functions, and higher-order functions. Nevertheless, in most cases, it remains difficult to develop large-scale AD programs in these extended tools due to their inability to support the division of an AD file into multiple files.

Although learning textual programming has become an evident need, the transition from the visual to the textual paradigm is not trivial, often lacking the consolidation of important theoretical bases of textual programming strategies; a drawback that gets even worse when addressing more complex design problems. Moreover, as it still takes time to achieve the level of programming proficiency needed to deal with large-scale design problems, which typically involve multiple context-specific design requirements, architects usually spend more time solving programming problems than in creative and design exploration processes. Also, given the uniqueness and variability of architectural design problems, architects often face unanticipated changes that are not contemplated in the structure of their AD program, lacking the parameters needed to modify the model in the desired way and thus forcing its redesign and delaying the design process [59].

### *3.2 Algorithmic Analysis and Optimization*

The growing awareness on climate change and the need to reduce the AEC sector's ecological footprint has motivated the implementation of several building regulations aiming at meeting the United Nations' SDGs [5]. This has forced architects to increasingly resort to analysis tools to check if their designs meet the established criteria and, when they don't, to rethink their designs and repeat the process, considerably increasing the complexity of their design processes.

With the advent of new computational design approaches, such as AD, these processes can be improved. Besides facilitating design changes and supporting higher levels of design complexity, AD allows automating labor-intensive and error prone tasks such as those of analysis processes, particularly, the generation of analytical models [60] and the setup of analyses whenever the design changes. Therefore, by using AD, it becomes possible to not only perform several iterative design analyses with less time and effort [15], but also automate them in optimization routines and evaluate larger design spaces in the search for better-performing solutions [61].

To address the need to use multiple design tools and evaluate the solutions regarding different metrics, several AD tools started to integrate functionalities that embrace different analysis and optimization strategies. One example is Grasshopper's plugins for (1) structural analysis and form-finding, e.g., Kangaroo, Karamba3D, Millipede, and Peregrine; (2) lighting and thermal analysis, e.g., Ladybug, Honeybee, DIVA, and ClimateStudio; and (3) design optimization, e.g., Galapagos, Goat, Octopus, Wallacei, and Opossum. Other examples include Dynamo's addons for structural, energy, daylighting, and thermodynamic analysis, and optimization.

Nevertheless, despite AD facilitating the application of design analysis and optimization routines since early design stages, their use remains difficult due to (1) the uniqueness and conflicting nature of most design requirements [29]; (2) the need to explore wide design spaces in order to achieve acceptable results [29]; (3) the technical complexity and poor intuitiveness of most analysis/optimization tools; and (4) the need to convert ADO problems into abstract, mathematical formulations [30, 62]. Despite the existing AD tools to solve some of these barriers, they are mostly based on the visual programming paradigm and thus quickly become unable to cope with the complexity typical of large-scale architectural design problems.

The need to make design analysis and optimization strategies more accessible to architects from early design stages has been increasingly addressed in the literature [4, 29, 35, 63, 64]: Schlueter and Thesseling [65], for instance, assessed the integration of a prototype tool to assist energy/exergy calculations from early stages; Petersen and Svendsen [66] presented a proposal to help designers make informed design decisions at early stages regarding energy and inside spaces' environmental performance [66]; Madrazo et al. [67] proposed a method to recover information from repositories, hold calculation results, and support early-stage design decisions; Attia et al. [68] developed an energy-oriented software tool to support the design of zero energy buildings in an Egyptian context; Lin and Gerber [69] presented a framework to guide early-stage design exploration and decision-making processes based on energy performance; Negendahl [70] proposed an alternative method to the current IFC implementation to support early stages design processes combining different design, AD, and analysis tools; Finally, Konis et al. [71] presented a framework to improve daylighting and natural ventilation performances at early design stages.

The proposed solutions, however, do not entirely solve the challenges of early-stage ADO problems due to still presenting (1) limited modelling flexibility; (2) reduced interoperability; (3) few performance criteria; and (4) a narrow scope of application.

## 4 The Case of Building Facades

Architectural design problems are unique because, besides involving several design requirements that can be global or context-specific, straightforward or abstract, and fixed or evolving, they must respond to unpredictable creative intents and design briefs [3, 4, 40]. The design of building facades is a particularly relevant case because of the environmental impact of this architectural element [7, 8], as well as its design complexity [6, 40] and critical role in improving the IEQ of buildings. Nevertheless, it is often the case that the design means used do not provide the flexibility needed to quickly explore and evaluate a wide range of design solutions, hindering not only the architects' creative process but also the search for more sustainable solutions.

Among its different applications, AD has proved to be particularly advantageous for facade design processes, providing the flexibility needed to coordinate multiple design requirements [21, 72] and thus achieve design solutions with reduced environmental impact and minimum energy demands. Moreover, AD motivated the gradual shift towards Industry 4.0, allowing not only the automation of manufacturing and construction processes, reducing their production times, energy consumption, and resource waste, but also the production of unconventional facade elements whose manufacture was previously not viable [73–75].

### *4.1 Geometric Exploration*

To reduce the complexity of AD and facilitate the algorithmic development of facade design solutions, several AD tools were released. One example is ParaCloud Gem, a generative 3D design tool that provides features to (1) map 3D elements on a mesh, (2) subdivide and edit surfaces, (3) integrate fitness requirements, and (4) 3D print the resulting solutions. Another example is Dynamo's packages Quads from Rectangular Grid, Ampersand, Clockwork, LunchBox, MapToSurface, Pattern Toolkit, and LynnPkg, which include features for surface paneling, mapping elements on a surface, and pattern creation. A last example is Grashopper's multiple plugins, such as: (1) PanelingTools, which provides surface paneling functionalities and rationalization techniques for analysis and fabrication; (2) LunchBox, which integrates functionalities to explore mathematical shapes, surface paneling, and wire structures; (3) Weaverbird, which contains mesh subdivision procedures and mechanisms to help prepare meshes for fabrication; (4) Parakeet, which provides functionalities to develop algorithmic patterns resulting from tiling, geometric shapes and grid subdivisions, edge deformation, etc.; and (5) SkinDesigner, which includes mechanisms to produce facade designs made of repeating elements.

Despite facilitating algorithmic activities typical of facade design processes, such as creating point-grids on a surface, mapping elements in different ways, manipulating the elements' size, shape, rotation, etc., by applying rules or attractors, these tools still present some limitations. The first shortcoming is the fact that most of these tools are based on visual programming and thus suffer from the limitations of this AD paradigm [48, 49], particularly, scalability. Another limitation is the tools' limited ability to directly address relevant facade design concepts such as materiality and tectonic relation between elements, often only addressing generic panelization, subdivision, and population of surfaces. Finally, most of these tools are limited by the available predefined operators, which can hardly be configured by the user to respond to more specific problems [45].

## 4.2 Analysis and Optimization

Building facades are one of the most optimized elements in architecture because of their important role in the buildings' environmental performance [4, 11, 12, 29, 63, 76–79], their design greatly contributing to meet the United Nations' goal of making the production and consumption of cities sustainable. Figure 1 presents a set of architectural examples whose building envelope design was guided by performance.

To deal with the design complexity of this building element and its multiple and context-specific design requirements, several facade-oriented optimization methodologies have been proposed in the literature. These include Bouchlaghem's [80] computer-based model to design building facades based on their thermal performance; Wang et al. [81] multi-objective optimization model to design green buildings; Ochoa and Capeluto's [79] model to materialize design ideas based on climate

**Fig. 1** Institut du Monde Arabe (©authors); Campus Kolding of the University of Southern Denmark (©Henning Larsen); Al Bahr Towers (©Andrew Shenouda); Louvre Abu Dhabi (©authors); City Hall (©authors)

and visual comfort strategies; Gagne and Andersen's [82, 83] tool to guide facade design exploration based on illuminance and glare levels; Jin and Overend's [84] optimization prototype to identify optimal facade designs regarding functional, financial, and environmental requirements; Gamas et al. [85] study on the use of evolutionary multi-objective algorithms to optimize building envelopes in terms of thermal and daylight performance; Elghandour et al. [86] method to improve facade design daylight performance; and finally, Pantazis and Gerber's [87] agent-based framework for generating, evaluating, and optimizing facade designs from early design stages.

Despite the extensive literature, most proposals are (1) context-specific [79, 81, 83], (2) have limited modelling flexibility [80, 81, 83, 84], (3) address a single requirement (mostly energy consumption) [80, 83], and (4) require knowing in advance which optimization technique best suits a specific problem (a task that needs experience and specialized knowledge) [81, 84]. These limitations therefore make the proposals' widespread application often difficult, forcing architects to master and use an extensive range of tools/strategies to address the multiplicity of requirements guiding facade design problems. Moreover, some proposals do not present a GUI displaying the resulting solutions [80, 81, 84], making their use little intuitive and insufficiently user-friendly, or do not directly communicate with the design tools architects use [79–81, 84], often leading to interoperability issues and increasing the efforts associated with the transition between tools. The existing exceptions [82, 86, 87], however, are based on visual programming, thus sharing its limitations [49].

## 5 Making Digital Real

The desire for unprecedented shapes and structures has always been present in architecture, becoming further accentuated with the emergence of digital design tools, which provided architects with the freedom to design any shape they wanted. However, given the limitations of traditional construction methods, the realization of such shapes is often compromised. Digital Fabrication (DF) strategies are gradually changing this reality, albeit still with some limitations [88]. By combining DF with AD strategies, architects can control the entire design-to-manufacturing process in an informed way, reducing the distance between design thinking and making [89, 90], which is critical to bring the AEC sector closer to the Industry 4.0 and ensure sustainable industrialization and production.

### *5.1 Digital Fabrication Strategies*

DF encompasses fabrication strategies based on Computerized Numerical Control (CNC) machines that automate manufacturing processes and the production of building elements of varying geometries and materials. These methods allow architects to control the entire design-to-fabrication process in an entirely digital manner [89] and not only achieve higher levels of design complexity and accuracy, but also produce nonstandard building elements that would otherwise be unviable to produce [91].

Ideally, DF strategies would enable the conversion of traditional manufacturing processes, where only the mass production and assembly of standard elements is economically viable [89], into new ones benefiting from mass-customization strategies to produce multiple unique elements at low costs [92]. This scenario, however, remains a challenge in the AEC industry because of the uniqueness of architectural projects, which require the production of multiple context-specific elements [92], and the limitations of the available manufacturing technologies in terms of cost, machining time, scale, material waste, and special spatial conditions. Nevertheless, their gradual cost decrease is motivating their increasing use in architecture [93].

DF encompasses a wide variety of manufacturing strategies that vary in terms of (1) the process used to shape the elements, e.g., by adding, removing, cutting, or deforming materials; (2) materials supported, (3) element shapes and scales allowed; and (4) types of surface finishing, e.g., smooth, textured, printed, perforated, bumped, etc. DF strategies are generally categorized into five groups of manufacturing processes, namely *additive*, *subtractive*, *formative* [91, 93–96], *cutting* [89, 97, 98], and *robotic* [99].

The first one, *additive*, is based on the addition of material layers to produce the desired shape [91], requiring the translation of the digital model into a sequence of two-dimensional paths [89]. 3D printing is the most popular *additive* process in architecture but there are other techniques available, such as stereolithography, fused deposition modelling, laser sintering, and digital light processing [91, 96]. These methods have the advantage of directly converting digital models into physical elements without requiring additional devices and allowing the production of a wide range of shapes in a viable way [96]. Moreover, the available machines are often silent, produce reduced material waste, and do not require programming expertise [89]. Among their limitations are the difficulty to produce large-scale building elements [93], the poor surface finishing quality achieved, and the large production times [96]. Examples of 3D printed facade elements include those of the *Arachne project* in China (Fig. 2 left), the *Cabin of 3D printed Curiosities* in California (Fig. 2 middle); and the *Europe Building* in Amsterdam (Fig. 2 right).

The second group, s*ubtractive*, uses electro-, chemically, or mechanically reduced techniques to remove or separate particles of raw material from an existing solid [91, 98] to achieve the desired shape [93]. In architecture, CNC milling and routing processes are the most applied techniques [93]. Compared to *additive* processes, these technologies support a wider range of element scales and materials, have a higher geometric precision and production efficiency [89], but also produce a lot more material waste [91]. These methods have been applied in architecture, for instance, to (1) carve facade elements, e.g., the cork panels of a house in Aroeira, Portugal (Fig. 3 left); (2) perforate and bump sheet facade panels, e.g., the metal panels of *de Young Museum* in San Francisco (Fig. 3 middle); and (3) produce customized molds to cast facade elements, e.g., the concrete facade of *MaoHaus* in Beijing (Fig. 3 right).

**Fig. 2** Additive manufacturing: Arachne 3D printed facade (©Archi-Solution Workshop); House of 3D Printed Curiosities (©Matthew Millman Photography/Emerging Objects); EU Building 3D printed facade (©Ossip van Duivenbode)

**Fig. 3** Subtractive manufacturing: cork facade (©GenCork and Sofalca); De Young Museum (©David Basulto via flickr); MaoHaus facade (©XiaZhi)

The third group, *formative*, uses mechanical forces to reshape or deform materials into the intended shape [93], often resorting to heating to make the material adapt to the new geometry and then to cooling to keep the new geometry stable [89]. CNC folding, CNC bending, CNC punching, hydro morphing, and welding are some examples [91]. In architecture, these techniques have been mostly applied in the manufacturing of (1) unconventional metal panels [92], such as those of the *Experience Music Project* in Seattle (Fig. 4 left), and (2) heat-slumped or heat-bended glass facade elements [100], such as those of the *Holt Renfrew flagship store* in Vancouver

**Fig. 4** Formative manufacturing: Experience Music Project (©Jon Stockton/CC BY-SA 3.0); Holt Renfrew flagship store in Vancouver (©Marc Simmons/FrontInc); Elbphilharmonie Hamburg (©Bahman Engheta/CC BY-SA 4.0)

(Fig. 4 middle) and the *Elbphilharmonie* in Hamburg (Fig. 4 right), respectively. Nevertheless, given the still expensive price of both the machines and materials used by these methods [91], their use remains limited in the field.

The next group, *cutting*, involves the extraction of two-dimensional planar elements from surfaces or solids by using strategies like contouring, triangulation, and unfolding, among others [91]. These processes follow a set of instructions provided by the digital model to produce flat components with the desired shape [93], often resorting to laser-beam, plasma-arc, and waterjet technologies. *Cutting* is a very popular strategy in the field, probably the most used one [89, 98], especially to produce complex facade panel patterns. Among its advantages are its geometric precision and both its reduced cost and production times. Among its limitations are the limited range of materials and thicknesses supported and the need to adapt the technology used accordingly [89, 98]. Examples of *cutting* applications include the ceiling of the *Trumpf Campus Gatehouse* in Stuttgart [101] and the facade panels of the *Megalithic Museum* in Mora, Portugal (Fig. 5 left examples).

The last group involves the use of *robotic* arms or drones to accurately place elements in layers by controlling their location and position. These methods make it possible to reduce or even remove the lack of accuracy typical of manual assembly processes, allowing a rigorous correspondence between the intended design and its final product [95]. Examples of *robotic* strategies include the brick facades of the *Chi She Gallery* and the *Winery Gantenbein* in Switzerland (Fig. 5 right examples).

**Fig. 5** Cutting and robotic manufacturing: House 77 by dIONISO LAB (©FG|SG Fotografia de Arquitetura); Megalithic Museum by CVDB Arquitetos (©Fernando Guerra|FG + SG); Chi She Gallery (©Su Shengliang); Winery Gantenbein (©Christoph Kadel via flickr)

## *5.2 Balancing Creativity and Feasibility*

Despite the currently available mass-production techniques to manufacture non-conventional elements at low cost, none of them is entirely suitable to deal with the geometric diversity of architectural design, which usually requires the manufacturing of hundreds or thousands of non-standard elements [92] that are often project-specific. To make the construction of free-form shapes and complex facade patterns possible, architects have been increasingly adopting *geometric optimization* techniques [102] in their design practice. These strategies allow architects to gain more insight and control over their designs [40], facilitating the latter's gradual adaptation until reaching the desired feasibility [13]. Popular examples of geometric optimization strategies for architectural design include *design rationalization* and *surface paneling*.

*Design rationalization* is an example of a *geometric optimization* strategy that focuses on subtly adjusting the building elements that are expensive to produce until meeting the established economic and construction requirements and without compromising the design's aesthetics [92, 103]. Based on the literature [13, 40, 104–106], design rationalization can vary in terms of temporal application in the design process, i.e., before, during, or after the design development process, and target of the rationalization process, i.e., the building elements to which it is applied, e.g., frames, facade panels, wall tiles, and shading devices. Figure 6 presents some architectural examples resulting from the application of rationalization strategies at different design stages.

*Panelization*, or *paneling*, is a geometric optimization strategy that focuses on dividing a large surface into smaller panels of constructable size and acceptable cost, while preserving the design intent [92, 106, 107]. This strategy involves two dependent tasks: the segmentation of the original shape into smaller pieces and the approximation of each smaller piece to a shape that can be manufactured at a reasonable cost.

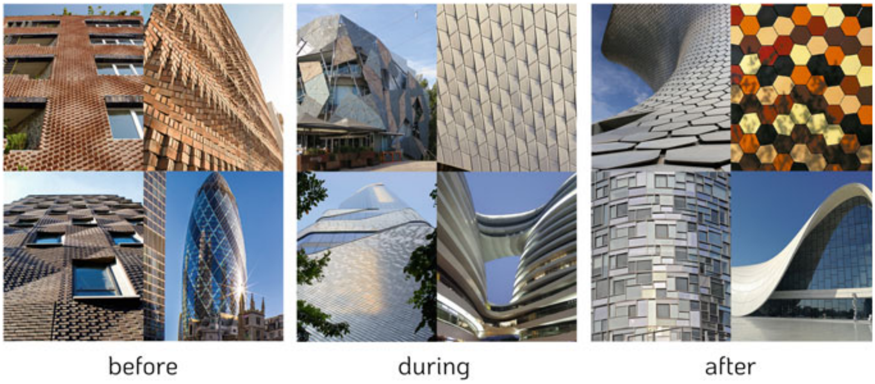


**Fig. 6** Architectural rationalization (from top-left to bottom-right): DIY For Architects (©Sstudiomm); South Asian Human Rights Documentation Centre (©AnagramArchitects); Federation Square by LAB architecture studio (©authors); MAAT (©Hufton + Crow/AL_A); Museo Soumaya by FR-EE/Fernando Romero Enterprise (©naturemyhome via Needpix); Spanish Pavilion 2005 (©Edmund Sumner); 290 Mulberry Street by SHoP Architects (©Amy Barkow); 30 St Mary Axe by Foster + Partners (©Suhail Akhtar via flickr[1]); Bangkok Central Embassy (©Hufton + Crow/AL_A); Galaxy SOHO by Zaha Hadid Architects (©authors); 100 11th Avenue by Ateliers Jean Nouvel—delivery architect: Beyer Blinder Belle Architects (©Philippe Ruault); Heydar Aliyev Center by Zaha Hadid Architects (©Aleksandr Zykov via flickr)

Dividing a surface into smaller planar surfaces of different polygonal shapes, like triangular, quadrilateral, and hexagonal, is the cheapest paneling strategy. Another strategy involves the division of the original surface into smoothly bent stripes, also known as single-curved panels or developable surfaces, that can be produced by simply bending a flat piece of metal sheet; a technique that has been showing gradual improvements over time [106]. Another paneling strategy focuses on dividing the surface into double-curved perfectly fitting panels, resulting in smooth curved surfaces with a high finishing quality. Among the three, the last strategy is the most precise but also the most expensive as it often requires the production of several customized molds [107]. Figure 7 presents some examples of paneling strategies organized by type.

Despite the variety of existing technologies and architectural examples, the production of large-scale free-form facades with either unconventional or intricate geometric patterns remains a challenging, and often expensive, task [107–110]. Moreover, the existing literature and practical examples mostly focus on simple patterning techniques, i.e., triangular, quadrangular, and hexagonal panels, rarely considering other shapes or geometric patterns.

To make the digitally produced design solutions feasible, several tools were released to facilitate the manufacturing and assembly of shapes with higher levels of design complexity. These include, among others, the Grasshopper's plugins HAL, FabTools, BowerBird, OpenNest, Kuka|PRC, Xylinus, Droid, RoboDK, Robot

[1] https://www.flickr.com/photos/192540662@N04/.

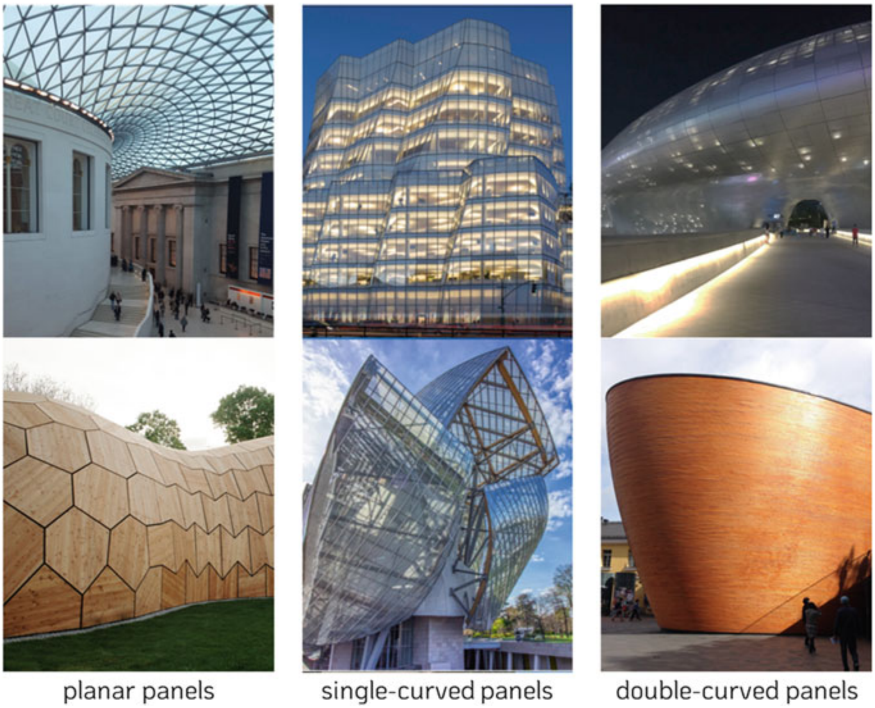


**Fig. 7** Paneling strategies (from top-left to bottom right): British Museum Great Court (©authors); IAC building (©Peter Miller via flickr); Dongdaemun Design Plaza (©authors); Landesgartenschau Exhibition Hall (©ICD/ITKE/IIGS University Stuttgart); Foundation Louis Vuitton (©BarrieT via flickr); Kamppi Chapel (©authors)

Components, Robots, Bark beetle, and Ivy; Dynamo's addons DynaFabrication, Fabrication API, 3BMLabs.DigiFab, and ParametricMonkey; and Blender's addon Laser Slicer. However, as these plugins only target the visual programming paradigm, the manufacturing of more complex solutions is often difficult [45, 48, 49, 51, 55–57]. Moreover, these plugins are mostly tool-specific, requiring the use of tools to assess different construction schemes. Additionally, they do not entirely automate the design-to-fabrication conversion nor the extraction of technical documentation, since they often depend on manual- or script-based interventions that are laborious, time-consuming, and error prone. Given the uniqueness of architectural design problems, these interventions can hardly be reused in different projects without major modifications, thus hindering the testing of different manufacturing possibilities to assess their aesthetic and environmental impact.

## 6 The Mathematics of Facades

AD has the potential to improve AEC's ecological footprint. However, it has also a higher level of complexity and abstraction that hampers its widespread use. To motivate the adoption of AD, it is critical to provide strategies systematizing and structuring the algorithmic generation of design solutions in an architectural-oriented way. We address this by proposing a mathematics-based methodology and framework to support the algorithmic development of building facades from conceptual to later design stages. The proposed solution considers the wide variety of design briefs as well as different aesthetic intents, performance requirements, and fabrication strategies. Its use promises to decrease the time and effort spent with the algorithmic implementation of new facade designs, while providing the flexibility needed to handle the design complexity and variability of facade design processes.

With this proposal we aim to promote informed design practices aligned with the need to reduce the environmental footprint of the AEC sector. By facilitating design experimentation and the coordination of different types of data and requirements, we expect architects to evaluate wider design spaces within an acceptable time and effort, increasing the chances of achieving more sustainable solutions in terms of energy consumption, environmental impact, waste production, etc. We also aim to increase the control over design-to-manufacturing processes, reducing the gap between what can be digitally explored through AD and its subsequent manufacturing. Lastly, by democratizing design exploration and manufacturing in an AD workflow entirely driven by architects, we also expect to increase the accuracy and quality of the produced solutions, as well as the perception of how different design strategies and DF technologies can lead to more sustainable design outcomes.

### *6.1 Structuring a Design Theory*

To successfully handle the variability and context-specificity of architectural design through AD, we must address the practice's challenges through a computational perspective. Considering that computational tools operate by following a set of instructions, described through programming languages that are increasingly imitating the universally understood language of mathematics, we propose using the latter formalism to (1) structure the AD methodology, (2) define the different AD strategies, and (3) implement both (1) and (2) in an AD framework targeting facade design processes.

During this process, it is important to ensure the resulting methodology supports the *variability* of architectural practice, the *uniqueness* of design briefs, and the *diversity* of existing design requirements in a coherent and flexible way. Clearly, covering all possible design scenarios would be an impossible task. Nevertheless, we believe that by providing the solutions that more frequently occur, or whose application is more generic, we can not only reduce the initial investment required

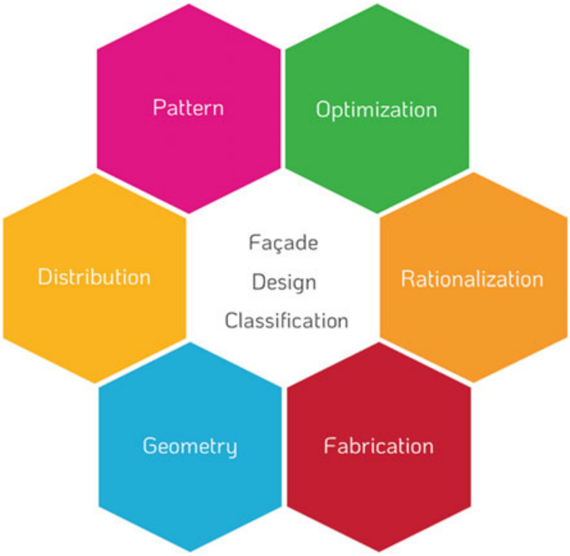


**Fig. 8** Algorithmic-based classification of facade design strategies according to their role in the design process

by AD, but also embrace a large range of design scenarios and problems. Moreover, by benefiting from these strategies since early design stages, we expect architects to spend much less time and effort with programming and debugging tasks, sparing them from having to write all the algorithms from scratch each time they start a new project.

Based on a previous analysis of a wide range of contemporary building facades and different facade-oriented classifications [111–115], the proposed methodology and framework is organized in a six-fold structure containing different types of facade design strategies, whose categorization follows an algorithmic perspective (Fig. 8):

1. Geometry: to shape the building facade.
2. Distribution: to differently distribute the facade elements.
3. Pattern: to geometrically manipulate the facade elements.
4. Optimization: to adapt the facade design according to one or more fitness criteria.
5. Rationalization: to control the facade design's feasibility.
6. Fabrication: to prepare the facade design for manufacturing.

By using this categorization, the architect is guided towards the most suitable algorithms in terms of design intent, performance requirements, available resources, and construction means. Not only does this resolve many of the limitations found when using AD, particularly those related with the programming task, but it also facilitates the architects' response to the context-specificity and variability of design processes. The idea to use generic solutions to recurrent design problems draws inspiration from previous works [47, 116–121], which focused on providing sets of predefined reusable algorithms to reduce AD's initial investment. Nevertheless, our solution has the novelty of (1) focusing on the textual programming paradigm, benefiting from its scalability and expressiveness; and (2) going beyond initial design stages, integrating relevant design strategies and specialized tools beyond those of geometric exploration processes, such as analysis, optimization, and fabrication. Some of the predefined AD strategies are illustrated in Fig. 9, their mathematical structure and implementation being further elaborated in [122].

Given the diversity and uniqueness of most facade design requirements, it is not reasonable to expect that this matching process yields a complete algorithmic solution. Our proposal therefore assumes the architect as the one responsible for (1) dividing the whole design into parts, (2) establishing the dependencies between them, (3) instantiating and combining the different strategies dealing with each part, (4) implementing additional algorithms when needed, and (5) evaluating the results. Even so, we believe our proposal will increase the architects' design freedom, while improving the design process precision and ability to adapt to different design briefs. Additionally, by smoothing the design-to-fabrication transition, we expect

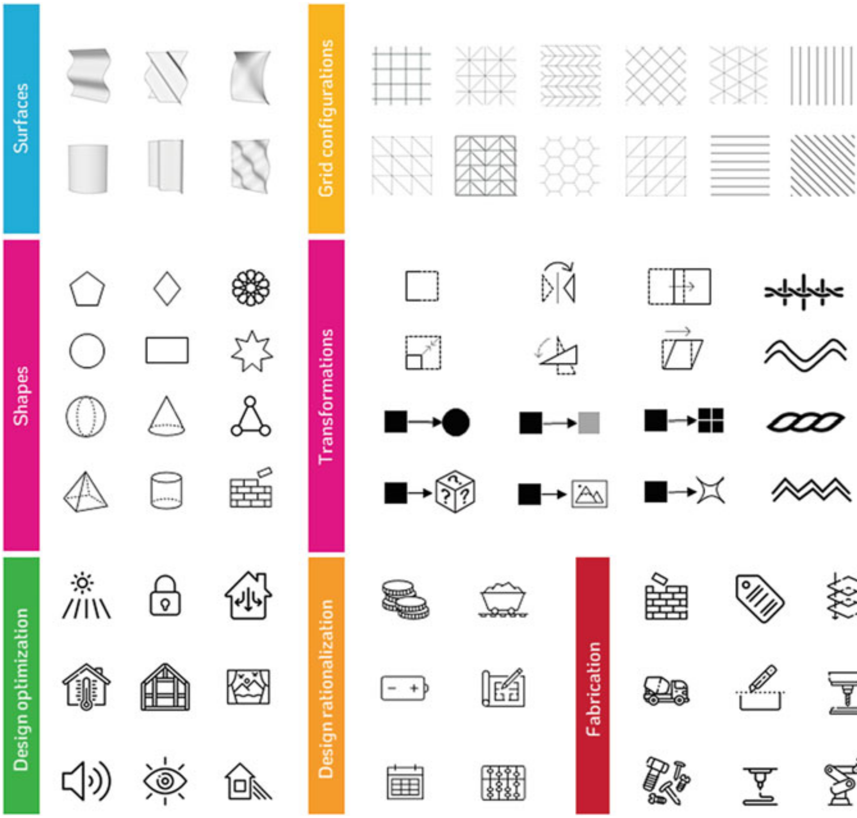


**Fig. 9** AD framework conceptual representation: some of the implemented facade design strategies organized by category

our solution to improve the coordination between the geometry-, performance-, and fabrication-related information, and thus support more informed design processes towards environmentally aware solutions.

## 6.2 Conscientiously Driven Design Workflows

As mentioned in the beginning of this section, the goal of this research is to simplify the use of AD. To that end, a methodology and framework are proposed, focusing on the field of facade design. To evaluate the proposal's suitability for architectural practice and its ability to support more conscientious design processes, we applied the framework in the development of a set of case studies in collaboration with practice-based architectural design studios without AD skills. Figure 10 presents an overview of the resulting AD workflows by establishing a correlation between the different design stages and the algorithmic strategies used in each one. Further details on the selected case studies and their results can be found in [123–126].


**Fig. 10** Case studies' AD workflow: the design stages encompassed (top) and the algorithmic categories used in each one identified with different colors (below)

The analysis of the previous results shows the ubiquity of the different algorithmic categories in the studios' design process, continuously supporting the architects' different design tasks, while actively coordinating the multiple types of data and tools involved.

Regarding the first example, the aim was to develop a set of facade shading panels made of horizontal wood elements whose size and position addressed different daylight/shading requirements and privacy levels. In the first stage (Geometric exploration), the design studio implemented the design intent and explored different variations of it by benefiting from different geometry-related algorithms (Fig. 11, blue, yellow, and pink lines), as well as performance and rationalization ones (Fig. 11, green and orange lines, respectively). While the first algorithms allowed the architects to set geometric constraints and dependencies between them according to their design intent, i.e., creating wood bars of alternating sizes, with the smaller bars randomly varying their length and position; the second algorithms allowed them to iteratively adjust the parameters and dependencies of the geometry-related algorithms, either increasing or decreasing the smaller bars' length and in-between distances according to the existing daylight/shading and privacy requirements. Finally, the rationalization algorithms enabled the architects to gradually decrease the design's geometric freedom to ensure the solution fit the budget, restricting the range of possible sizes for the small bars.

As it is visible in Fig. 11, a similar scenario occurred in the following design stages (Design analysis and optimization), since both processes were guided by

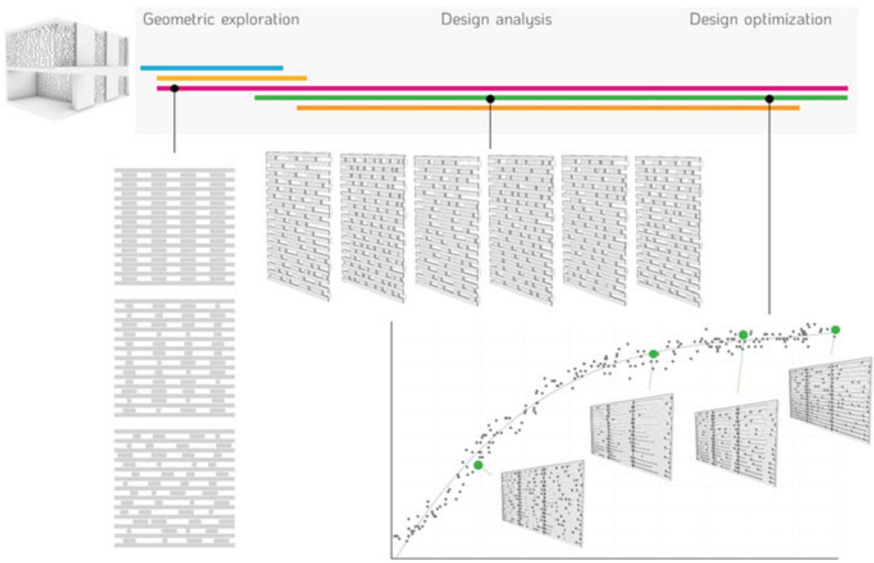


**Fig. 11** Design workflow of a set of facade shading panels with some key moments of its AD process (from left to right): design intent implementation, environmentally driven geometric variation, and design optimization

performance requirements and analysis results (green line) as well as aesthetic and cost considerations (pink and orange lines). The result was a set of design solutions that comply with the architects' creative intent and the existing cost, shading, and privacy requirements, from which the architects could then select the one that most pleased them.

In the second example the aim was to develop a set of building facades entirely made of *cobogó*-inspired elements of unique sizes and shapes, whose geometric characteristics created a complex, apparently random, visual effect and simultaneously adapted to the building inside functions. Like the previous case study, the first stage (Geometric exploration) benefited from geometry-related algorithms (the blue, yellow, and pink lines in Fig. 12) as well as performance and rationalization ones (the green and orange lines in the same figure).

The same can be said about the second stage (Design analysis), which benefited from the same categories of algorithms to iteratively adjust the design's geometric characteristics according to the existing daylight, privacy, and natural ventilation needs. The result was a set of *cobogó*-inspired elements of different opacities, whose random spatial distribution met the performance needs of each adjacent area (Fig. 12, Design analysis).

Regarding the Design optimization stage, it focused on minimizing the solution's fabrication costs (Fig. 12, orange line), reducing the variety of facade elements without compromising the design intent and the existing performance requirements (Fig. 12, pink and green lines). This concern was carried over to the ensuing design stage (Fabrication) and coordinated with the available resources and manufacturing means (Fig. 12, red line).

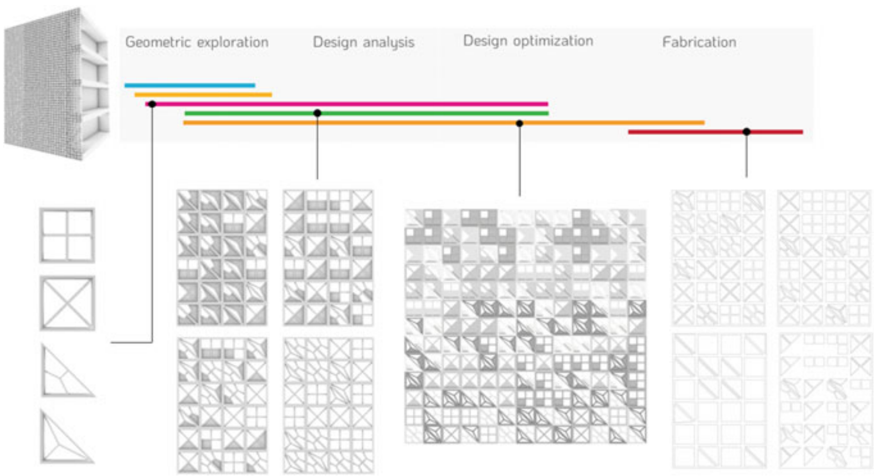


**Fig. 12** Design workflow of a set of *cobogó*-inspired facade panels with some key moments of its AD process (from left to right): *cobogó* elements geometric exploration, aesthetic- and performance-based design variations of the facade panels, control of manufacturing costs, and automatic extraction of technical drawings for fabrication

Regarding the third case study, the aim was to create a visually dynamic brick facade responding to different privacy and daylight requirements. As in the previous examples, all design stages (exploration, analysis, and optimization) resulted from a coordination between aesthetic intents, performance requirements, and economic constraints. As illustrated in Fig. 13, in the first stage (Geometric exploration), the architects used different categories of algorithms to implement their design intent, namely (1) geometry-related algorithms (blue, yellow, and pink lines) to generate a facade pattern made of differently sized and randomly distributed and protruded bricks creating punctual voids, and (2) cost-related algorithms to reduce the design geometric freedom, restricting the range of possible brick sizes and protrusion positions. In the second stage (Design analysis), the architects added some performance algorithms to the previous combination to test different design variations with varying levels of permeability and ratios between brick sizes and protrusion positions. In the third stage (Design optimization), the architects used the available rationalization algorithms to control the range of configurations allowed, reducing the solution's manufacturing costs and waste. In the last stage (Fabrication), the architects took advantage of the existing manufacturing-related algorithms (Fig. 13, red line) to detail the solution as well as to extract information about the quantities and position of the existing brick typologies.

Regarding the last example, the architects adopted the workflow of Fig. 14, where the different geometry-, performance-, and fabrication-related algorithms all contributed to the design development of a set of unconventional facade panels, from conceptual exploration to manufacturing preparation. In this case study, the aim was to produce a facade design prototype made of different metal panels, whose varying shapes created a visually complex and irregular surface stereotomy and whose different levels of permeability responded to the existing performance requirements.

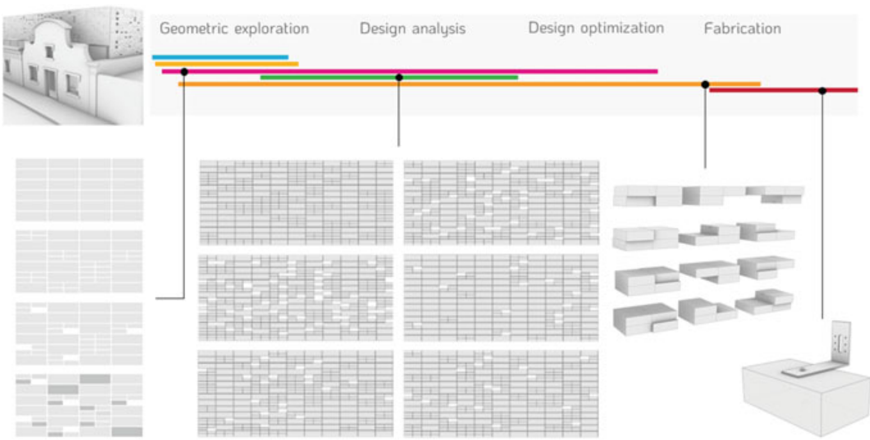


**Fig. 13** Design workflow of a brick facade pattern with some key moments of its AD process (from left to right): pattern geometric evolution, aesthetic- and performance-based design exploration, design rationalization, and design detailing

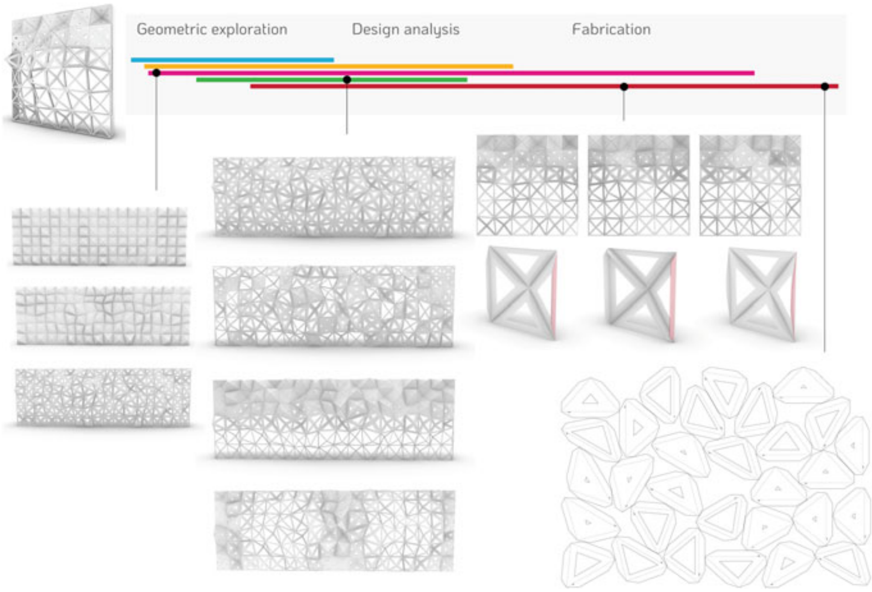


**Fig. 14** Design workflow of a facade design prototype with some key moments of its AD process (from left to right): design intent implementation, aesthetic- and performance-based design exploration, design detailing, and manufacturing documentation

As illustrated in Fig. 14, the workflow started with the implementation of the design intent, which benefited from geometry-related functionalities, and proceeded with the panels' geometric exploration, coordinating the previous algorithms with performance-related ones. The result was a set of facade panels with the desired geometric irregularity and volumetry and simultaneously presenting different levels of permeability that met the existing shading and privacy needs. The process continued with the integration of additional manufacturing-related strategies, allowing the architects to (1) segment the facade design into smaller parts to facilitate the subsequent assembly and transportation processes; (2) create connection details between the panels, and between the panels and the facade structure; and (3) automatically produce technical drawings for manufacturing (in this case, laser cutting), while benefitting from labeling and nesting strategies to reduce both material waste and assembly complexity.

As it is visible in Fig. 14, the architects also benefited from the available fabrication strategies during the geometric exploration of this case study. By coordinating the design intent with manufacturing constraints, the architects could extend their creative process, not only increasing the range of construction schemes considered, but also gaining a better insight on the impact of each manufacturing scenario on the solution's aesthetic quality.

## 7 Discussion and Final Considerations

Buildings are one of the main contributors to the greenhouse effect, which explains the growing concern about reducing their environmental footprint. Given the great influence facades have on the environmental performance of buildings, their design has been increasingly integrating performance requirements in addition to the traditional aesthetic and functional constraints. Recent computational design strategies, such as Algorithmic Design (AD), have lowered the barriers to the adoption of performance-based design strategies, but their use remains shy in the field mostly because of their technical complexity and level of abstraction.

Nevertheless, to meet the 2030 Agenda's and Industry 4.0 goals of creating more sustainable built environments, architects must adopt AD strategies. To help such adoption, we propose reducing the complexity of AD approaches by structuring a methodology and framework containing different algorithmic strategies that can be easily combined in the development of new design solutions. Given the environmental relevance of building facades, the proposal focuses on this building element, encompassing not only its different design stages and requirements but also the variability and diversity of architectural design problems. The aim is to support AD workflows that coordinate aesthetic, performance, and construction requirements in a flexible and responsive way since early design stages, promoting the search for more sustainable solutions.

### *7.1 Design Workflow*

To evaluate the proposal, we applied the framework in a set of case studies developed collaboratively by architects with and without AD skills. Multiple design scenarios were considered, and various design requirements addressed. Based on the results, we conclude that the use of the AD framework improved:

1. The design freedom—given the ease with which architects could select and combine different algorithmic strategies and apply iterative design changes, multiple design variations were tested in all case studies, and a wide range of design scenarios was considered.
2. The coordination between different requirements since early design stages—given the solutions' algorithmic nature and parametricity, the architects could easily apply performance-and manufacturing-related principles to drive geometric exploration processes and the other way round, i.e., using geometry-related principles to guide design optimization and fabrication.
3. The architects' decision-making processes—the design freedom combined with the flexible integration of different types of data provided architects with more insight on the quality of the solutions as well as on the impact of design changes.

4. The design space explored—because of the greater design freedom and coordination between different requirements, architects could devote more time to creative exploration, increasing the range of solutions considered.
5. The quality of the solutions achieved—as the architects' decisions were more informed, they could more easily guide the design development process towards better solutions.
6. The control over design-to-manufacture—the ability to automatically extract technical documentation for manufacturing, combined with the flexibility to test multiple design variations, allowed architects to consider multiple construction scenarios, while assessing the impact each one had on the solution's aesthetic and sustainability.

Despite not considering all possible design scenarios, our proposal was successful in responding to the most common design problems, while adapting to more specific circumstances when needed. In these cases, the developed extensions were then incorporated into the AD framework, becoming available for future use. The possibility to incrementally extend the framework with the results of its practical application is intentional, allowing us to not only increase the range of predefined strategies available, but also refine and adapt the existing ones to real case requirements and constraints.

## *7.2 Meeting Sustainable Development Goals*

Despite the simplicity of the presented case studies, they demonstrate the potential of the proposed methodology and framework to support AD workflows and promote more informed design processes towards more sustainable facade design solutions. As the integration and coordination of different performance requirements is facilitated, architects are left with more time to explore the design space and consider other solutions beyond those initially imagined. This in turn allows architects to gain more control over the design development process, increasing the chances of achieving more sustainable solutions that meet the 2030 SDGs Agenda of making the built environment sustainable in terms of production and consumption [5].

This ability is visible in the first case study, when the architects combined performance analysis results with their aesthetic preferences, ensuring the obtained solutions complied with both the design intent and the performance requirements. Besides guiding the design space navigation towards the architects' preferences, the proposed solution facilitated the analysis of the trade-offs between aesthetic and performance requirements.

The case studies also proved the ability of the proposal to facilitate the concretization of less conventional design solutions, while increasing their production efficiency and sustainability by minimizing both energy consumption and waste. This was demonstrated by the second and third case studies, where the architects gradually reduced the cost and material waste resulting from the solutions' manufacturing without compromising the design intent and performance requirements.

To sum up, we conclude that the proposed AD methodology and framework allowed architects to approximate their creative thinking with the design making, a critical step towards the Industry 4.0 and its goal for sustainable industrialization and production.

**Acknowledgements** This work was supported by national funds through *Fundação para a Ciência e a Tecnologia* (FCT) (references UIDB/50021/2020, PTDC/ART-DAQ/31061/2017) and the PhD grant under contract of FCT (SFRH/BD/128628/2017).

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# Volatile Data: Strategies to Leverage Datasets into Design Applications

**Edoardo Tibuzzi and Georgios Adamopoulos**

**Abstract** As the AEC industry is approaching a stage of maturity in the digital transformation journey, AKT II's p.art team has been pioneering it since its inception over 25 years ago. Data as an underlying driver of design, informing decisions earlier on and addressing issues from the macro scale of social impact to the micro scale of structural, environmental, and sustainable optimization has been the principal focus of this practice driven research team. Below 3 main examples are chosen to describe how tapping into intangible knowledge hidden in internal or external datasets, helped exploiting it into targets, processes and design solutions. The intention is to critique the current availability of datasets, how to understand and avoid data bias, and finally the hurdles to overcome into getting from raw data to implemented design drivers. Those pioneering exercises are exploring the novel opportunities provided by the hybridization of processes and cross disciplinary datasets, to enhance the built environment and to learn from the more granular availability of relevant data. In an effort to provide support to the architectural industry, the examples covered below are showcasing how technology can be leveraged to expedite the achievement of some of the Sustainable development goals set by the U.N., specifically in "Part 1", we will demonstrate how accessing an existing dataset and using state of the art software visualization techniques is supporting the team in highlighting issues and potential mitigations of goals 11 (sustainable cities and communities), 13 (climate action), 14 (life below water) and 15 (life on land). "Part 2" is showcasing the opportunity on one side to make existing datasets available to the public through a mobile app, and on the other end, to use the same app to gather specific user data. In "Part 3" we will demonstrate how novel design techniques helped us design a waterless garden in the desertic climate of Sharjah, proving that using an inter-disciplinary approach, mixing architectural design, building physics knowledge, computational fluid dynamics simulation and parametric modelling, helped the team predicting the best geometric output for the garden landscaping that provided a recreation of

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_38

a natural environment to facilitate indigenous plants growth, effectively targeting U.N. goals 2 (zero hunger), 3 (good health and wellbeing), 7 (affordable and clean energy), 11 (sustainable cities and communities), 12 (responsible consumption and production), 13 (climate action) and 15 (life on land).

**Keywords** Data driven design · Bioclimatic design · Computational fluid dynamics · GPU accelerated data visualization · Data farming · AR · VR

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 13. Take urgent action to combat climate change and its impacts

## 1 Part 1: Geoscope 2 at the 2021 Venice Biennale

Starting from a macro scale in 2021 we have been involved in the "Geoscope 2".

The architects Daniel Lopez-Perez and Jesse Reiser (Principal of RUR architecture) have together re-thought R. Buckminster Fuller's iconic Geoscope concept for the 2021 Venice architecture biennale "How we live together".

The installation featured a dynamic video animation which has been designed and produced by AKT II's computational team.

The video was conceived to newly visualise the proliferation of atmospheric carbon, globally, that's occurred so far during our 21st century. The video is based on satellite data that's freely available online. Yet for many visitors, this has been a first experience of truly seeing the formerly intangible $CO_2$ catastrophe. The climate crisis is a shared problem, and to solve it we need a shared understanding (Fig. 1).

### *1.1 Visualizing 20 years of Daily Global $CO_2$ Data in Real-Time 3D*

To produce this film, we designed and programmed in the Unity game engine a real-time particle simulation of global $CO_2$ emissions for the period 2000–2018 using publicly available data.

The narrative device we employed was that of a globe surrounded by violently shifting gases traversing borders, continents, and hemispheres. The main point, delivered implicitly, was those acts of any single country, eventually become the problem of everyone, as nothing ever stays local in the stratosphere.

During the film, millions of luminous particles flow rapidly around a three-dimension model of the Earth, following historical wind velocities. The particles'

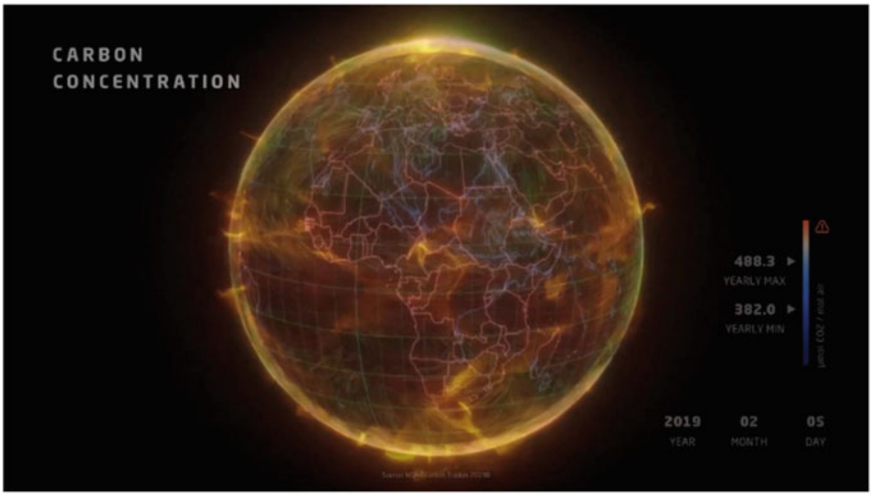


**Fig. 1** Carbon concentration dataset visualised on the terrestrial globe

colour and transparency are mapped to historical $CO_2$ concentrations sampled at each particle's position.

The colorization range remains fixed throughout the animation period. The result is, sadly, striking A globe that appears mostly dark and blue during the first years of the millennium, with a few dissipating plums of $CO_2$ produced by the developed nations of the north hemisphere, turns into a bright red hellscape towards the end of our decade, trapped underneath a turbulent veil of $CO_2$ levels that remain constantly high everywhere (Fig. 2).

## *1.2 Visualization Philosophy*

We deliberately attempted the shift from a static, data-science-oriented presentation style, to a dynamic, artistic interpretation using techniques and tools borrowed from the visual effects and gaming industries.

In most, if not all, presentations of climate-related datasets, a common visualization strategy is employed: The data are presented on a globe or some form of rectangular projection, using a colormap to colorize and accentuate the underlying values.

The narrative in that case, is a presentational one: the truth is laid to the observer as is, with a colour legend being a crucial, indispensable feature. The qualitative evaluation of how "good" or "bad" the situation presented is, is left to the observer's ability to associate the presented values with their physical, real-world meaning. In other words, the people able to decipher the meaning of the data, are the ones that are already familiar with the science behind.

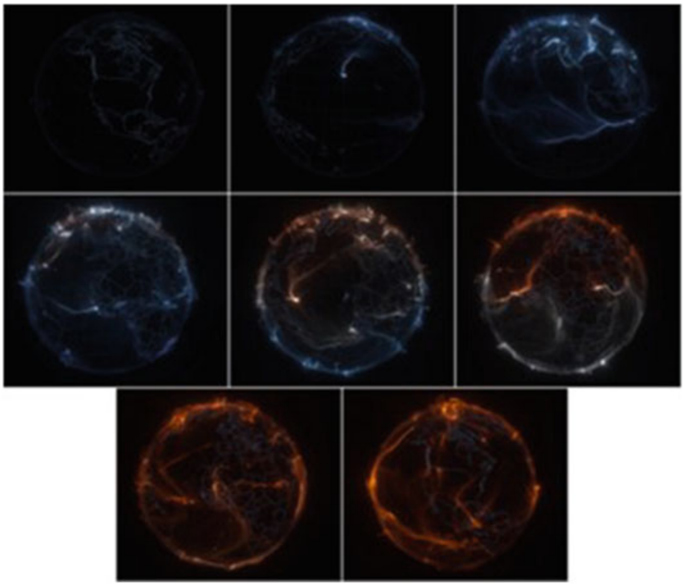

**Fig. 2** Frames from the game-engine, showing the carbon concentrations at various years. From top to bottom, left to right: 2000, 2001, 2002, 2005, 2008, 2010, 2014, 2017

In our case, we moved towards a dramatized interpretation of the data, that prioritizes the visual impact and the viewer's emotional response, while staying faithful to the underlying values.

The understanding of the data in this case is a perceptual one. Simply put, one does not need to have prior knowledge of the data or even climate change itself, to perceive how radically the situation has changed in the last 20 years, and how a relatively local problem has engulfed the whole planet.

A legend with numbers and colours in this case is unnecessary, because the perception of the direness of the situation is direct, present in the emotional response of the viewer to the visuals. One does not need to know "how much", because they simply see it.

### *1.3 Motivation*

Our motivation for this work was the deep belief that important data, like global $CO_2$ emissions, must be presented in ways that maximize their impact in people unfamiliar with the scientific field that produced them. One should not need to develop a sold grasp of climate science to form an educated opinion about climate, or to be convinced about the criticality of our current situation. Projections of future $CO_2$ levels in the atmosphere and the associated climate forcing, as well as our ability to control $CO_2$

levels, depend substantially on our scientific understanding of the natural carbon cycle [3]. As an example, in 2003, growing vegetation in North America removed approximately 500 million tons of carbon per year (± 50%) from the atmosphere and stored it as plant material and soil organic matter [4].

In other words, the natural and inevitable knowledge difference between experts and no-experts, must not stand obstacle in the process of forming a common ground about important, urgent, global issues, such as climate crisis, global pandemics, or world warfare. Knowing how the structure and function of arctic terrestrial ecosystems are responding to recent and persistent climate change is paramount to understanding the future state of the Earth system and how humans will need to adapt [5].

We strongly believe that visual storytelling can form bridges across knowledge fields and transform scientific data into real-world impact. This project was an opportunity to put this belief to the test.

### *1.4 Datasets*

Although there's a wealth of real-world carbon observatories, such as NASA's OCO-2 (Orbiting Carbon Observatory-2), the datasets they typical produce are sparse and point-like, unable to cover the entirety of the globe. For the purposes of our simulation, we required dense, texture-like datasets with 100% coverage of the Earth. We therefore turned to the U.S. NOAA's (National Oceanic and Atmospheric Administration) Global Monitoring Laboratory, and their Carbon Tracker tool, a $CO_2$ measurement and modelling system developed to keep track of sources and sinks of carbon dioxide around the world.

Carbon Tracker uses atmospheric $CO_2$ observations from a host of collaborators and simulated atmospheric transport to estimate these surface fluxes of $CO_2$ [1].

The "co2_total" dataset we chose, sums all available $CO_2$ components (background, land biosphere excluding fires, fossil fuel, wildfire, and air-sea exchange fields) in a global $3 \times 2$-degree grid. The dataset contained 7017 daily files in netCDF format, covering the period from 2000 to 2018, and totalling at 554.8 Giga Bytes.

Each file contained 3-hourly data for the day of the year it represented. The data were volumetrically structured, shaped in a grid 120 voxels in longitude, 90 voxels in latitude and 25 voxels in elevation, following the atmospheric levels of the TM5 (Transport Model 5) model, ranging from 0 to 80 km from the surface of the Earth [2].

Out of the 25 atmospheric levels available, we chose to use and animate only level 1 (elevations up to 34.5 m) due to its immediate relevance to the ground level air-quality where most of human activity takes place. The temporal resolution of 3 h was far too detailed for our time-lapse animations, so the eight daily 3-h intervals were combined and averaged in singular daily files. Finally, from the data fields included in each file, the relevant ones in our case were the $CO_2$ mole fractions, and the U

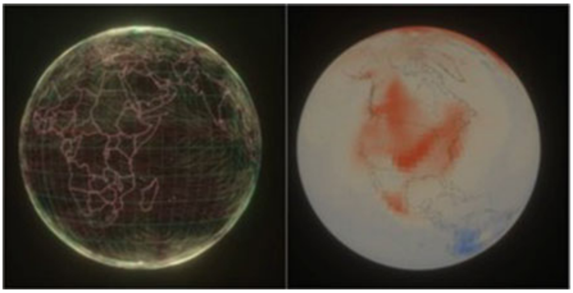

**Fig. 3** Wind velocity vector field (left) and $CO_2$ mole fractions (right) mapped to spherical coordinates

and V wind velocities for the real-time simulation of aerosol particle flows. All other fields were dropped from the dataset.

The above operations were performed using the open-source tool nco hosted in Ubuntu Linux.

## *1.5 Game Engine*

The particle simulation was programmed in the Unity game-engine. To make the original dataset compatible with the game-engine's native entities, an encoding process had to take place, to turn the cleaned-up netCDF files into GPU-friendly Texture objects (Fig. 3).

## *1.6 File Parsing*

The primary parsing of the files inside the Unity environment was done using Microsoft's Scientific Dataset Lite (SDSLite) C# library. The netCDF data was loaded in memory as standard C# arrays of double precision numbers, representing $CO_2$ mole fractions and wind vectors.

Data Encoding

One obvious and memory-efficient way to sequence the daily data slices, would be to encode the files as video frames, and then play-back the video into a Render Texture object. The limitation of this solution is that interpolation between frames is not possible during play-back, and thus undesirable "sleepiness" would be apparent as each frame would sharply snap to the next.

To smoothly transition through the daily data, we decided to encode the whole dataset into a Texture3D object, to take advantage of the game-engine's native ability to bilinearly interpolate in three dimensions. This way even slow animation speeds still produced pleasing transitions.

Unfortunately, a Texture3D resource has an upper bound in its resolution on any axis. Specifically, it cannot exceed 2048 × 2048 × 2048 voxels. Our data contained 7017 slices on the temporal (Z) axis, clearly impossible to fit in a single Texture3D. To address this, we split the data in multiple Texture3D objects. For logical clarity and simplicity, we decided to split the dataset by year, producing 18 volumes, with a resolution of 120 × 90 × 365 voxels each. At any time, a maximum of 2 volumes were loaded in video memory, in the transition of one year to another.

Particle Simulation

The actual particle simulation takes place entirely on the GPU, utilizing Unity's Visual Effect Graph.

Each particle moves around the globe using spherical coordinates, which are remapped into normalized texture space and used to sample the velocity and $CO_2$ field at the current temporal slice. In every frame, the sampled value of the 2D velocity field is remapped to spherical coordinates and used to push each particle to its future position. The sampled value of the $CO_2$ field is used to colorize the particle and adjust its alpha (transparency) value. The particles are colorized using a modified Kelvin range gradient, and rendered as single-pixel-wide lines, using additive blending.

## 2 Part 2: Beyond the Map, a Live Environmental and Social Data Visualizer for London

Another example on how we have demonstrated the potential of accessing, understanding visualizing and using data is the prototype augmented-reality service Beyond the Map (2019) In this speculation for the LFA, we have built an app that makes several, formerly intangible social, economic, and environmental qualities newly visible and accessible for the public. AKT II led the computational R & D—which leveraged existing data and bespoke analysis, to encompasses metrics such as air pollution, wind comfort, pedestrian safety, and property value—to make the information visible and user-rateable, through augmented reality, using a standard smartphone camera. The development focused on engaging with real world 'key activators', tapping into the GPS functionality of the mobile devices, to begin the experience at designated locations. Specific data sets then were illustrated through augmented reality displayed on the device screen, allowing space to reflect and experience intangible threshold that surrounded the user. The overall experience aimed to start a conversation on the role of data gathering and visualisation in today's society (Figs. 4 and 5).

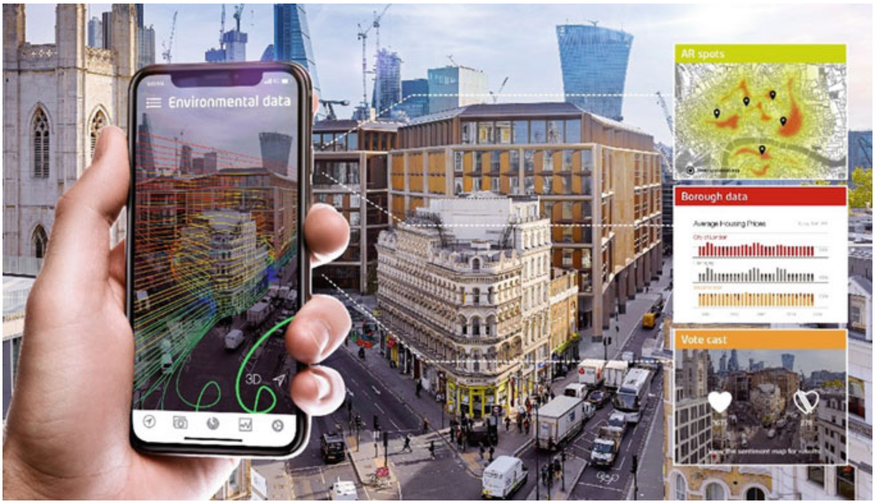


**Fig. 4** A diagrammatic visualization of beyond the map app

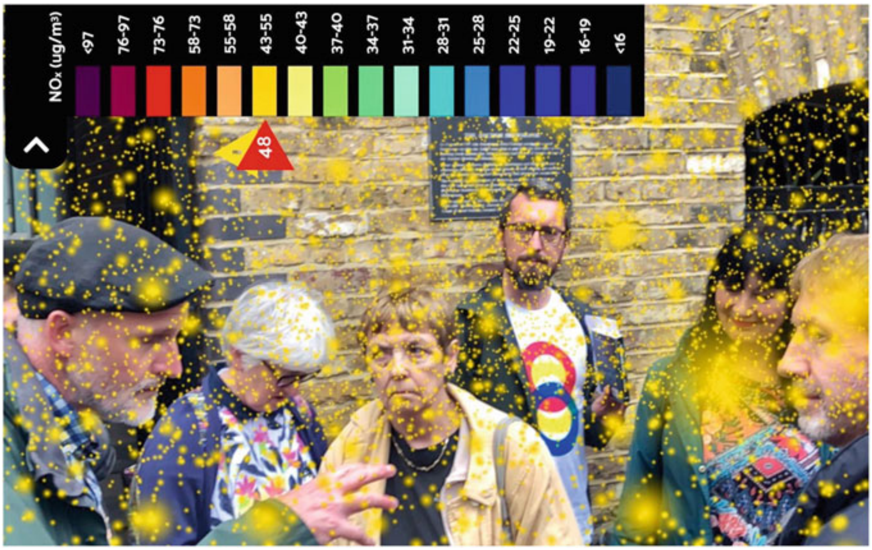


**Fig. 5** Real time pollution concentration visualized through the AR capability of the app

## 3 Part 3: Becoming Xerophile, an Experiment to Design with Data

Lastly, we reflected on the application and role of technology to create green spaces in an extreme environment. In support to Cooking Sections and as part of 2019 Sharjah Architecture triennial we developed a new model for a non-irrigated urban garden using Bioclimatic design tools and live sensors to design and monitor the performance of the gardens. As a prototype, this project extended past the initial Triennial and has been monitored to gauge success. We only used technology, in this case, the bioclimatic tools we normally use for master planning and envelope design, have been fundamental to define the geometry of the gardens and enhance the microclimate of the earth mound structures (Fig. 6).

From the Greek terms ‘xeros’ (meaning dry) and ‘philos’ (meaning loving) ‘Becoming Xerophile’ sets out to challenge the idea of the desert as a bare landscape and instead develop a new model for a non-irrigated urban garden. Nine earth mounds have been carved on the site of an old, disused school. These structures with various microclimates enable the desert plants to have the optimal environment they require to flourish. The ‘water without watering’ model is based on ancient techniques of cultivation. The earth mounds make use of the soil and rubble from the local school’s renovation and contain (between them) over 40 different species of desert plants.

With this region facing environmental challenges in which high temperatures and infrequent precipitation contribute to water scarcity, pilot projects that embed adaptive research into design such as Becoming Xerophile are urgent and extremely relevant.


**Fig. 6** Becoming Xerophile garden in Sharjah two years after construction

To design a series of optimal spaces in the harsh conditions of the city and promote the proliferation of vegetation we have used Computational fluid dynamics and a bespoke digital tool developed in-house to assess the optimal diameter and depth of the different "sand bowls" by running microclimate analysis on a series of different shapes and iterations. A full microclimate study was performed looking at the impact of wind and solar radiation over the proposed scheme by varying the defined geometries of the sand bowls and select the best performers.

The study investigated wind flow patterns in the garden as influenced by its layout and proposed plant shelter geometries. The analysis relied on probabilistic local weather data to calculate and visualize wind flow paths and velocities for 16 main incoming directions. The local weather was based on the Sharjah International Airport data measured roughly 15 km West of the site.

Urban location of the garden by a major road along the same direction can thus rendered it exposed to relatively strong wind flows incoming from the sea (North-West), potentially causing discomfort for garden users. The aim of the analysis was to assess impact of these flows on local conditions and the tempering effects of its proposed geometry.

A closer look over the garden area reveals that even in exposed conditions wind speed remains low in areas where the plants are based in deeper pits. In the largest pit with seating provision the conditions are shown to remain practically unchanged throughout (Fig. 7).

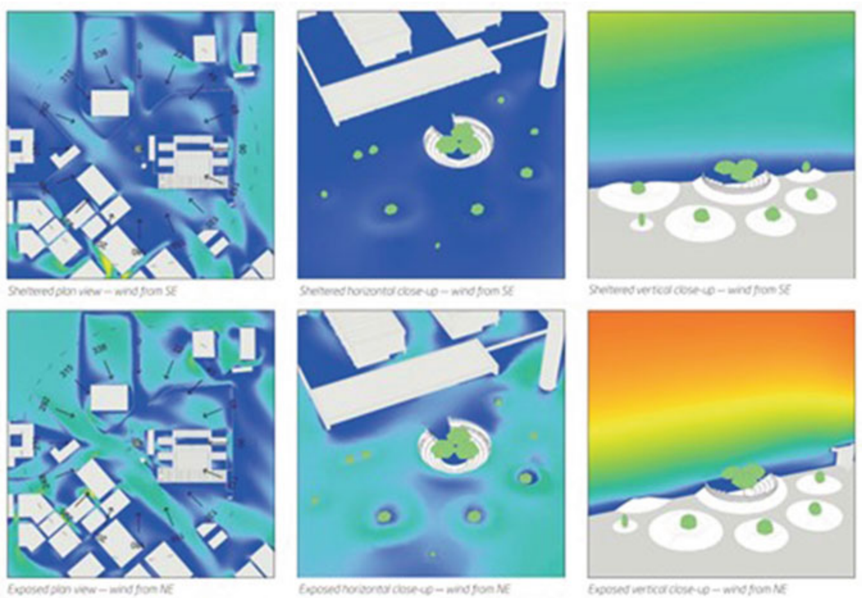


**Fig. 7** CFD wind simulation analysis of the different design proposals for the garden geometry

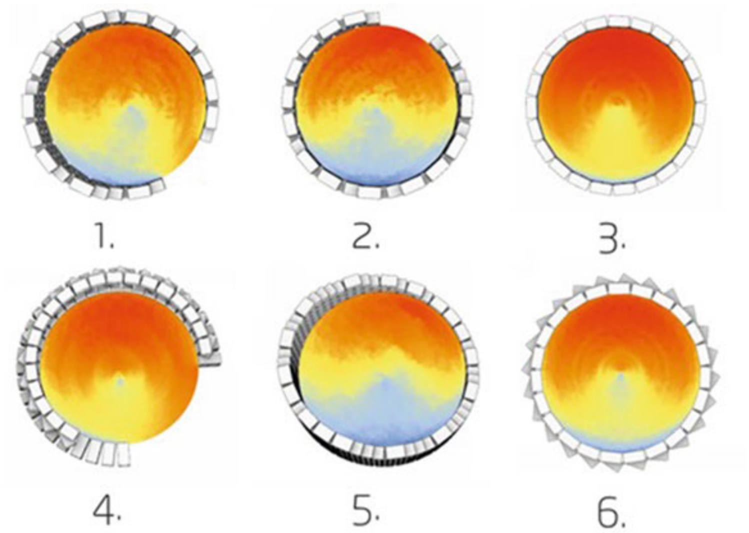


**Fig. 8** Radiation analysis of different brick typologies

Subsequently to the wind comfort a radiation analysis was performed on 6 brickwork bowl typologies.

For reference the bowls were numbered and colour coded as shown in Fig. 8.

Examined parameters included bowl orientation, cone depth and bowl diameter.

Incident radiation was tested for 360° range of bowl orientations. The results indicated that radiation within the bowl is minimized when the shading area that is oriented towards South-East is maximized. In other words, increasing wall area in SE direction has the greatest effect in creating shade within the bowl.

Changing bowl depth changed the side angle and thus the angle at which radiation hits the surface. Five cone depths were studied, downwards from the ground level in 0.5-m increments.

The analysis found that incident radiation per unit area reduces when bowl depth is increased.

Increasing bowl diameter increases incident radiation per unit area. This is due to the bowl slope angle approaching the ground plane, increasing the amount of radiation falling on unit area in the process.

The analysis was revised for the updated bowl designs. Annual, summer solstice and winter solstice analysis periods were considered.

During the summer solstice the baseline incident radiation per $m^2$ is roughly double that of the winter solstice and is the expected annual maximum radiation day. High sun angle in summer period will make shading with vertical walls relatively less effective than horizontal shading.

Growing foliage in the garden will block an increasing fraction of incident radiation from reaching the bowl surface. That fraction is dependent on crown geometry and density. For existing plants, crown density this is normally assessed using density cards. For future estimates it is best approximated on basis of existing examples growing in similar environmental conditions. Increased crown size and density reduce incident radiation on the ground below the plant.

Analysis results for each bowl in the garden are shown in Fig. 8, whilst a Comparison between annual radiation with and without foliage can be observed in the Fig. 9 (Fig. 10).

After the above study, the garden bowls were constructed and planted. The garden was also equipped with a suite of sensors that measure the small microclimates generated by the earth mound structures. The sensors measure rainfall, solar radiation, wind speed and direction, air temperature and relative humidity, soil moisture, and leaf wetness. Through their materiality, shading, depth, and positioning, the structures optimise both air humidity and moisture drawn from the water table. The condition of the plants inside and outside the earth mounds are monitored at fifteen-minute intervals, and data has been gathered for the next three years (Figs. 11 and 12).

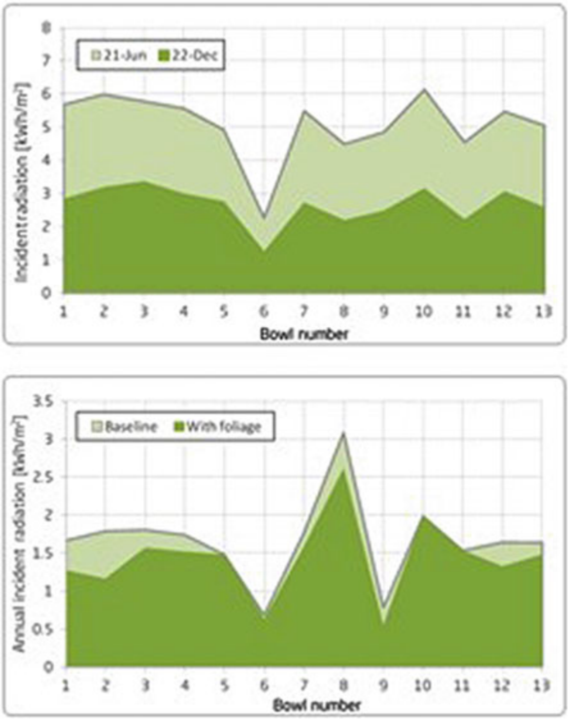


**Fig. 9** Annual incident radiation results for each bowl

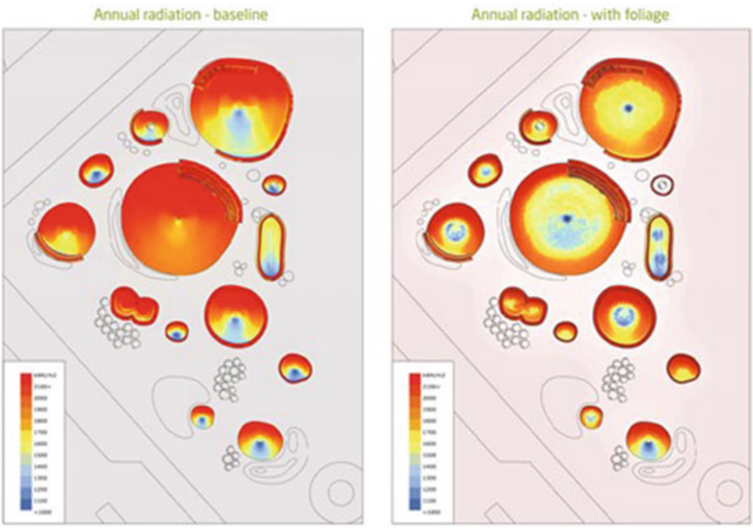


**Fig. 10** Comparison between annual incident radiation with and without foliage

**Fig. 11** Total station sensor installed at the center of the bowl

The intention of this chapter has been to focus and explore, with the help of delivered research project, how blending data farming and interpretation, with advanced computational skills under the design lead approach can help Architects, engineers, and Environmental designers to overcome the challenges our industry is currently facing.

**Fig. 12** Shot of the large central bowl during final phases of installation

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# Simulating Energy Renovation Towards Climate Neutrality. Digital Workflows and Tools for Life Cycle Assessment of Collective Housing in Portugal and Sweden

**Rafael Campamà Pizarro, Adrian Krężlik, and Ricardo Bernardo**

**Abstract** This chapter compares two digital workflows and tool selection for best practice renovation simulation in Portugal and Sweden. Both workflows are part of ongoing research projects that seek to provide a robust workflow adapted to different user needs and scale implementation. While in Portugal, the focus is on the building, the assessment is scaled up to the neighbourhood in Sweden. Geographic information systems datasets are used to streamline the modelling of buildings. The resulting models are used for the simulation and optimisation of renovation scenarios. These scenarios are evaluated as an equilibrium fit between user well-being (thermal and visual comfort), planet (entire carbon life cycle) and cost-effectiveness (energy and cost efficiency). The workflows presented are an example of computational architecture at work. Both workflows successfully interconnect different databases and disciplines to help the design teams and be a useful working tool for the different stakeholders in a renovation project. A complex context in which being flexible and transparent is necessary to make better and more informed decisions.

**Keywords** Renovation · Automation · Urban modelling · LCA · Digital workflows · Decarbonization · Performance-based decision-making

**United Nations' Sustainable Development Goals** 3. Ensure healthy lives and promote well-being for all at all ages · 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 13. Take urgent action to combat climate change and its impacts

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_39

# 1 Introduction

## *1.1 Background*

The urgent need to reduce carbon emissions and mitigate climate change has put the spotlight on buildings and the construction sector, which is responsible for nearly 40% of global greenhouse gas emissions. The European Union (EU) has committed to becoming the first climate-neutral continent by 2050, with Sweden aiming to achieve this goal by 2045. Despite this, around 75% of buildings in the EU are not energy efficient [1], and deep energy renovations remain rare, with an annual rate of only 0.2% in the EU28 [2, 3]. However, energy-efficient renovations and on-site renewable energy production are critical to achieving decarbonisation goals, and scaling up these efforts to entire neighborhoods can have an even more significant impact [1, 4, 5]. Fortunately, digital tools and databases have become accessible to practitioners in the last decade, providing new opportunities to estimate the impact of buildings in their lifecycle.

## *1.2 The Renovation Wave*

The Renovation Wave [6] initiative by the European Commission aims to achieve a deep renovation of existing buildings, with a focus on energy poverty, public buildings, and decarbonization of heating and cooling [7]. The Renovation Wave initiative and the EU's goal to become climate-neutral provide an impetus for the AEC sector to fully embrace the 4.0 paradigm. With the digitization of traditional processes, the AEC sector has an opportunity to implement decarbonization targets and transition from a primary focus on creating new architecture to redesigning the existing buildings through comprehensive renovation workflows. This requires a shift in focus from formal research to a holistic approach that involves the entire supply chain, from first-level training courses to the creation of innovative companies.

Each European region is facing different challenges with renovation. They are related to building tradition, skills, age of the building stock, legislation, climate, and available resources, among the most critical factors [8–10]. From an Industry 4.0 point of view, new renovation strategies should integrate new technologies and make them accessible to the different actors involved [11].

For this transition to Industry 4.0 to be successful, the new workflows should allow different users, whether they have technical knowledge or not, to make use of them. In addition, these processes must be flexible to cover the different stages, from digital design work, through digital manufacturing and construction processes, to smart buildings and their operation, as summarised in Fig. 1.

At the moment, there is no generic digital workflow for all European locations. As there is no homogeneous architecture or construction market. At national level it


**Fig. 1** Workflows 4.0 from design to operation

differs in various aspects, such as interpretation of the EU directives to the local policies, maturity of understanding the challenges of sustainability and decarbonisation workflows, digitalisation level, size of companies, and education of professionals. Therefore, any workflow must be flexible and transparent, but at the same time case-specific to be effective. A balance between top-down and bottom-up approaches is necessary to accelerate the implementation of more extensive renovation projects. Authors do not exclude the fact that some of the elements of the proposed workflow may not be accurate for some of the markets in the short term.

## *1.3 Measuring Carbon in a Building's Lifecycle*

Measuring carbon in a building's lifecycle involves using Life Cycle Assessment (LCA), an analysis technique that allows for assessing environmental impacts associated with all the stages of a product's life. LCA assesses the Global Warming Potential (GWP), which associates the amount of carbon monoxide and other greenhouse gases released into the atmosphere with undertaken activities. It is measured using unified metrics for all the gases, $CO_2$eq. Digitalizing the LCA workflow requires all the stakeholders to register and publish data in an interoperable and transparent way. There is no universal LCA method; however, ISO 14040 standards have been developed as a base for LCA.

LCA 14040 is a framework that evaluates carbon used by the industry, starting from sourcing and manufacturing through design and construction, and operation until demolition. Figure 2 shows LCA 14040 divides a building life cycle into four parts: Stage A (Production and Construction), Stage B (Operation of the Building), Stage C (Deconstruction and Waste Processing), and Stage D (Building Afterlife).

Various aspects of the LCA have been researched in Portugal [12], including material studies, comparison between refurbishment and demolition [13], roof retrofitting, embodied and operational carbon of a steel frame building [14], embodied carbon of cladding [15], and the cost and embodied carbon of renovation of traditional architecture [16]. After careful revision of articles on the carbon impact of the LCA stages in Portugal [17, 18], it appears that the most critical are A1–A3 (related to material production) and B6 (related to building operation), which encompass more than 95% of GHG emission of the LCA. Therefore, a balance between these two stages was selected to use for the presented workflow.

In Sweden, studies conducting LCAs for different building typologies have shown that the construction stage (A1–A5) accounts for over 50% of the total carbon impact, followed by the operational energy stage (B6) with around 40%. The trend

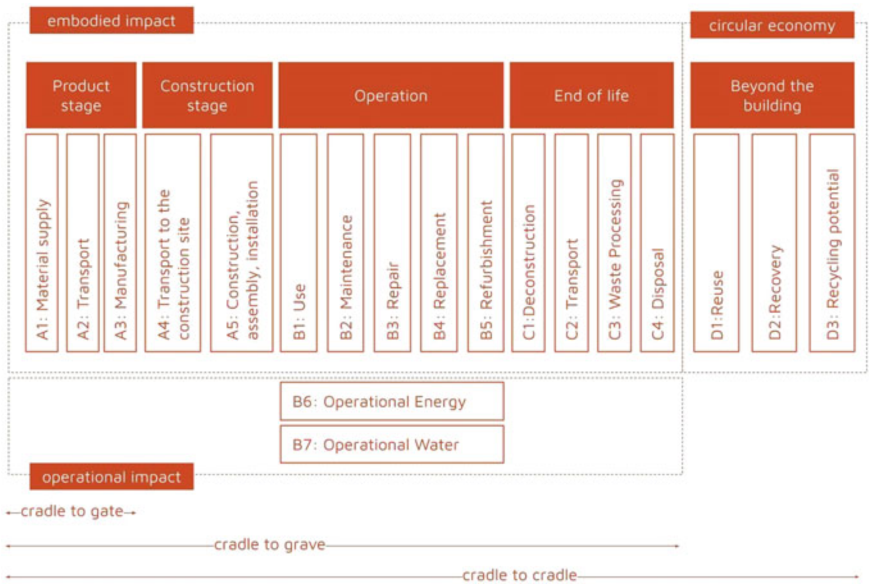


**Fig. 2** Life cycle assessment stages in ISO 14040

of construction, especially in the Nordic region, has an increased focus on reducing the carbon footprint of buildings by reducing heat loss to lower operational energy. It is important to find the balance between the two, by using biogenic and low-carbon materials, sourcing locally where possible to minimize transport impacts, and optimizing the construction process to renovate buildings and decrease the existing high energy demand of the current building stock.

## *1.4 Carbon Neutral Definitions*

Buildings and their construction contribute to approximately one-fifth of Sweden's greenhouse gas emissions, making it crucial for the sector to adopt methods that support low emissions and carbon neutrality [19, 20]. While the Swedish government has introduced a climate declaration requirement for all new buildings constructed after January 1, 2022, and plans to include the end-of-life stage in climate declarations from 2027, there is a lack of definitions and guidelines on how to achieve carbon neutrality for specific buildings, especially during renovation projects.

To address this, various carbon–neutral definitions have been developed and implemented around Sweden, Europe and globally. The Swedish Green Building Council (SGBC) [21] created Noll$CO_2$ [22, 23] as a method for certifying new buildings targeting net-zero climate impact. According to Noll$CO_2$, a building is considered "climate-neutral" when its construction, operation, and end-of-life aspects are

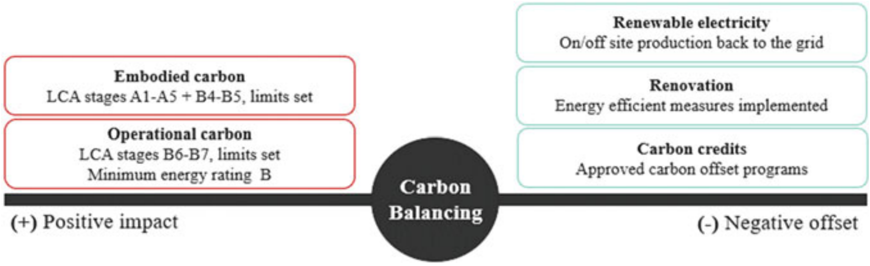


**Fig. 3** Noll$CO_2$ carbon balance considerations. *Source* Adapted from [19]

weighed against any climate actions or offsets that balance the total climate impact to zero. Noll$CO_2$'s carbon balance considerations are shown in Fig. 3.

However, it is important to note that carbon neutrality is not well-defined, and the lack of clarity is even more critical in building renovation projects. It is unclear which stages should be considered and which compensation measures should be used [24]. Therefore, flexible processes that can adapt to different definitions and success factors of various stakeholders are necessary.

Existing tools and databases could empower the entire renovation process, from design to decision-making, and assist in achieving carbon neutrality [25–27]. Moreover, the use of renewable energy sources and the adoption of energy-efficient practices during construction and operation can significantly reduce emissions.

In summary, while the adoption of carbon–neutral certification methods is a step in the right direction, it is crucial to have clear guidelines and definitions for achieving carbon neutrality during building renovation projects. The use of flexible processes, existing tools, and databases can support decision-making and assist in achieving carbon neutrality goals.

## 2 Creating a Robust Workflow for Renovation

The proposed workflow for Portugal and Sweden needs to reflect the countries specifics, starting from the climate conditions, building culture and tradition to ownership structure.

### *2.1 Portugal*

To accelerate the transformation, and to enhance thermal comfort levels and reduce energy consumption of an existing building stock a new digital workflow is needed. The workflow proposed for deep renovation and retrofitting in Portugal is divided into five phases.

**Virtual Model (VM) Building**. The model is based on the existing documentation (e.g. original project, evacuation roots drawings), on-site survey and photogrammetry. The 3D model is constructed to reflect the requirements of (a) energy and daylight modelling, (b) calculation of the quantity of materials used in the building.

**Building Energy Model (BEM)**. Completes the VM with climate data, information on materials and construction systems, program, passive systems, occupation and operational schedules, users and their behavior and HVAC systems and their settings and more. All data is compiled into a BEM and later an energy performance simulation is run. The outcome of this step is the total energy consumption in the period of 30 years.

**Embodied Carbon**. The VM is used to quantify the materials used in the building, it is measured according to the functional units[1] declared in the Environmental Product Declaration or other available data sets.

**Building Daylight Model**. The VM and BEM data are completed with sensor distribution grid, daylight settings and simulation thresholds. The outcome of the simulation is spatial Daylight Autonomy.

**Operational Carbon** is a product of total energy consumption in the operation phase and values of the energy mix projection for the next 30 years, including the official decarbonisation plan. A simple calculation with prediction is made using native Grasshopper components.

A crucial element of the workflow is model calibration and comparison with existing benchmarks. Such a practice reduces allows to reduce errors and incorrect assumption. Only after calibration does a full-scale simulation brings result close to the actual building performance.

Once all the simulation is completed values for three metrics are obtained:

- Energy Balance (kWh/m$^2$/year), which allows comparing the impact of energy flows (heating, cooling, lighting, infiltration) throughout the year on the overall energy consumption, Thermal Comfort demonstrates levels of standard and adaptive comfort throughout the year and in different rooms,
- Life Cycle Carbon (kg$CO_2$ eq) combines the values of embodied carbon and operation carbon but excludes end of life carbon (due to lack of data)
- Daylight Autonomy (%) evaluates how much of the simulated spaces receive enough daylight according to pre-established thresholds.

A graphical abstract of the workflow can be seen in Fig. 4. All the phases are strictly interconnected. To perform the Energy Modelling, the Virtual Model is necessary. The Daylight Model is built on top of the Energy Model. Material data used for Energy Model and Daylight Model are used to calculate the Embodied Carbon For better understating of multiple options, a Pareto front representation is draw. There

[1] Functional Unit (f.u.) is a unit that allows comparing different materials with the same purpose, for example a 1 m$^2$ of insulation of the thermal transmittance of 1.0 W/m$^2$ K regardless the thickness of the material, or a column resistance of 2,222 kN regardless it thickness or material.

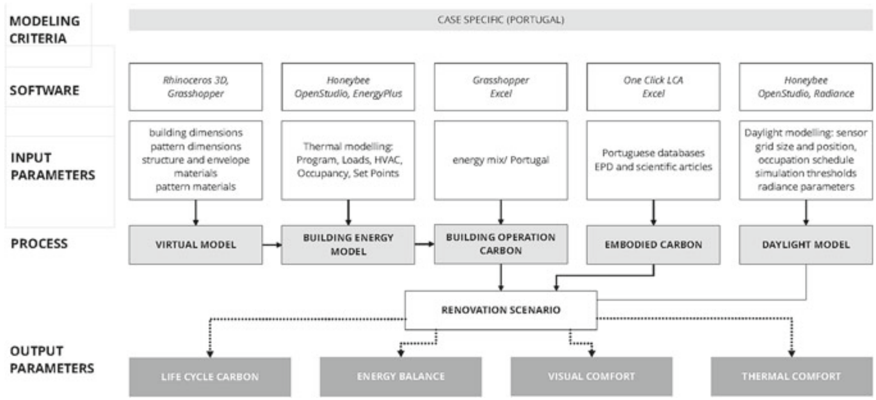


**Fig. 4** Graphical abstract for the workflow of Portugal

is no best solution but a range of non-dominated best renovation scenarios. Each of them performs the best in some or other categories.

The renovation methodology workflow responds to homeownership structure in Portugal. Most of the houses are owned by the tenants, which means that renovation will happen on a building scale.

## 2.2 *Sweden*

Similarly to many other countries in Europe, Sweden experienced a period of intensive building construction in the post-war years. Even today, 40% of the country's total multi-family housing stock dates from this period [28].

Consequently, there is room for significant improvement in energy performance. In addition, after almost half a century, most of these buildings require considerable renovation. Therefore, there is an excellent opportunity to refurbish buildings of this period, recognised for having the highest energy-saving potential in the Swedish building stock [29]. This is the reasoning why the authors decided to test this group of buildings as a priority in the Swedish workflow. Indeed, these buildings have relatively simple geometrical shapes, which facilitates their modelling. Additionally, are grouped in great numbers in whole neighborhoods and districts, which helps scale the evaluation to urban areas. The process is graphically summarised according to its main stages in Fig. 5.

The workflow proposed for deep renovation and retrofitting in Sweden is divided into five phases:

**Selection of the building or neighbourhood**. A preliminary characterisation is carried out to analyse several relevant aspects: urban metrics and geographic and climatic aspects.

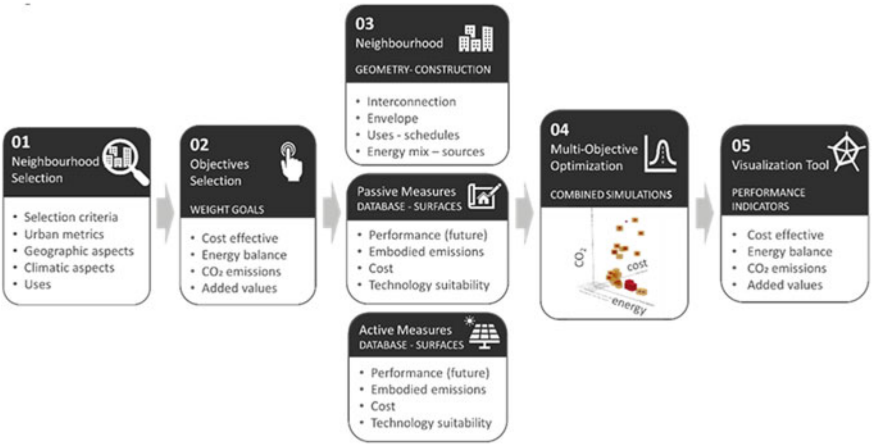


**Fig. 5** Main stages of the Swedish workflow

**Selection of objectives**. To tailor the process of modelling, simulation, and optimisation; it is necessary to define the objectives and which indicators are most suitable and informative for the end-user. Since the focus is on the decarbonisation potential of existing neighbourhoods, the objectives are defined as an equilibrium fit between cost, energy balance, $CO_2$ emissions, and other added values such as thermal comfort. To evaluate the usefulness of the workflow and what goals should be considered, a group of property owners, designers and researchers with experience in renovation projects in Sweden joined the research as reference group. The objectives varied significantly when moving from one building to an entire neighborhood, where improvement of the common and outdoor spaces, along with other co-benefits became most relevant. Overall, the main objectives focused on reducing environmental impact, reducing energy consumption, and improving indoor comfort and energy resilience. Economic profitability was not considered as important as cost-effectiveness, i.e. not seeking a better economic return through the renovation, but rather making it as economically viable as possible and maximising use of the available funds.

**Modelling and characterization**. The parameters that will define the building model are assigned. These variables are structured into geometry-dependent and database-dependent variables. These variables are extracted from various sources and optimized before being transferred to a BPS engine. The modelling process is automated using freely available GIS sources, where the user enters the building address or selects the building on a map. The associated footprint is downloaded from OpenStreetMap, and metadata from the footprint is used to obtain the corresponding Energy Performance Certificate (EPC), from which the number of floors and heated floor area can be obtained [30]. Other necessary data for geometry generation, such as average height values and thermal properties, are obtained from existing databases.

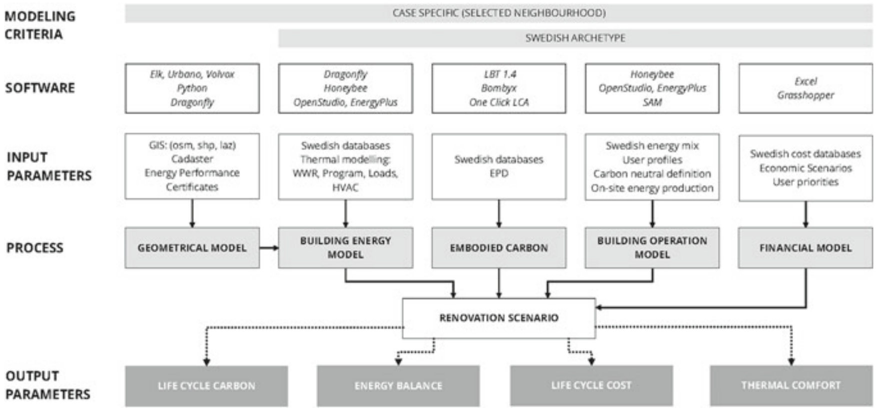


**Fig. 6** Graphical abstract for the workflow of Sweden

This section provides a brief overview of the building energy modelling process, indicating that it is not an in-depth description. The authors may have chosen to provide a concise summary because they have already published an article that specifically details the energy modelling process [30].

As detailed in Fig. 6, the procedure is case specific for the geometrical model but provides approximate inputs when better data is unavailable. Therefore, a BEM can be automatically generated from the footprint and no other inputs from the user. Indeed, the monitored annual energy need for heating from the EPC is used to benchmark the resulting energy need from the simulation. The number of stories obtained from to the Energy Performance Certificate corresponding to each footprint.

### Simulation and Evaluation

Resulting BEM or Urban Energy Models (UEM) are simulated. A baseline as predefined "anyway renovation" is assigned. Depending on the number of variables and steps defined as inputs, the different iterations for renovation scenarios are calculated. Various simulation tools are coupled depending on the number of buildings to simulate. Since the entire workflow is natively working in Grasshopper, other plugins can be added to the "workflow ecosystem". Indeed, different optimisation plugins, with different built-in algorithms, were studied to actively influence the number of simulations needed to obtain a specific (single) objective or combination or range of different (multi) objectives. The studied optimisation plugins are shown in more detail in the Tools sections.

### Visualisation Tool

Due to the parametric simulation approach, large amounts of data are handled as outputs. To handle the input and output parameters, an interactive parallel coordinate diagram is employed.

Parallel coordinates graphs are a visualization tool that allows the user to plot multiple variables on parallel axes and visualize their relationships [31]. This technique is particularly useful for analysing large datasets and identifying patterns and relationships between variables. Several studies have demonstrated the effectiveness of parallel coordinates as a visualization tool for building performance analysis [32–34]. The advantages of parallel coordinates for building renovation scenarios include the ability to explore a large dataset in a single visualization, to interact with the data in a flexible and intuitive way, and to easily identify outliers and anomalies in the data. Based on the demonstrated strengths and capabilities of parallel coordinates graphs in the literature [35–38] we are confident that employing this visualization tool in our study will contribute to a robust and comprehensive analysis of building renovation scenarios.

Figure 7 shows a parallel coordinate diagram with the total number of iterations obtained for a number of different input and output variables (Fig. 7).

This type of diagram groups both inputs and outputs and scales the available range of data per variable in the vertical parallel axis. Each axis represents a variable, and each line crossing the axis represents an iteration (Fig. 8).

In Fig. 9, it can be seen how users can filter the results according to their interests. Maximising energy savings, minimising environmental impact or defining an available cost range are objective examples that can be selected intuitively. Once the objectives are selected, the different iterations leading to those results are highlighted.

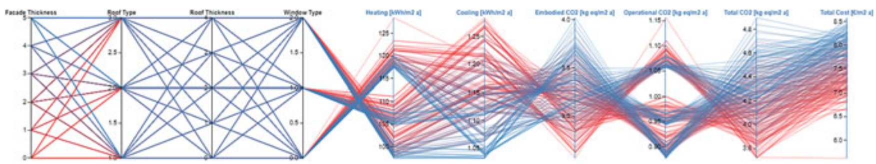

**Fig. 7** Parallel coordinates diagram containing all the resulting iterations

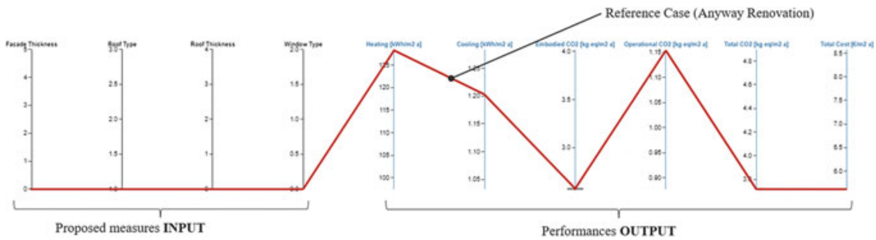


**Fig. 8** Definition of the baseline condition in the parallel coordinates diagram (in this case anyway renovation) for benchmarking

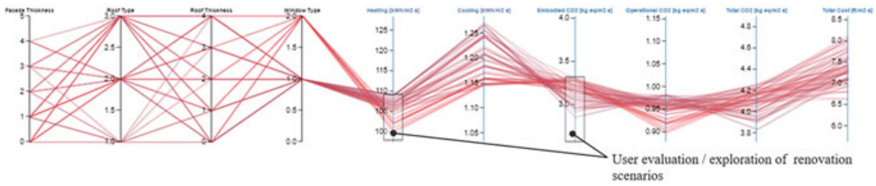


**Fig. 9** Parallel coordinates diagram with two range-filters applied by the user to the building performance outputs. All the renovation scenarios complying with those outputs are highlighted

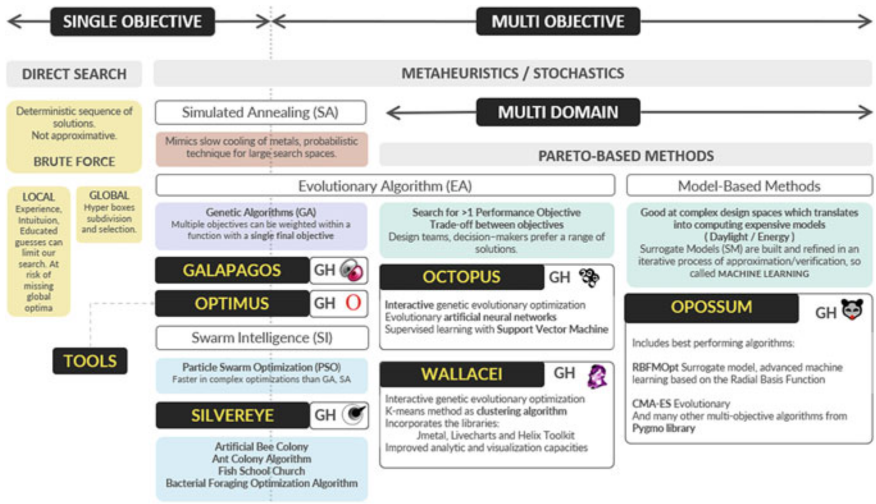


**Fig. 10** Optimisation tools and plug-ins evaluated and tested in the Grasshopper 3D environment

# 3 Tools

## *3.1 Geometry Model/Virtual Model (GM/VM)*

For both workflows, the models are generated from CAD software (Rhinoceros and Grasshopper). Additionally, Grasshopper, a Visual Programming tool, will serve as a platform to connect all the steps of the proposed workflow. Grasshopper is integrated in Rhinoceros 3D modeler, allowing for native interoperability. The choice of Grasshopper/Rhinoceros over Dynamo/Revit or other modelers was motivated by a greater availability of open-source plugins in Rhinoceros 3D (Food4Rhino) [38]. However, it is possible to integrate Grasshopper with Revit or other formats, although the study was limited to the Rhinoceros 3D environment. To create a Building Energy Model, Ladybug Tools (LBT) [39, 40] are employed. LBT is a set of parametric tools and a user interface that allow energy modelers and architects to define parameters such as occupancy schedules, HVAC setpoints, and programs.

Later the generated numerical model is exported to a.idf file that will be analysed by EnergyPlus. For the block and neighbourhood scales, Dragonfly's [40] LBT plugin is used in parallel to Honeybee's LBT. This translates into adding the UrbanOPT layer over Energy Plus as the simulation engine. URBANopt is a Software Development Kit (SDK)—a collection of open-source modules focused on underlying analytics for a variety of multi-building design and analysis use cases using OpenStudio and EnergyPlus [41]. EnergyPlus is a whole-building energy simulation engine to model both energy consumption—for heating, cooling, ventilation, lighting, and process and plug loads, it was developed with the support of the US Department of Energy Building Technologies Office.

To create a Building Daylight Model again LBT tools are employed, they serve as a tool to set-up parameters like occupancy schedules and material radiance. The model is connected to Radiance and Dayism. Radiance is a raytracing engine integrating a suite of tools used to perform lighting simulation, principally daylight analysis and glare. Daysim, daylighting analysis software, serves for simulation of annual daylight performance.

One-Click LCA and Bombyx are two software used for the calculation of the embodied carbon in a building. One-Click LCA uses material data from multiple partners and also has a generic database for materials. It is of the highest importance to use a national or regional database, ideally using GWP data provided by the material producer, otherwise, the calculation is likely to be inaccurate.

For the Portugal workflow, other calculations such as operational carbon and financial model are calculated with Excel, data are exported and imported to and from Grasshopper.

For the Swedish workflow, cost calculations are integrated in the Grasshopper environment and coupled to the energy and the embodied carbon models. The financial scenarios and LCC calculations are also integrated in the Grasshopper environment. The goal for this full integration in Grasshopper was to enable complete interoperability with other tools, from GIS, to optimisation and data handling plugins available in that same Grasshopper ecosystem. In Fig. 11, the optimisation tools tested in both workflows are summarised and organised according to their approach regarding objectives (single or multiple) and the used algorithms and libraries [33, 42–53].

Finally, an overall caption of the whole Swedish workflow, as seen in the Grasshopper canvas, is shown in Fig. 12. The script integrates a traditional building energy modelling process with input flows from GIS and open access databases in order to process different building(s) renovation performances. Other Grasshopper plugins can be coupled to include additional capabilities, such as (but not limited to) optimisation and automation.

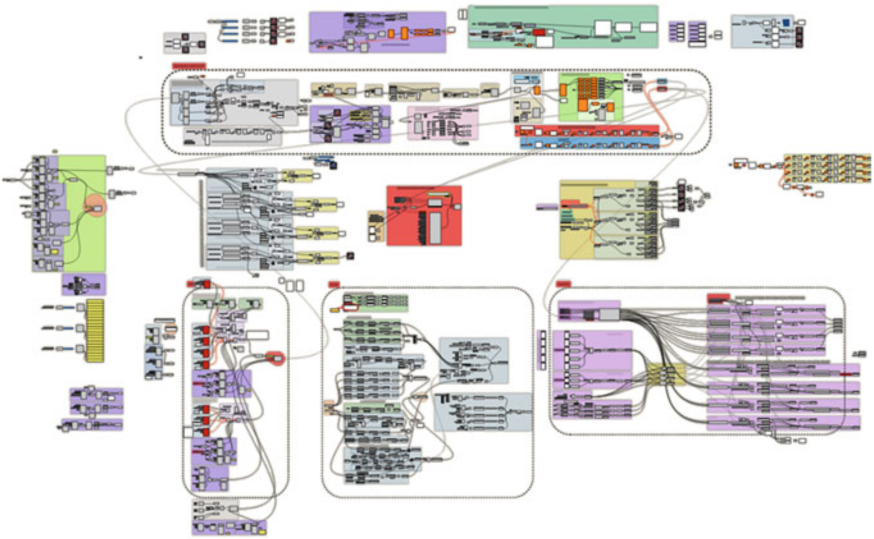

**Fig. 11** Grasshopper definition script of the Swedish workflow, as seen in the Grasshopper visual programming canvas

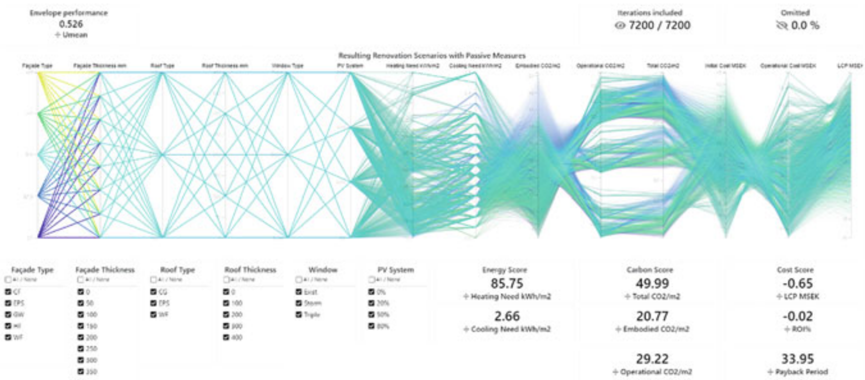


**Fig. 12** Graphical user interface proposed for renovation scenarios evaluation

## *3.2 Graphical User Interface (GUI) for Evaluation*

In this section, we introduce a Graphical User Interface (GUI) designed to facilitate the visualization and analysis of the various renovation iterations simulated in our study. The GUI is shown in Fig. 12 and employs parallel coordinates to effectively display the multi-dimensional input and output data, enabling users to efficiently compare and evaluate the performance of the renovation scenarios in terms of energy, cost, and environmental aspects.

To demonstrate the utility of the GUI, we present a step-by-step decision-making process based on an overall best performance profile, which was tested with users to ensure its effectiveness in guiding informed choices for sustainable renovation strategies.

**Step 1**: Optimal facade thickness is determined by balancing energy, carbon, and costs scores. Users evaluate different facade thicknesses in the GUI, identifying the most appropriate solution that meets the performance criteria (Fig. 13).

**Step 2**: Similarly, the optimal roof thickness is determined by evaluating the trade-offs between energy, carbon, and costs scores. Users analyze various roof thicknesses using the GUI to select the most suitable option (Fig. 14).

**Step 3**: Users assess whether to keep, upgrade, or change the windows based on their performance in terms of energy, carbon, and costs scores. The GUI allows users to

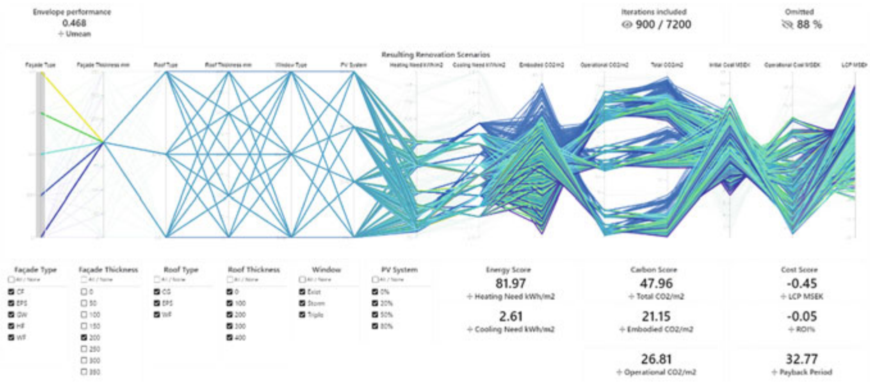


**Fig. 13** Optimal facade thickness is 200 mm


**Fig. 14** Optimal roof thickness is 200 mm

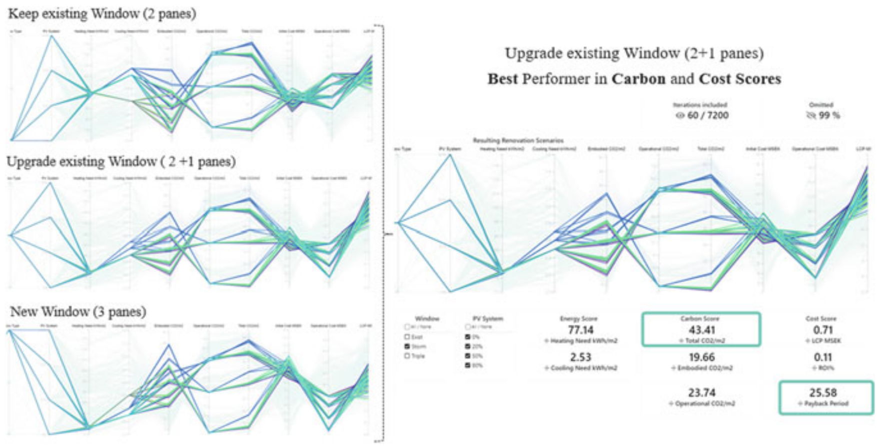


**Fig. 15** Optimal window measure is upgrade existing window with an additional pane on the exterior side

visualize and compare the impact of each window option on the overall renovation strategy (Fig. 15).

**Step 4**: The inclusion of photovoltaic (PV) solar panels is evaluated, considering the available roof area and the potential contribution to the building's energy performance. The GUI helps users to determine the optimal PV panel coverage by visualizing the trade-offs between energy generation, carbon emissions, and costs (Fig. 16).

**Step 5**: Lastly, users decide on the insulation materials for the facade and roof improvements. This variable is considered last, as it has the least influence on the overall performance of the renovation strategy (Fig. 17).

The GUI allows users to assign different colors to each insulation material, which aids in the visualization of their impact. When the outputs display distinct color zones, it signifies a higher influence of the material on the variability of outputs. Conversely, a blurred mix of colors indicates a lower influence of the material on the outputs. A Figure illustrating this "coloring" difference is presented, further emphasizing the importance of material selection in the decision-making process (Fig. 18).

Through this step-by-step example, we showcase the applicability and effectiveness of the proposed methodology in guiding informed decisions for sustainable renovation strategies, using the GUI to visualize and analyze the trade-offs between energy, carbon, and costs scores in a comprehensive and user-friendly manner.


**Fig. 16** Optimal roof utilization for PV panels is 80 of the available area

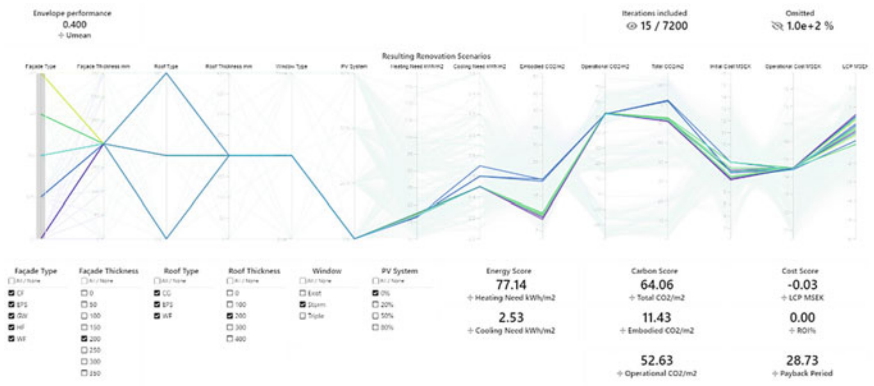


**Fig. 17** Insulation material choice for the façade and roof

## 4 Discussion and Conclusion

The proposed workflows have demonstrated their effectiveness for modeling and assessing existing buildings and neighborhoods in Portugal and Sweden. In Fig. 11 we can see a graphical overview of the two workflows, where the tools used for modelling are highlighted. The Portuguese workflow excels at the individual house

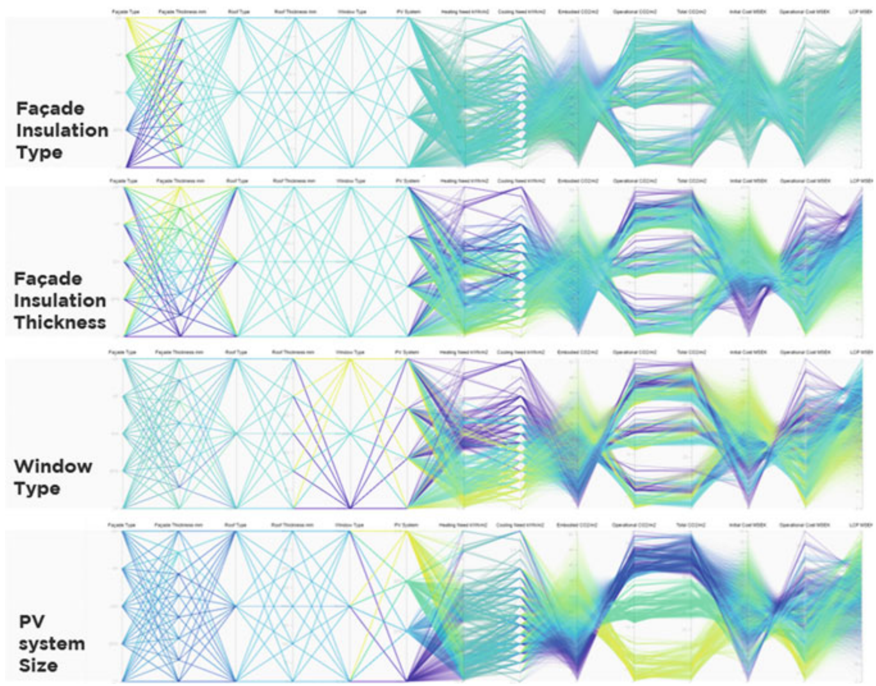


**Fig. 18** Impact of different measures on the final renovation relative performances

and building scale, whereas the Swedish workflow is tailored for the neighborhood scale. These complementary approaches offer a comprehensive and adaptable framework for analysing renovation scenarios and identifying context-specific strategies for sustainable urban development (Fig. 19).

The integration of both workflows within the Grasshopper environment enables a seamless transition between the Honeybee and Dragonfly plugins from Ladybug Tools. This interoperability facilitates the exchange of energy models, allowing the two processes to benefit from each other's strengths, thereby enhancing the overall modeling capability. Despite challenges in data availability and quality, the workflows successfully provide meaningful results by incorporating average values from archetypes when required.

In conclusion, the proposed workflows offer promising solutions for modeling and assessing renovation scenarios in Portugal and Sweden, while considering the influence of Industry 4.0 on architecture and sustainable urban development. The flexibility, adaptability, and potential for future improvements of these workflows hold great promise for advancing the field in this context. Recognizing that the workflows are still in their experimental phase, further calibration of the energy and

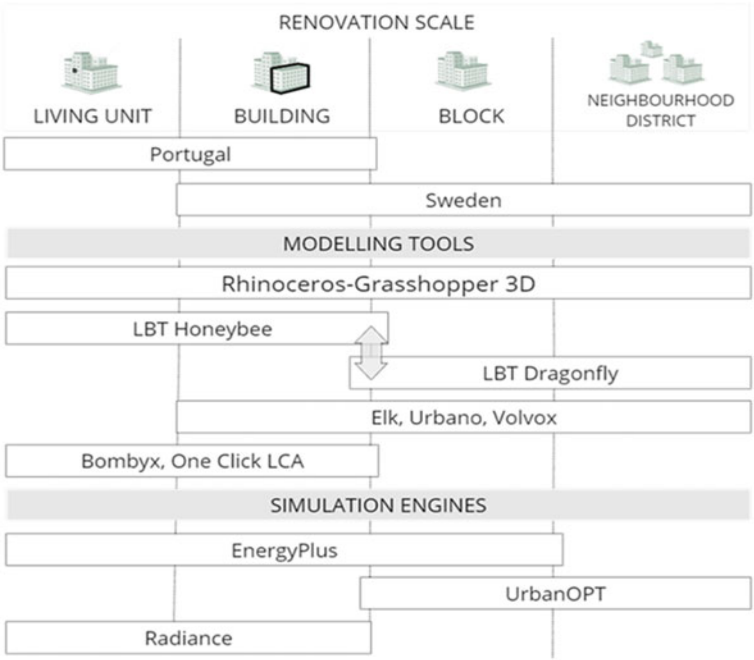


**Fig. 19** Comparison of the renovation scales, modelling tools and simulation engines of each workflow

carbon models is necessary to improve their accuracy and reliability. Future work should focus on refining the workflows by:

- Incorporating additional data sources to enhance the quality and completeness of the input data, thereby reducing the reliance on average values from archetypes.
- Expanding the application of the workflows to various building types and urban contexts to validate their performance and versatility.
- Collaborating with local stakeholders, such as urban planners, architects, and policymakers, to ensure that the workflows address real-world challenges and contribute to sustainable urban development.
- Investigating the integration of other digital tools, such as BIM and other design software, to further enhance the workflows' capabilities and enable a more comprehensive assessment of renovation scenarios.
- Exploring the potential of machine learning and artificial intelligence techniques to optimize the workflows, streamline the modeling process, and generate data-driven insights.

By continuing to refine these workflows and exploring new avenues for collaboration and innovation within the framework of Industry 4.0, researchers and practitioners alike can develop more effective strategies to address the pressing challenges of urban sustainability. The integration of these workflows with Industry 4.0 technologies will ultimately contribute to the transformation of the architectural and construction sectors, fostering a more sustainable and efficient built environment.

**Funding** This research was jointly supported by the funding received by the authors.

Adrian Kreżlik was funded by the MPP2030-FCT PhD Grant, financed by the Portuguese Foundation for Science and Technology (FCT), under the MIT Portugal Program.

Rafael Campamà Pizarro and Ricardo Bernardo were funded by The Swedish Energy Agency, as part of the project "Renovation towards Climate Neutral Neighbourhoods in Sweden" (project number: 51696-1).

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# Configurator: A Platform for Multifamily Residential Design and Customisation

**Henry David Louth, Cesar Fragachan, Vishu Bhooshan, and Shajay Bhooshan**

**Abstract** Game technologies in Architecture, Engineering and Construction (AEC) industries are currently utilised for a variety of analytical, and single author applications such as test fitting, simulated city fabric, and evaluation of feasible solution sets. Advances in materials and fabrication technologies, design for manufacture and assembly (DfMA), and industrialised construction of building components, continue to shift the housing paradigm from standardisation toward mass customisation. These recent developments are trending toward user focus, negotiated planning, and choice prioritisation in design, production planning, and manufacture. The authors' research is motivated by game technologies' suitability to negotiate problems facing integration of design customisation, user choice, and negotiated governance in supply chain integration and procurment pipeline. The paper presents the author's research into decentralised multi-author decision making, co-authorship, contribution of digital experts, and incentivisation models. Game engine technology is outlined to deliver user-focused, participation-driven, mass-customised housing outcomes. A real-time online platform use case configurator and the corresponding digital tool-chain integration is presented and discussed. The multiplayer gameplay of such results in construction feasible customised housing developments. The footprint, unit mix, and spatial organisation of which, conventionally authored by an architect or developer, herein is authored by the participants aggregate decisions.

**Keywords** Gamification · Modularity · Mass customisation · Housing · Industrialised construction

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_40

# 1 Introduction

The technology platform presented, developed by the authors, is the latest build in the ongoing applied research into game technologies suitability toward architectural design and procurment planning. The research is motivated by game technologies capacity to negotiate consumer and stakeholder priorities, to democratise an emerging digital property marketplace, and to reduce housing procurement timelines. The technology platform and toolchain address problems facing implementation in downstream supply chains and procurement including:

1. modular housing design strategy for mass customisation
2. suitability of prefabricated elements to supply chain (SC) integration
3. continuity issues of an end-to-end digital fabrication toolchain
4. flexible procurement models to shifting consumer demand

The paper details an application of game technology in architectural design, a configurator for multifamily residential design as well as the systems design strategy and components implicit to its creation. Gamification principles, a multiplayer sequential turn-based gameplay, and participant incentivisation result in emergent massing properties in a residential community design development. In a configurator, the needs of the customer, in this instance the occupiers themselves, are met through a customisation process, often autonomously through a virtual interface. The paper discusses the capacity of such a configurator platform to disrupt conventional procurement processes and bring stakeholders together earlier in the design process than in a conventional delivery process. The additional roles and capabilities required by design professionals are outlined including user experience and interface design, backend asset optimisation, database integration, and cloud services deployment.

The game environment demonstrates a real-time digital platform that negotiates variations and decentralised non-expert buyer actions through consensus design planning. The paper argues stakeholder decision-making and game mechanics governed by expert participants' knowledge result in construction feasible, engineering-aware outcomes. The utilisation of such and the corresponding modular *kit-of-parts* benefit early design planning and procurement of the configurator results.

## *1.1 Contributions and Organisation*

This paper describes the use of game technologies in architectural design, the benefits of user-centric design, and a systems design approach utilising modular content for multi-family residential through a use case configurator (Fig. 1). The main novel contributions of the paper are as follows:

1. The configuration of a community of residences by the residents themselves through a technology platform.

**Fig. 1** Configurator: game screens

2. The rulesets for the game mechanics are the digitised result of the participation of the engineering disciplines' validation of feasible solution sets in the system design.
3. The curvilinear components in architectural design are procedurally created through a discretised volumetric data structure.
4. The mass customisation of multifamily residential units inclusive of positioning, cladding elements, space plan, furnishing, and contractual use rights (Fig. 2).
5. The use of timber cladding elements as a kit of parts is amenable to robotic fabrication supply chain integration (Fig. 3).

**Fig. 2** Visualisation of a configuration

**Fig. 3** Visualisation of a configuration

The Sect. 2 provides a brief survey of precedent in stake holder participation in the housing domain, outlining the role of industry, manufacture, and supply chain to address customisation, and discusses the motivation and engagement of participants using principles in behavioural science to enhance immersive gameplay. In Sect. 3 we present a brief survey of building industry configurators, their usages, and target audiences and the benefits of such. In Sect. 4 we discuss relevant prior work in game technologies and platform technology development at Zaha Hadid Architects (ZHA) including legacy builds, dashboard development, and content creation. Section 5 describes the configurator use case through the initial Pilot Build and corresponding session results. We discuss the analysis and present the features, functionality, and content modifications planned and validated via engineering participants for the subsequent build. The Sales Release is summarised, and its corresponding session results are presented. In Sect. 6 we present the workflow and custom toolchain for the configurator, the game mechanics, rulesets, and content created for the kit of parts. The technical components of the system architecture are subsequently discussed and detailed. Section 7 describes foreseeable challenges and future work trajectories and conclude in Sect. 8.

## 2 The Promise Mass Housing as a User Centric Product

Discrete modular organisation in residential design planning and systems design thinking in housing has a longstanding history. Gropius explored the combinatoric opportunity of ‘spatial bodies’ as a set of distinctive shape typologies in creating

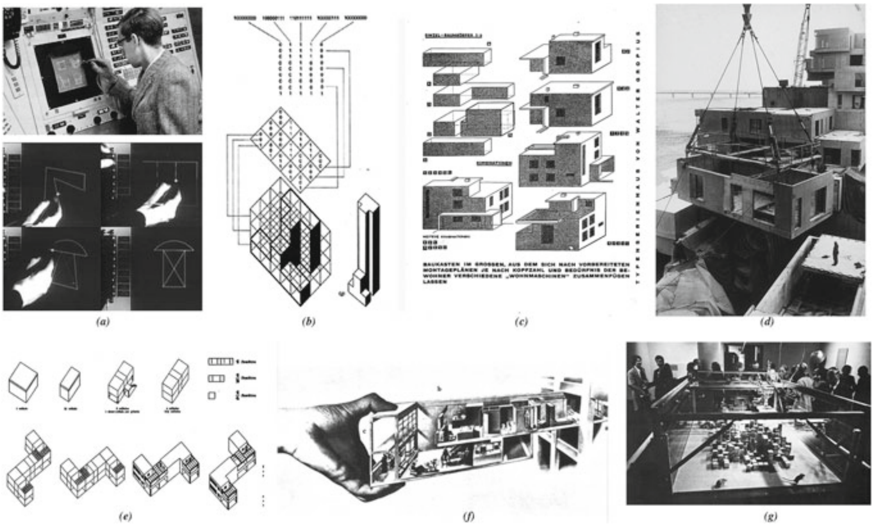

**Fig. 4** Configurator seminal projects: **a** Ivan Sutherland Sketchpad [39], **b** Lionel March Binary System of Encoding Volume [71], **c** Walter Gropius and Adolph Meyer Spatial Bodies [1], **d** Habitat 67 [3], **e** Corbusier Quartier Fruges [2], **f** Corbusier Wine Rack Concept for The Unité d'habitation [2], **g** Negroponte Man–Machine [40]

unified spaces [1]. Le Corbusier implemented cellular units and standardised proportioning ratios for the working classes in Quartier Fruges and subsequently conceptualised a dual schema for 'slot-in' flexible interior layouts into a rigid structural armature in Unité d'habitation [2]. The aggregate composition of self-similar repeating units was later explored by the Metabolists and influenced the early prefabricated unit cluster arrangements and the success in Habitat 67 to form community, and access to light, air, and garden space [3] (Fig. 4).

## *2.1 Platform Approach: Modularity and Mass Customisation*

The platform approach to construction references a strategy inherited from automotive industry [4] for system design where variations in design are achieved by adaptation and alteration of components onto a base type (BT) creating instances [5, 6]. Modularity of physical components and assemblies is adapted from fixed positions [7, 8] via a so-called *kit of parts*. Together the system, kit options, and rules augmentation define the platform.

The paradigm shift from mass production to mass customisation (MC) is rooted in the desire to focus products on the customers they serve [9]. Gilmore outlines a customisation framework comprised of strategies in assessing how best to redesign a product or process to engage customers [10]. Mass customisation of spatial qualities and cladding kits varied to demographics is evident in English worker class row housing [11]. Later examples of post war homes catalogues and plan books [12] demonstrate variation to suit a variety of stylistic and spatial demands, as well as tailor to the region and vernacular [13].

Product relevancy is a concern as consumer trends and priorities fluctuate from design to delivery stages [14–16]. The alignment of the product offered and its manufacture in the production phase—a so called agile production and lean manufacture [17, 18]—necessitates continuity of end-to-end digital toolchain in supply chain and procurement [19].

Advances in materials and fabrication technologies [20–22], design for manufacture and assembly (DfMA) [5, 23] and industrialised construction of building components [24], continue to shift the housing paradigm from standardisation using dimensional elements toward mass customisation [9, 12]. These recent developments are trending toward user focus, priority, and choice via agile manufacture [14–16].

Harnessing innovation of fabrication technologies in industrialised construction has demonstrated mixed results taking advantage of mass production capabilities in the production of premanufactured kits as housing products [25]. For instance the conversion of post-war aerospace metal-works factories toward the housing sector by Lustron yielded roughly 2500 homes [20], while Fuller's dymaxion vision net only one such structure and Prouve's Maison Tropicale only three such structures [26]. In Prouve's case the structure cost more than the market housing intended to supplant, while Fuller's suffered from inflexibility of the system to modification, and a general lack of customisation to siting and regional climatic considerations [27]. Edison's housing scheme exhibited assembly and decanting complexities of roughly two thousand unique mould components. Similarly, interiors infill kits and layouts amenable to buildings systems integration such as Matura are equally complex [28].

### 2.2 Gamification: The Role of Behavioural Science to Engage and Motivate

Gamification is the step of converting a design from a function-focused design (FFD) into a human-focused design (HFD) by employing concepts of behavioural science to engage human emotions through human psychology to motivate and incentivise users [29]. It is more notable for corporate applications, e-learning, and for non-game applications to engage users [30]. Research of benefits of gamification for the player include developing higher-order thinking skills [31] and problem-solving skills [32] in social cooperative settings [33]. As such, there is a changing generational attitude toward work and learning [34].

Early 'Intrinsic Instruction' frameworks identified 'heuristics for designing enjoyable user interfaces' [35]. Contemporary gamification frameworks identify *core drives* [36] while playfulness frameworks identify a broader spectrum of characteristics that exist within humans [37] and motivate us to engage in activities. Further,

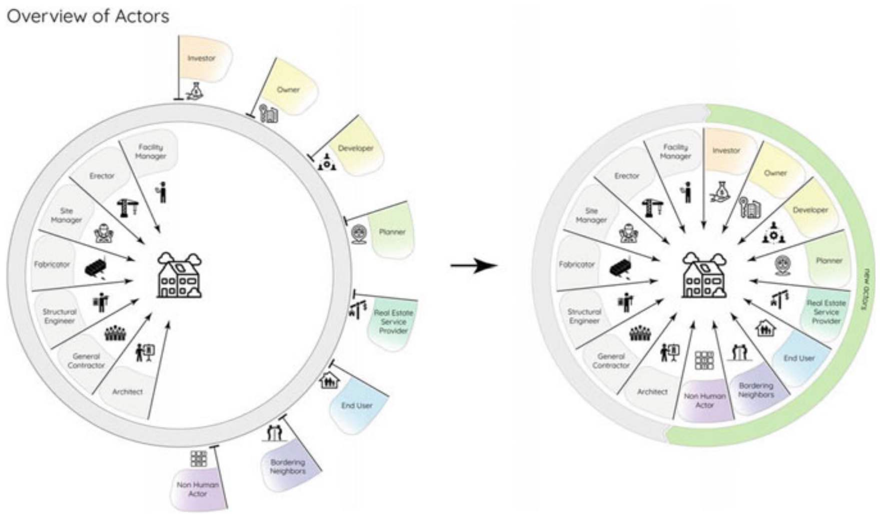


**Fig. 5** Stakeholders brought together in a real-time platform

the user interface (UI) components and their integration strategy contribute to viewer perception of immersion and categories of engagement in the active world [34, 38].

User engagement and motivating strategies in the design discipline include Sutherland's Graphical User Interface (GUI) 'sketchpad' is attributed to the birth of computer graphics, drawing as a novel communication medium [39]. Likewise, Negroponte's explorations in the role of man–machine in collaborative negotiated environments [40] is consistent with the role of non-player character (NPC) role to advance, and steer gameplay and in general co-authorship of a negotiated game state (Fig. 4).

The concepts of co-authorship, mutual consensus, and civic responsibility are present in so-called 'DIY urbanism' [41]. Multiplayer dialogue is exhibited through a "panel of experts" participating on behalf of a particular motivator (Fig. 5). Each occupier, regulator, engineer, planner, etc. can be seen in analogue community board games in housing, land utilisation, and town building [42–44] and further digitisation of 'actors' in city building games.

## 3 State of Configurators in AEC

Configurators are comprised of components (the building blocks), processes (the rules, and taxonomies), a knowledge base (datasets for economic evaluation) and people (the users). These reduce a configurator design process to a series of transformation vectors in distinct domains. Customer attributes (CA), functional requirements (FR), design parameters of the physical solution (DP) and the variables governing the production process (PV) are in separate domains in a so called axiomatic design [45, 46].

Configurator typologies in architecture range depending upon target user audience and address different design stages, the extent of which is extensively discussed in [47]. Life cycle costs can be attributed to early design decision making [48] and therefore, design controls in conceptual stages are financially motivated. The levels of control or governing constraints asserted onto built elements is defined by actors in the system's man-built environment, the community formed by the authority, operator, developer, and occupier [49].

Most notable of the stand-alone application configurators to arrange Floor plans [45, 50, 51] and Buildings Components [52] for specific supply chains include Precast concrete [53], Curtain wall systems [54], Precast concrete panels [55], Timber walls and Floors [24, 45, 56].

Configurators have seen a rise in web-enabled apps as exploration for property search and acquisition, residential test fitting, site planning and land utilisation as early-stage planning toolkits [57–62]. Each offers a form of procedural, and generative creation of feasible solution sets, qualitative analysis, result ranking, and filtering as near real-time in early design in lieu of precision engineering [63], while few offer a collaborative co-authoring platform for project stakeholders as controlling actors [64].

There are a few commercially deployed web-based configurators of which HiStruct Steel structures [65], AGACAD Wood Precast concrete elements [66], Creatomus Private homes and apartments [67] and Projectfrog [68], are most notable.

## *3.1 Technical Considerations*

Configurator technical considerations include the building sector, features and functionality requested. In the case of building components, these include—the geospatial coordinate system, the serialisation of volume into discrete volumetric system grid, so-called voxels allow component hosting [69–72], tiling discrete geometry [73, 89], and procedural environment creation [74, 88] and compression and encoding consideration of such [71] (Fig. 4).

## *3.2 Benefits*

The benefits of configurators are extensively documented in [47]. These include, increases variation [6, 55, 75], ensures feasibility of solutions in the supply chain [45, 50, 53, 55, 56], minimises manual input [50, 54], smoothens on-boarding [45, 50], reduces time and cost for design production [6, 55, 56, 75], enhances coordination efficiency, [24, 53, 70] and preserves knowledge for reuse on the next product [75].

In the trend toward data-driven real estate and property technologies (PropTech), product configurators are well suited to contend as digital marketplaces for real-estate bidding, negotiation, and property valuation. As digital cloud-based applications, they are web 3.0, and democratised decentralised blockchain based collaboration ready [76].

# 4 Relevant Prior Works

Platform design initiatives started in 2018 and subsequent platform development was formalised through ongoing development at Zaha Hadid Architects (ZHA), Computation and Design Group (CODE) (Fig. 6), in collaboration with The Manufacturing Technology Centre (MTC), and continued teaching affiliations and enquiry in academic settings at Architectural Association, Design Research Lab (AADRL) and UCL Bartlett Research Cluster 10 (RC10) as well as workshops with Digital FUTURES (DF).

## 4.1 Legacy Configurator Builds

Oikos created for Architectural Association Design Research Lab AADRL, Nahmad/Bhooshan Studio is a cooperative multiplayer residential configurator exploring user-directed design and authored space plans, non-player character (NPC) interaction, and downstream supply chain considerations for furniture elements in urban infill scenarios. The game mechanics feature t-Distributed Stochastic Neighbour Embedding (t-SNE) [77] to visualise data in 144 dimensions. The user's decisions were analysed using a clustering analysis, a form of unsupervised machine learning, to

| | DRL | Mobie | V2 | Ikigai | Beyabu BETA | Beyabu RELEASE |
|---|---|---|---|---|---|---|
| Game Mode | Multiplayer - Turn By Turn Agent-based | - Sandbox<br>- Challenges | - Procedural Arch Geom Explorator | - Configurator | - Explorator - Configurator | - Configurator |
| Player Actions | -Select Cluster<br>-Select Voxels -> Expand Unit<br>-Create Rooms<br>- Create Furniture<br>- Rent or Buy | - Site mass<br>- Module Placement<br>- Space - furniture customization<br>- Style customization | - Unit Selection (Explorator)<br>- Tectonic Preference<br>- Space customization | - Cluster Selection<br>- Unit Select and Placement<br>- Air Rights<br>- Space layout selection<br>- Style Selection | - LevelSelection<br>- Unit type and Placement<br>- Add Ons<br>- Air Rights<br>- layout Selection | - Cluster Selection<br>- LevelSelection<br>- Unit type and Placement<br>- Add Ons<br>- Air Rights<br>- layout Selection - Flip |
| IO | - Procedural<br>- Static Prefabs .OBJ | - .OBJ Static | - Procedural | - .OBJ | - JSON + .OBJ | - JSON + .OBJ |
| Camera | - VR - First Person | - Rotation | - Orbit<br>- Pan<br>- Zoom | - Orbit<br>- Pan<br>- Zoom | - Orbit<br>- Pan<br>- Zoom | - Orbit<br>- Pan<br>- Zoom |
| Pixel streamed - Web | - No | - No | - No | - Web App | - Yes (AWS) | - Yes (AWS) |
| UI Framework | - Unity UI Components | - UE4 Widget BP | - UE4 Widget BP | - React JS | - Javascript, Html, CSS | - Javascript, Html, CSS |

**Fig. 6** Configurator legacy builds comparison

categorise data for potential end-buyers. A downstream agent-based simulation evaluated user parameters and proportions to gauge population sentiment. Content was created by discretising rooms into volumetric sub-modules (Fig. 7) for bespoke furniture configurations (Fig. 8). The proportion and scale of the modules corresponded such that downstream procedural creation of furniture objects, for instance, two modules configure a chair, four modules configure a table, and eight modules a single bed.

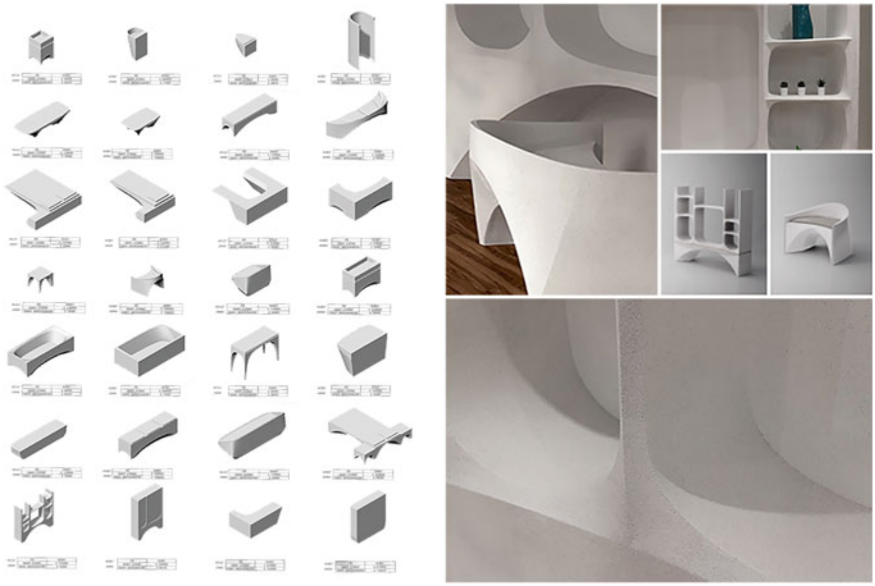

**Fig. 7** Conversion of volumetric modules to customised furnishing. *Image Courtesy* Oikos, AADRL

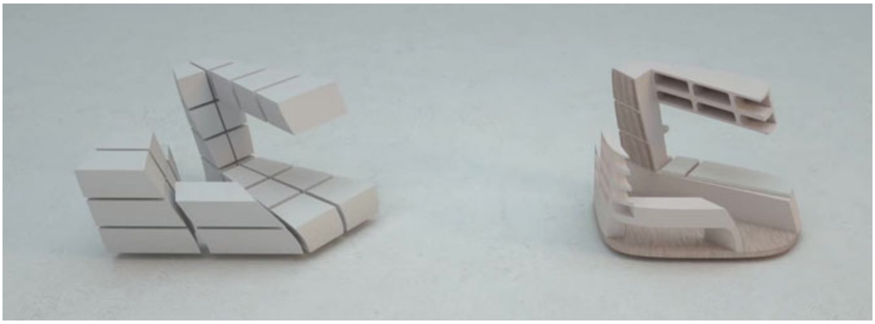

**Fig. 8** Robotic hot wire cut furniture set. *Image Courtesy* Oikos, AADRL

Robotic hot-wire cutting (RHWC) technologies were leveraged in the production of 1:1 mock-up for a chair, and a bookshelf (Fig. 7). The design of architectural geometry [78] as fabrication aware and complete digital design to the production pipeline. A 6-axis robot carved polystyrene foam blocks to achieve ruled cuts following curvilinear toolpaths in a fraction of the time of CNC milling or conventional carpentry for similar shapes [79].

The Ministry of Building Innovation and Education (MOBIE) Design Challenge 2020 is a single-player residential configurator exploring human–computer interaction (HCI), and gamification principles. MOBIE features challenge modes as training sessions to familiarise with the GUI, content types, and to teach mechanics. For instance, users are asked to orient rooms vectors to face views encircling a courtyard, and in another to construct a contiguous stairway between a given set of rooms and obstacles in a section with only a fixed number of rotations or fixed number of tiles in the latter to accomplish this objective.

Subsequent ZHA platforms focused effort in integration to the zSpace framework in C++, [80] the procedural creation of geometry, the creation of building components kits in walls, floor slabs, façade panels, columns, and dashboards for a variety of user groups, as a design-assist toolkit.

### *4.2 User Interface and Dashboard Development*

Interface design at ZHA is tuned to specific package deliveries and profiled to specific user audiences. In general, the dashboards are tuned to non-expert users, with a filtered set of design templates available for selection, with limited onscreen functionality amenable to tablet and mobile (Fig. 9). In master planning, we are exploring Microsoft PowerBi integration for parcel exploration for buyers, facade panel exploration for fabricators, interior fit-out modifications for occupiers, building components swap for architects, and site planning development. Progress bar advancement, real-time analytics, display dashboards profiled to users, and incentive mapping are notable. The gamification principles implemented in the Configurator are detailed in a sequence of storyboards that serve to set-out the backend infrastructure.

### *4.3 Components: Content Creation*

Recent rapid advances in the field of form-finding have led to the popularity of architectural geometry [78, 81] as fabrication-aware design geometry incorporating essential aspects of function, fabrication into the shape modelling [82, 83]. The use of discrete mesh geometry representation is ubiquitous in computer graphics and animation industries, and hitherto utilised for intuitive design manipulation, and lightweight computation in a Mesh Modelling Environment (MME) [84].

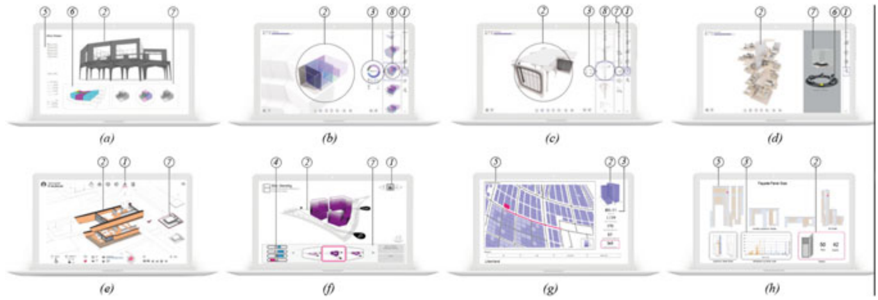


**Fig. 9** ZHA dashboard design for: **a** designer, **b** occupier: house plan, **c** fabricator: house fabrication method and style, **d**, **e** occupier: house furniture selection, **f** masterplan developer, **g** masterplan investor, **h** tower facade fabricator. Dashboard elements: 1. progression stages indicator, 2. current selection, 3. analysis/performance info panel, 4. warnings/prompt info panel, 5. selection menu: home, 6. selection menu: component, 7. selection menu: variation, 8. selections filtered by availability

The shape modelling of building components is informed by innovations in fabrication becoming stylistic drivers a so called 'Tectonism' [85]. Industrialised construction building components have been developed in each RHWC concrete and singly curved columns for robotic abrasion cutting in timber (Figs. 10 and 11).

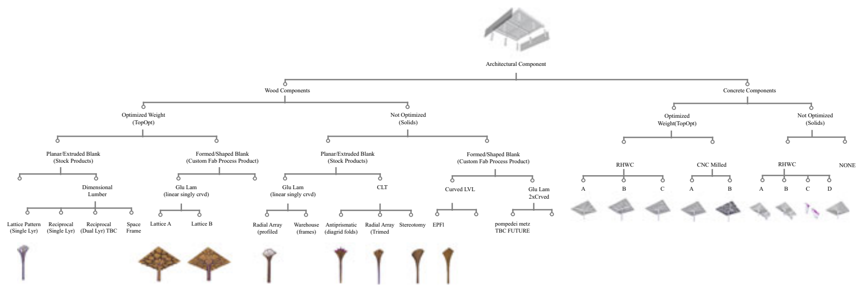


**Fig. 10** Content creation: industrialised construction building components tree

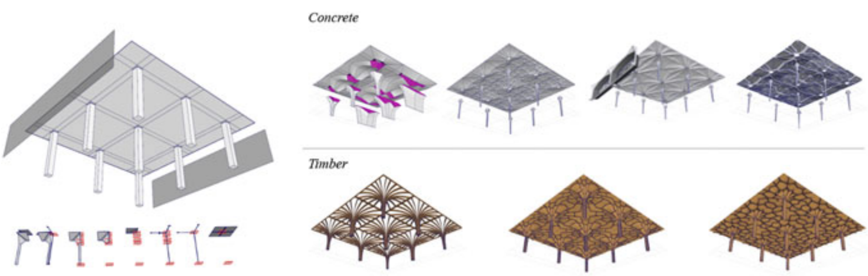


**Fig. 11** Content creation: style sets of building components

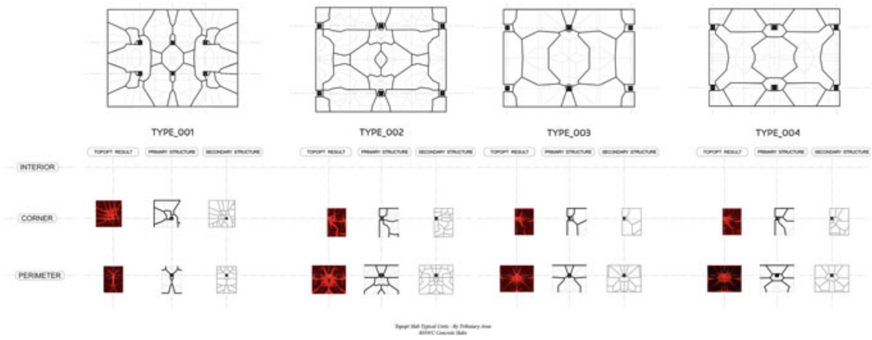


**Fig. 12** Content creation: topology optimised floor slab tile components

Likewise, lightweight high-performing floor components exhibit material reduction via a so-called topology optimisation (TO) [86] extrapolated according to the grid position as interior, perimeter, or corner condition (Fig. 12).

## 5 Configurator

The Beyabu configurator (Configurator) is an extension of platform design at ZHA toward residential applications in remote island economies for subtropical coastal sloping terrain, leveraging mass timber in kit of parts components. It invites prospective home buyers and investors to design a customised residential development in a buyer-directed and planned community arrangement for a charter city development made possible through a Zone for Employment and Economic Development (ZEDE) governance model in Roatan, Honduras.

The game actions designed for the user experience (UX) (Fig. 13) represent an easy-to-use gameplay where buyers can configure the unit typology, aggregate placement, cladding add-ons such as roof types, development usage rights, interior space layout and fittings (Fig. 14), while cladding elements such as windows, and opaque walls, and balconies are automatically placed to maintain consistency of the overall development.

ZHA conducted two sessions of client builds using the platform separated by a 6-month period. After the first round (Pilot Build) we gathered data and user requests including datasets from the build itself and additional feature requests from a verbal questionnaire format. The verbal and numerical feedback was analysed, and insights were extracted to update the unit typologies for engineering feasibility, the game mechanics, rules, kit of parts components on offer, and functionality in gameplay. A second session (Sales Release Build) of configuration was conducted with the updated environment model, engineering feasibility, game features and functionality for thirteen buyers.


**Fig. 13** Configurator game stages and progression

**Fig. 14** Configuration toggles for a modular interior

## *5.1 Configurator: Pilot Build and Customer Needs Aquisition*

The Pilot Build sessions of the platform were remotely conducted in a real-time web-based application and simultaneously the designer, client, and prospective buyer linked via video conferencing. A client representative communicated motivations and next steps not in-game, while a ZHA representative presenter explained the Configurator interface, general capabilities, and provided passive in game guidance during the configuration session. For instance, at each screen progression the presenter provided supplemental info content types on offer not yet in-game. Additionally, the presenter collated game feedback at end of the build session for content, add-ons for future selection development assessed to be likely in closing a sale. Likewise, the presenter recorded the gameplay features and functionality that would empower future autonomous use of the Configurator without video conference assistance.

An environment model with an empty system grid of the available terrain on offer—*a gameboard*—was presented to each buyer alike. After running thirteen configuration sessions, during which several configurations were tested, the final configuration options of each player were submitted, and a report of the configuration itself was generated for the buyer to retain. A total of 72 configurations were conducted. The system is distinctive from later builds in that it presented:

1. one unified system grid to position within
2. the buyers all made first placements in the development
3. three available space planning layouts per unit typology
4. air and development rights were explicitly selectable and procurable.
5. balcony projection distance was offered.

### 5.1.1 Session Results and Feature Planning

The selections per stage of the Configurator were automatically logged per player, per selection, to a spreadsheet. The session selections include system grid selected ID, transform matrix (position, rotation, and scale), space plan layout typology, development rights selection, balcony extension typology, and roof typology selected. The results were extracted and replicated as a 3D composite of selections and trends (Fig. 15) evaluated by the design team. User preferences and trends are as follows:

1. top-level grid spaces were preferred in comparison to lower spaces, for the expanded view vistas and for preserving the void above without having to purchase the rights to retain such.
2. end of block ‘aisle’ grid spaces in lieu of middle grids as it guaranteed a multi-window aspect unit, limiting the potential for demising walls to a neighbour while also preserving the immediate vista (at least to the property line itself) without having to purchase the rights to retain such.
3. space layouts that maximised the quantity of beds/number of people hosted to sleep.
4. social areas, which for Latin America included both the living and kitchen, contain panoramic views, which are predominantly the forward-facing voxels.

Buyers tended toward larger balcony upgrades including deck and cover area with the rationale the proportional cost relative to the unit total was trivial. While only a

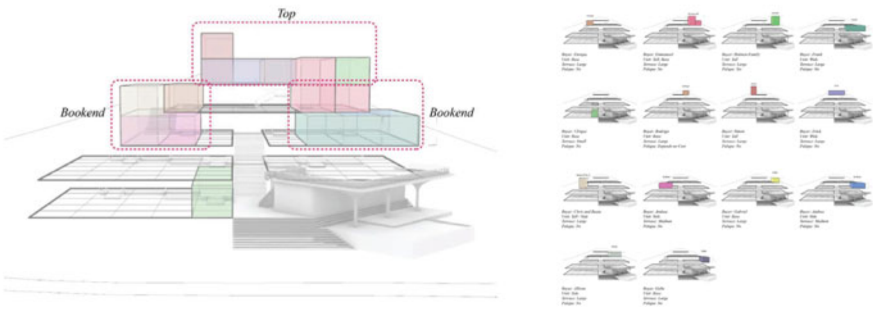


**Fig. 15** Position selections in game sessions overlay

minority of buyers chose to purchase view preservation rights in neighbouring left and right voxels to maintain a neighbouring buffer and increase window aspects of their unit. Buyers tended to select development air rights to actualise private roof terrace upgrades and custom vaulted rooftop known as 'palapas' regionally (Figs. 16 and 17).

As early adopters of the planned development, buyers could steer content offerings for the subsequent Configurator build. Buyers made verbal requests during the sessions which were tallied offline and sorted as feature requests, functionality requests, or content creation requests (Fig. 18). Most requests sought to increase the occupiable gross floor area (GFA) without paying for additional voxels focused on the interior layout and space planning stage of the Configurator.

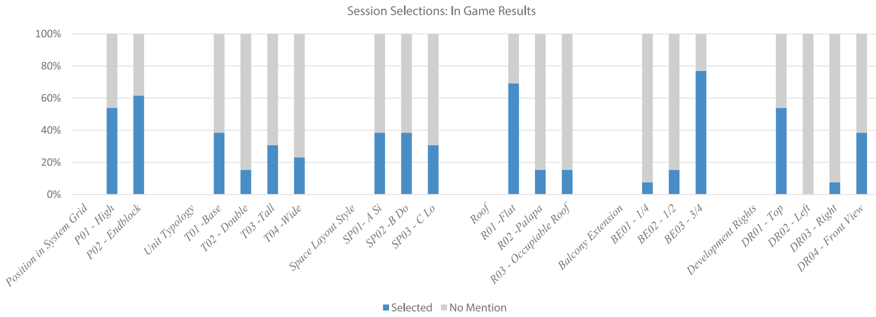


**Fig. 16** Buyer selections data

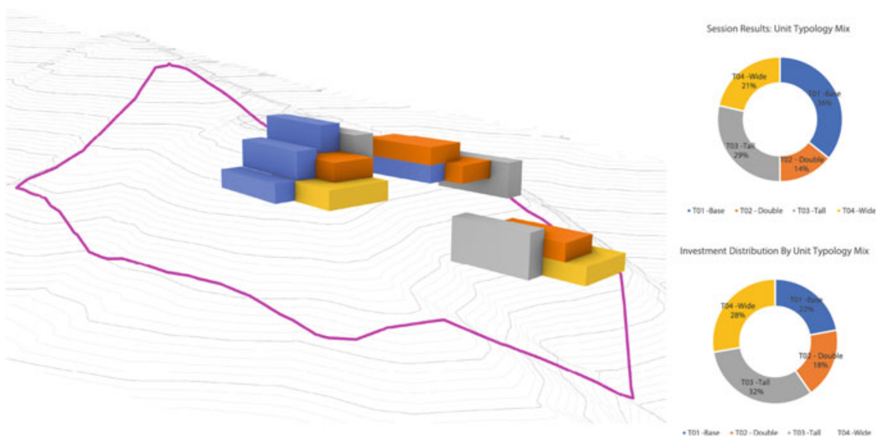


**Fig. 17** Buyer unit typologies selections

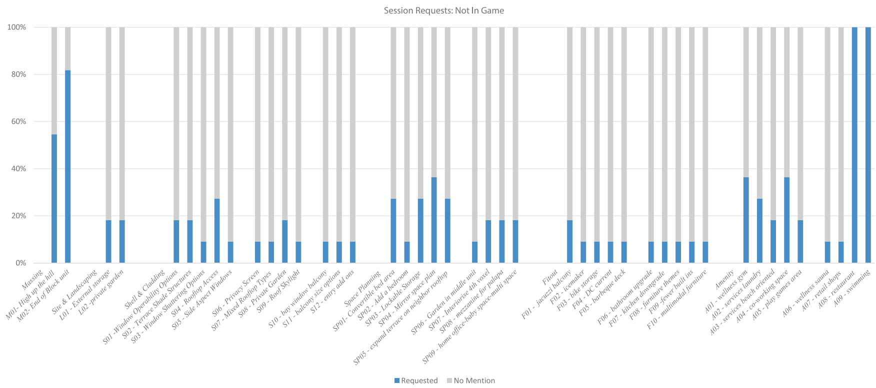


**Fig. 18** Buyer requests data

The notable session trends are below:

1. Mezzanine—Height permitting, when a unit is upgraded for a palapa roof, exploit the unleveraged voxels in secion above resulting in an infill mezzanine floor option.
2. Increase occupiable interior area—To increase interior space, optimise habitable space already committed in the voxel count for the typology by swapping an exterior voxel for an interior voxel.
3. Increase sleepcount—As the primary motivation for living is long stay, there was a desire to increase sofas, increase bed count in smaller units, and increasing bedroom counts in larger units.
4. Layout context awareness—Depending on their position on the stack, the direction of side windows or the orientation of the living room relative to the view needed mirroring capability.

## *5.2 Configurator: Engineering Feasible Solution Sets and Rule Set Creation*

The Pilot Release demonstrated low-density residential design and planning principles could be extended interactively to non-experts via a technology platform to empower customisation in real-time to participants around the world.

Construction feasible configurations planning for Sales Release necessitated resolving challenges posed by Pilot Release. Engineering integration in a fixed subset of RBU configurations development and applicability as systems design principles to broader permutations. The relative applicability and market alignment of feature and functionality requests by a small initial number of respondents.

Content such as rooftop access, bathroom size upgrades, and side balconies for multi-aspect unit configurations posed challenges to the spatial proportioning system as sub-voxel ratios. While side facing unit plans, balcony projections, and tall units posed structural challenges to the system design conceptually in its panelised assembly, assembly build-up, and primary spanning direction allowed in the 5 × 5 grid.

The compositing of the Pilot Build results exposed several preferential tendencies. Since few users selected horizontal view rights, and predominantly users selected end-of-block grid positions. The Pilot Release results challenged the idea of explicit sale of development rights and challenged the default relative equality of grid positions in the game board. Taken in combination, the results suggested implicitly capturing the result of horizontal view rights by way of increasing the quantity of end-of-block cells in the game board would result in greater monetisation potential, and reconciliation of positioning demand experienced in Pilot Release.

Considerations for regulatory feasibility rules in the game board creation were planned between releases. For instance, the maximum height positioning on existing cells considers the building type regulation for mass timber construction in residential occupancy. Similarly, the consideration for fire regulation is demonstrated in the minimum distances between community grids set out. Each affect the system grid creation prior to game play and active cells available for during game play.

The period between Pilot Release and Sales Release resulted in several functional improvements to the game mechanics, but more importantly the content and feasibility of content offerings on offer. The kit of parts, superstructure, space planning, and land planning principles were validated across the engineering spectrum via Structural, Mechanical, Plumbing, Electrical, and Fire consultations (Figs. 21 and 24).

The use of identical gameboards in the Pilot sessions necessitated a reconciliation operation to understand the implications of overlapping units as community spatial preference and understand the implications of regulatory feasibility for planning the Sales Release. Reconciliation consists of extraction of elevation height and end-of-block view aspect to sort the selections (Fig. 19). These preferences are superimposed with the regulatory land planning principles for mass timber residential construction. Together with a Sales Release amenable grid, the position principles are redeployed manually to provide a suitable basis community amenable to Sales Release development in parallel to engineering development on a basis community aggregate.

This approach exposed the need for more end of block unit positions, which implicitly retained side view rights offered in Pilot explicitly. It also exposed a general tendency toward reduced density for the overall development driven by buyer preference as void 'aisles' between clusters reduced the developable footprint possible compared to a conventional elongated frontage coastal condominium development (Fig. 20).

A component strategy was established between build releases to encode construction feasible engineering principles in the system design ruleset planned for Sales Release. For instance, incoming electrical service walls, fixture positioning in voxel relative to timber cassette knockout panel corners, and number of air handling

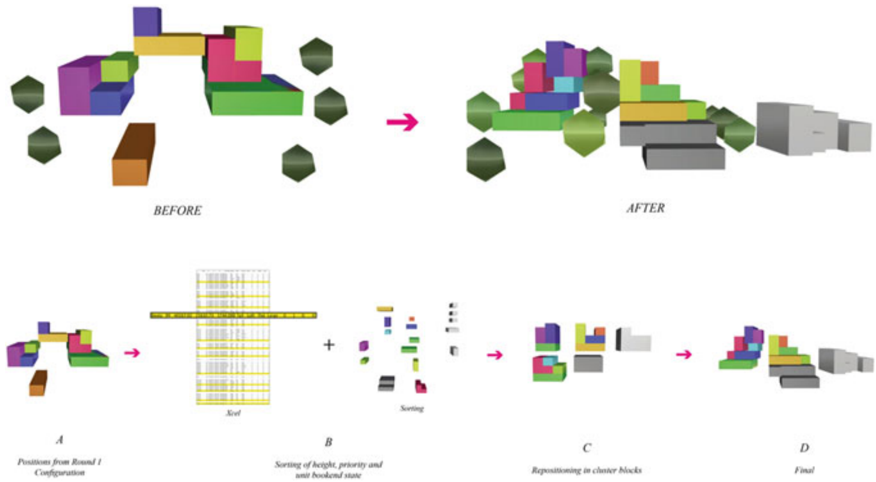


**Fig. 19** Reconciliation of buyer positions

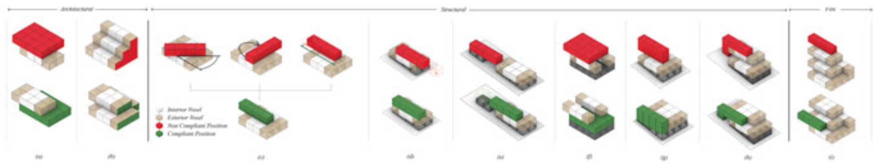

**Fig. 20** Game mechanics unit rulesets visualised. **a** place wide units toward bottom, **b** avoid multi-story co-planarity, stagger units in plan, **c** maintain unit-to-grid parallel orientation, **d** avoid unit cantilevering overextension, **e** stagger units in elevation, **f** avoid void spaces on plinth, lower center of gravity, **g** place vertical units in contact with plinth, **h** limit excessive vertical access, increase horizontal aspect ratio, **i** maximum cluster height: 3 levels

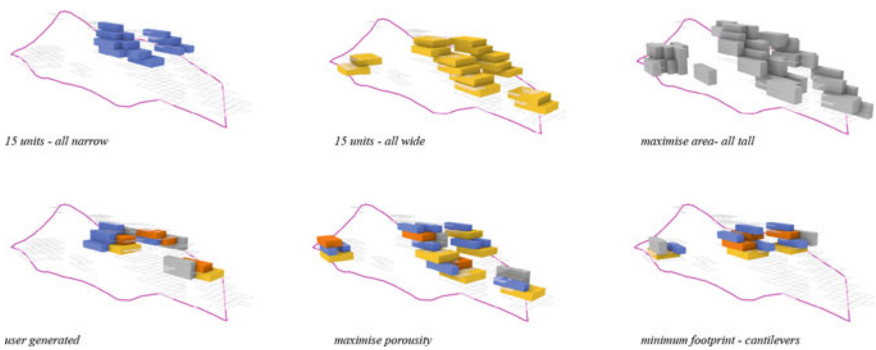


**Fig. 21** Feasible permutations of community positioning directed toward specific objectives

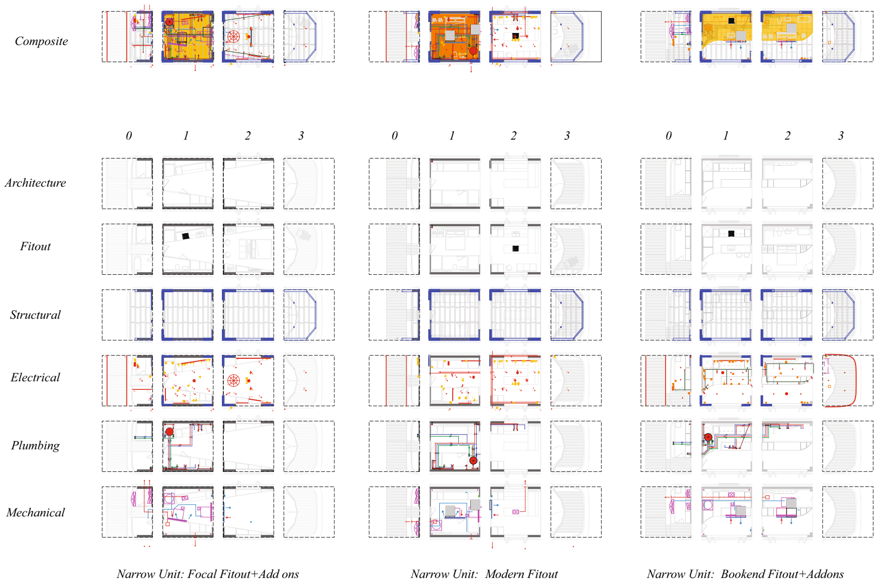


**Fig. 22** Engineering principles validated in systems design

cassettes per voxel were developed in conjunction with engineering disciplines as examples of Configurator principles (Fig. 21). The Configurator results in subsequent platform build Configurator sessions are engineering aware resulting in construction feasible solution sets due to the system design platform approach to the engineering discipline's design. Likewise, the general rigid body physics, stacking, and unit associations allowed at the community aggregate level are structurally aware in game play. System design principles for stacking rulesets explicitly encoded for future game board terrain typologies exhibiting varied sloping properties (Fig. 22).

The more notable of structural principles includes clusters must be wider than tall, tall units must reside on the concrete plinth for steel interfacing, and the units are parallel in placement not perpendicular or skewed, though may translate away or toward the hillside. These assume a mass timber panellised structural design for remote coastal sloping deployments.

Likewise, the space planning kit of parts rulesets are developed for modular voxel-based interior layouts in 3 style sets (Fig. 23). Notable Sales Release content add-ons and upgrade selections include bathroom upgrades, such as exterior sheltered bathing and freestanding fixture-oriented bathrooms, added mezzanine floor kits, truncated 1/2 voxel floors inside balcony view units, and rooftop access via private stairwells (Fig. 24).

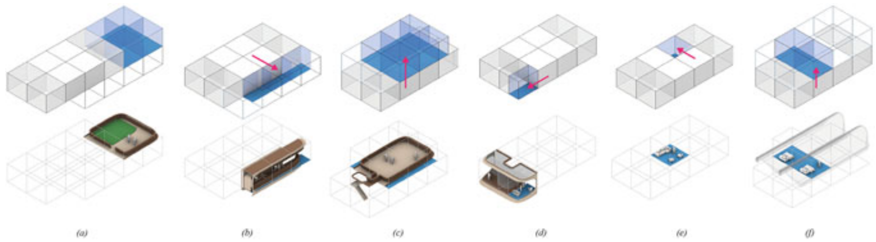


**Fig. 23** Customised interior fitout raft as style set

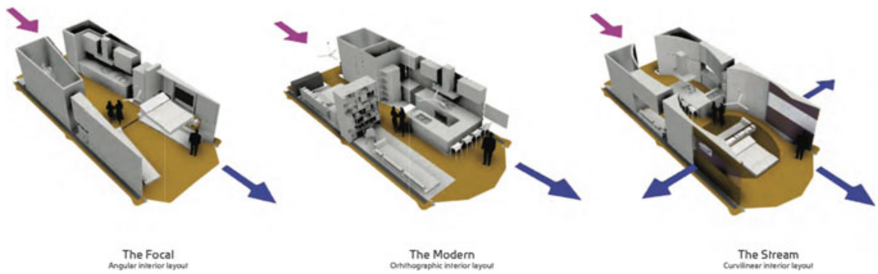


**Fig. 24** Construction feasible unit upgrades and add-ons **a** extended terrace over bottom unit, **b** side balcony, **c** roof terrace, **d** entryway voxel customisation, bathroom expansion, **e** internalised outdoor living, **f** mezzanine

## *5.3 Configurator: Sales Release Build*

During the Beyabu Sales Release the client broadened the audience pool to include early adopters, and investment buyers. The Configurator was packaged as a stand-alone application identical to Pilot. The sessions were conducted without the presence of the design team. A client-side representative was trained in general technical considerations, such as the need to restart a session, or reboot the application remotely. After running forty-two sessions, during which several configurations were tested, the final configuration options of each player were submitted, and a report of the configuration itself generated for the buyer to retain. A total of twelve configurations were conducted. The system grid generation was updated to reflect a new property boundary with more sloping terrain.

The Sales Release took into consideration the turn-based placement by previous buyers in the gameboard presented in the current game session. On game initialisation all previous player actions were procedurally reloaded in the scene. As such the sequence of the sessions influenced the decisions of the following sessions. The first buyer had priority to choose positions from a blank gameboard, much like the Pilot Release (Fig. 25), but subsequent sessions the aggregate of units became more and more tailored to the direction of the community of buyers. Once an order was processed the system locked all the voxels reserved in session. Sessions could see


**Fig. 25** Gameboard initial screen comparison

both the on-screen units by their previous placed neighbours as well as who owned it, whether it was an investment property or would be occupied by owner and the configuration options they had selected.

The system is distinctive in that it presented:

1. Multiple system grid sets around a hillside to position within
2. buyers were presented all prior session RBU's at initialisation
3. air and development rights were implicitly managed via the system grid creation number of grids wide
4. balcony projection distance was discontinued
5. Engineered upgrades not implemented in the Configurator platform at time of release were offered through a supplemental buyer catalogue
6. Selecting a palapa roof upgrade unlocked an additional fourth space plan option to optimise GFA via an infill mezzanine floor.
7. Space plans could be mirrored depending on their location and sunlight preferences.

### 5.3.1 Session Time

On the Sales Release hosted on AWS users on average spent more than 5 min per session which is less than the United States average of 6–10 min on e-commerce websites [87] (Fig. 26).

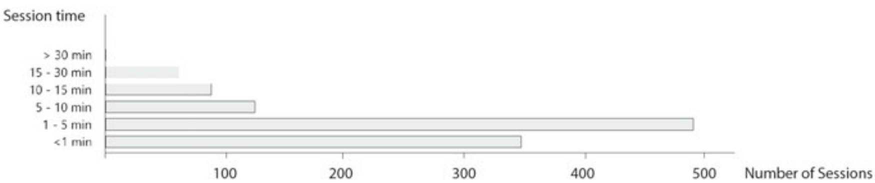


**Fig. 26** Session time

# 6 Workflow and System Design

The Configurator was produced in Unreal Engine 4 (UE4). A bespoke toolchain was developed and implemented across a small team of six as detailed in (Fig. 27).

Content creation, data preparation, storyboarding and GUI design, and software front-end and back-end development were delineations of internal task splitting.

## 6.1 *Mechanics*

The Configurator session guides a buyer through several configuration session states, from positioning, to RBU cladding options, to contractual options, to interior layout options. The gameplay progression states are detailed in (Fig. 28). The session is advanced with each selection. The configuration state is visible and toggled selections comparable in first person perspective as walkthrough or globally in an aerial camera.

Several gamification core drives enhance gameplay as outlined in (Fig. 29). Info panels displaying the community selections, and what positions have been frequented provide a sense of inclusion and urgency (Figs. 30 and 31). Cost reporting of the selections is calculated in real time. The daily shadow casting preview gives a visual

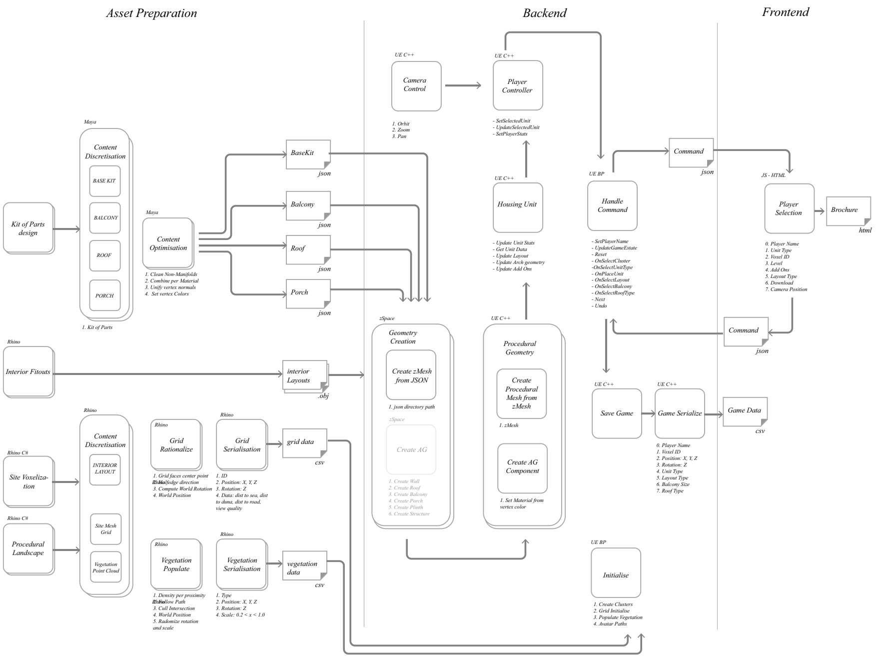


**Fig. 27** Bespoke tool-chain and workflow

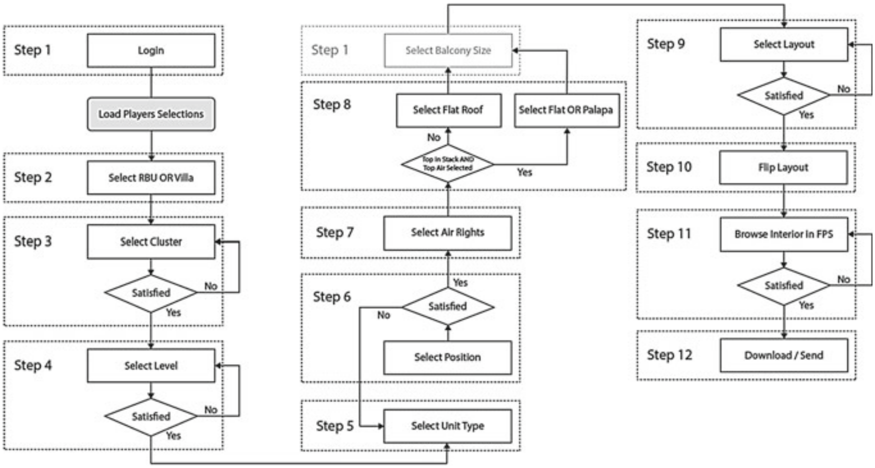


**Fig. 28** Game mechanics diagram

indication of the overall community massing upon the selected position, as well as the illumination falling upon the windows, balconies, and roof. The Configurator concludes in a downloaded report of the unit configuration.

While the system grid is created outside the platform and statically loaded as a ‘gameboard’ each session, the active positions within the session are managed dynamically (Fig. 32). There are several positional dependencies which result in an active grid cell highlighting on rollover. The system analyses the available voxels

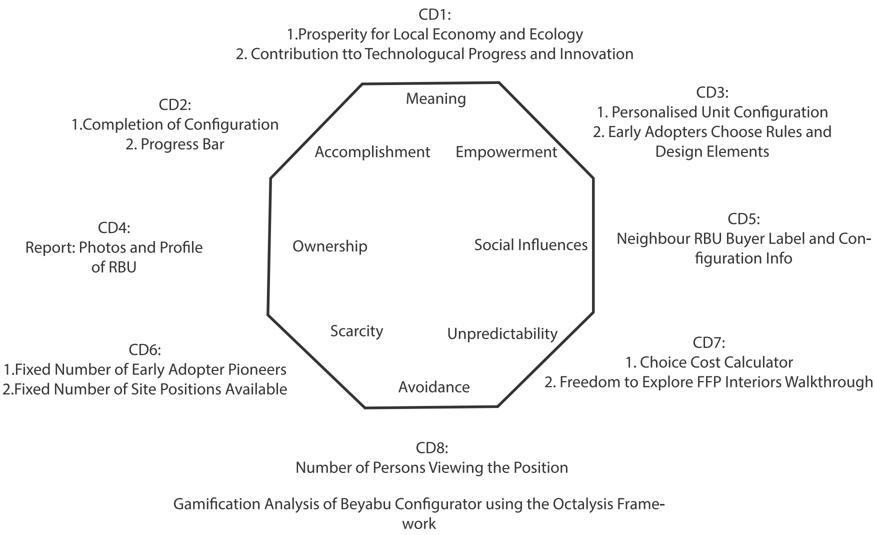


**Fig. 29** Configurator gamification analysis using octalysis framework

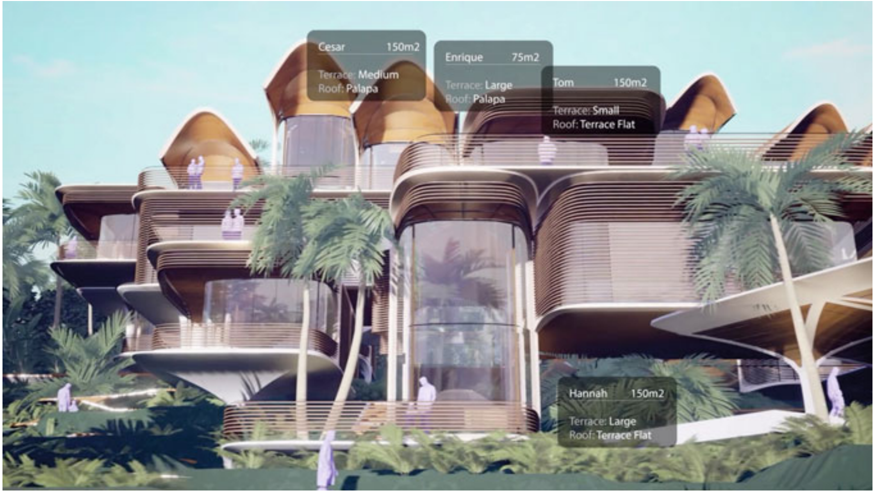


**Fig. 30** Overlay of kit of parts selections of neighbouring units


**Fig. 31** Overlay of space organisation arrangement of neighbouring units

required for the specified unit typology voxel count, computing collisions, and if the unit overextends the available cluster grids in the gameboard (Fig. 33). If the constraints are satisfied and the unit highlights as a valid system placement.

Similarly, the system enforces rules for the kit of parts dependencies. For instance, if the player selects "top air rights" in session and no unit exists above the selection, the system 'unlocks' a palapa roof type content option in the roof type selection stage. While there are 54 permutations of an RBU in the Pilot Release, there are

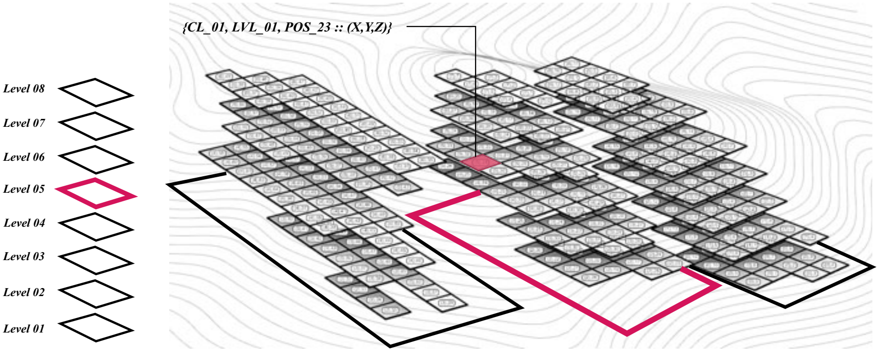


**Fig. 32** System grid data-structure

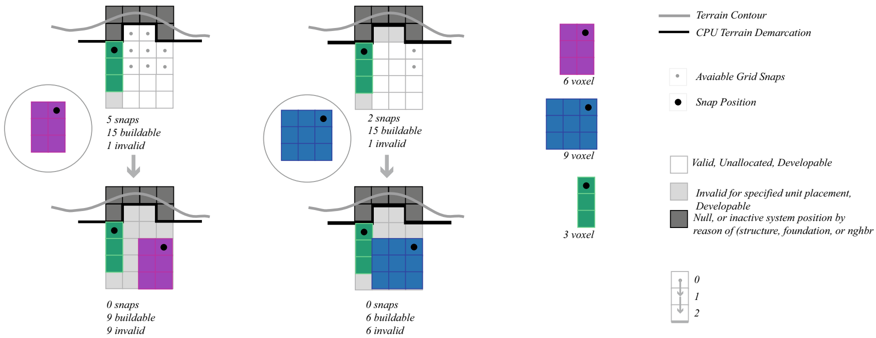


**Fig. 33** Unit placement dependencies and dynamic grid state change

roughly 300 active grid cells available in the gameboard when initialised, resulting in over sixteen thousand feasible community aggregations (Fig. 34).

The shadow analysis function gives buyer feedback on exposure of the unit envelope, glazing. It is further extended as a colour coded depth map to nearby unit obstructions such as property vegetation and neighbouring units to give relative visual feedback on the selected position relative to the overall community mass and line of sight to various site features (Fig. 35).

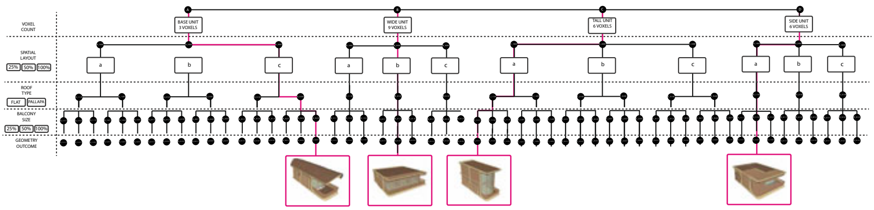

**Fig. 34** Possible variations

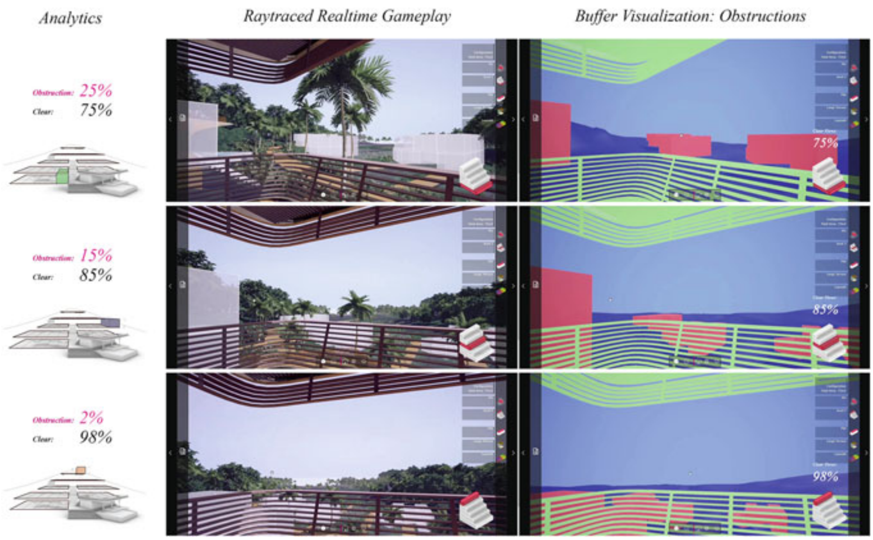


**Fig. 35** Unit obstruction and depth mapping in-game

## *6.2 Assets and Content Creation*

The environment design terrain mesh, system grids gameboard creation relative to sloping terrain, access-ways, and context building and water were procedurally generated in Rhino and exported to UE4 as separate OBJ's. While the vegetation, entourage, lighting, and materials were natively created in UE4. The RBU geometries consisting of cladding panels, structural assemblies, interior partitioning, built-ins and furnishing elements were modelled procedurally in Autodesk Maya and broken into a kit of parts in Rhino to be hosted to a voxel face edge or vertex using a half-edge data structure (Fig. 27).

The environment terrain and system grid are procedurally created in Rhino (Figs. 36 and 37). A custom utility was created to discretise the terrain into volumetric voxels corresponding to the unit floor-to-floor height and with a buffer distance to the intersection to the sloping terrain. The cells are controlled in grid groupings of between 6 and 12 cells wide radially arranged about the hill faces toward the water. The lowest datum allowed is pre-set, but all subsequent datums 6 voxels away from the hill intersection (corresponding to a unit maximally 10 m forward of the hill) are returned as viable system grid positions for the gameboard (Fig. 38).

Manual polygon modelling and parametric data preparation were used to organise and transfer assets to the Configurator. The kit of parts consisting of cladding, structure, interior layout, concrete plinths, roofs is detailed in Fig. 39. The combinatorics of such results in variations in unit shell and spatial arrangements (Fig. 38).

They are manually modelled and broken into per-face components and assigned coloured attributes per vertex. Interior partitions and furniture are combined in UE4


**Fig. 36** Variations in a system grid generation and resulting aggregates


**Fig. 37** Massing qualitative analysis of unit positions. *Image Courtesy* Hilson Moran

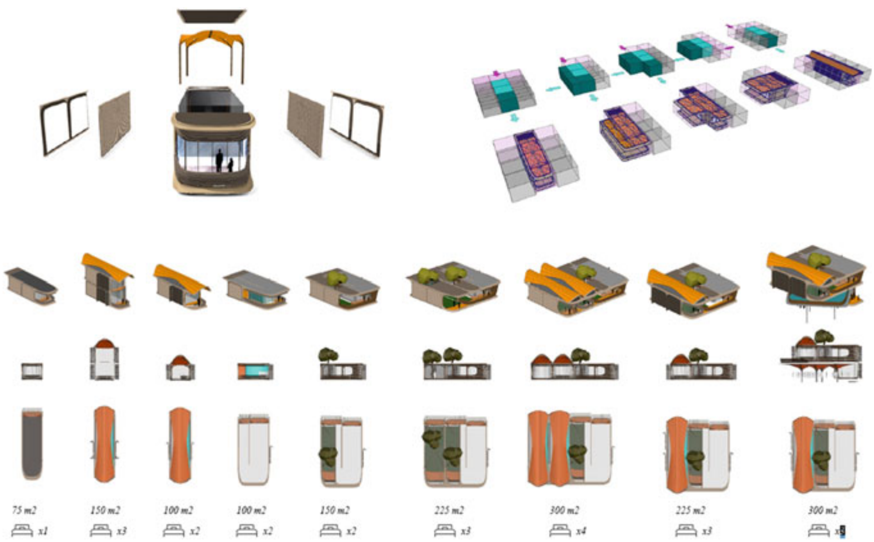


**Fig. 38** Unit variation from a digital kit of parts

**Fig. 39** Configurator kit of parts

per spatial layout typology and assigned the corresponding material per face. Assets are manually exported from Rhino about the origin and composited in UE4 for collision checks.

In addition to the 3D kit of parts, the corresponding 2D technical drawings for 13 unique unit variations leveraging every kit of parts component per produced to a RIBA stage 3 for architecture, interiors, structural, mechanical, plumbing, electrical, and fire protection with particular attention to the system design principles for deployment across multiple sites in the lifespan of the technology platform.

Lastly, the GUI and buyer downloadable report (Fig. 40) consisted of renderings, diagrams, illustrations, and iconography developed for the Configurator and from various stages in platform technology development.

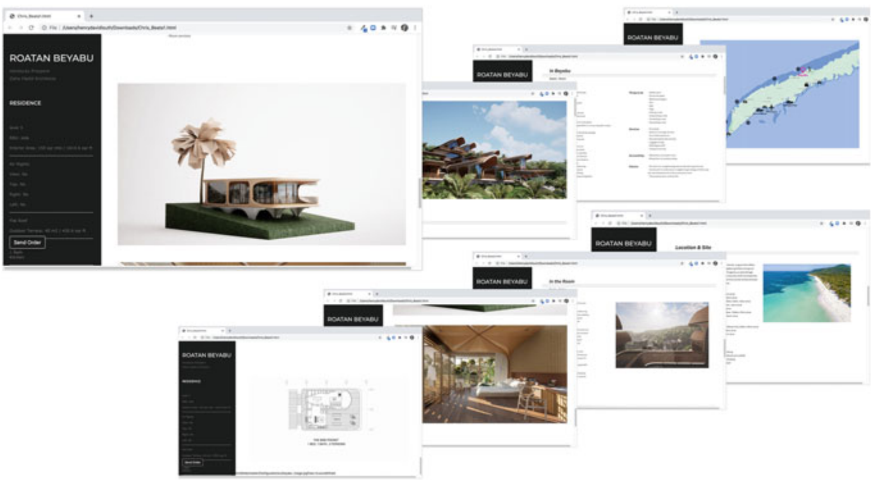


**Fig. 40** Configuration downloadable report

## 6.3 System Architecture

The system architecture of the technology components of the configurator are as follows:

1. Data preparation
2. Asset Transfer API
3. Backend Server
4. Database
5. Client API
6. Client Frontend

### 6.3.1 Data Preparation

The grid gameboard is imported into UE4 and its corresponding analytics data is created per cell. Each grid geo-location holds information not only about its physical transformation in 3D space, position, rotation and scale, but also further contextual data analytic such as distance to the sea, distance to the road, distance to the clubhouse, number of steps required to climb, height above sea level, view quality and radiation exposure. This data was serialised into CSV format and plugged into the platform corresponding to the data structure needed for game initialisation (Fig. 41).

Utilising a half-edge mesh data structure hosted at a voxel face, edge, or vertex. Attributes such as materiality were given through vertex colours which could be transferable as a JSON format across multiple software. Every asset is manipulated through matrix transformations during gameplay, so all the assets had to share the same origin relative to the host voxel.

Space plan layouts and interior layouts are also organised per unit type in UE4 and with a curated style of finishes. They also need to be organised with a common origin matrix matching the parent voxel hosting them.

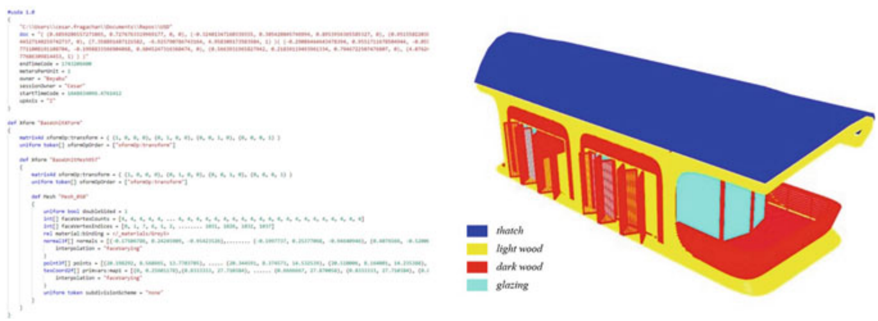


**Fig. 41** Asset coordination and data preparation

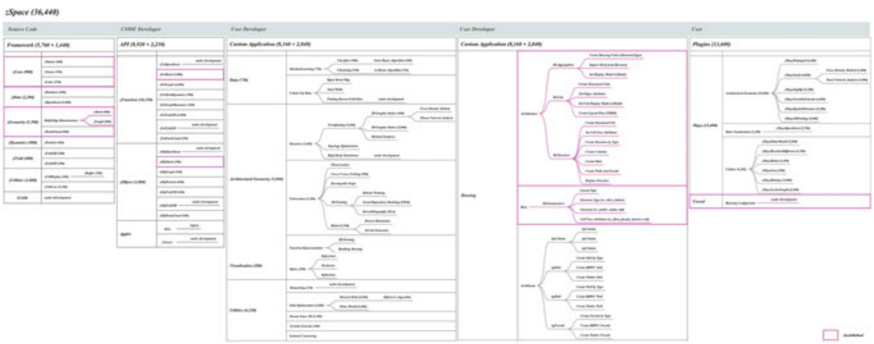

**Fig. 42** zSpace C++ framework

### 6.3.2 Asset Transfer API

To keep a non-destructive workflow, we have developed a data-transfer protocol to manage the platform assets. The components are exported as JSON objects holding vertex and face attributes based on materiality. The interior layouts are exported as separate high-resolution polygon meshes in OBJ format with its corresponding finishing (material) file.MTL. The grid gameboard and the vegetation information from the landscape design are exported as a CSV file that holds per-voxel attributes per row and positional data, respectively.

### 6.3.3 Backend Server

The platform back-end is the core of the system developed in-house. *VaRest*, a UE4 plugin that handles REST[1] server communications at runtime, and Pixel Streaming (PS),[2] a UE4 internal plugin to enable a packaged UE4 application to run on a server in the cloud. The *zSpace* libraries handle the procedural generation of geometry at run-time while processing the JSON asset files (Fig. 42) [80]. The UE application runs on a server, either a local host or Amazon Web Services (AWS) host, and it handles the Client's request and updates the game state per action.

[1] A RESTful API is an architectural style for an application program interface (API) that uses HTTP requests to access and use data.

[2] Pixel Streaming allows a packaged Unreal Engine application to run on a server in the cloud, and stream its rendered frames and audio to browsers and mobile devices over WebRTC, a free, open project that enables web browsers with Real-Time Communications (RTC) capabilities via simple JavaScript APIs.

### 6.3.4 Database

Once a player reserves and RBU and the session completes, the system packages a brochure available to download as an HTML file with variables and collects images corresponding to each of them from a cloud-based database. The Client front-end collects every action or buyer decision and keeps a record of the variables as an order of selection for each customised RBU. These include Player Name, Selected Cluster ID, Selected Level Number, Selected Unit Type, Geo-location of placed Unit (Voxel ID, X, Y, Z), Selected Roof type, Selected interior Layout, and other Voxel-specific data such as distance to the sea, distance to the road, and distance to the Clubhouse.

### 6.3.5 Client API

The Client's request is handled by PS and communicates as a two-way stream between the Client front end and the server. Since they are separate applications written in different languages, they communicate through a JSON response that is parsed and processed at either end.

The Configurator was deployed on an Amazon Web Services (AWS) Elastic Compute Cloud (EC2) G4 instance shared through a secured link.[3] We extended UE native API for PS to avoid client-side hardware requirements and technical support. Leveraging Eagle3DStreaming[4] cloud orchestration, controlled instance creation on demand for buyers. Using native UE4 GUI and Widget components during PS caused latency issues. We developed the front end using a traditional web development framework using HTML, JavaScript and CSS styling, to enhance the user experience.

### 6.3.6 Client Front-End

The Configurator is built on top of Unreal 4.26 game engine leveraging real-time ray tracing technology. UE4 handles all the UI, and client-side code written in HTML, and Javascript (JS) and styled in CSS, manages the assets, handles the Client's request, procedurally instantiates the in-game actors and controls the rules of the "game." It uses C++, Blueprint (BP) classes, and has a dependency on zSpace.

[3] Amazon EC2 G4 instances are cost-effective and versatile GPU instances for deploying machine learning models such as image classification, object detection, and speech recognition, and for graphics-intensive applications such as remote graphics workstations, game streaming, and graphics rendering.

[4] Eagle3DStreaming is a third-party cloud hosting orchestration provider for Unreal Pixel Streamed applications.

## 7 Outlook and Future Work

The paper has demonstrated that AEC industries can engage stakeholders, to design, co-author, effectively crowd source and democratise the design process. The following areas of work could be improved:

1. **Incentivisation**—Value maps could be implemented on system grid positions and adjusted in session in response to various environmental, and session criteria to enhance feedback available onscreen to steer and inform unit positioning. This feature would be scalable to address multiple data streams and assimilated using visual cues much like theatre or flight seating maps. Currently only active and inactive positions receive onscreen alerts.
2. **Supply Chain Integration**—The digital end-to-end pipeline can be extended to the level of detail of fabrication parts, supply chain planning, and manufacturing data of timber structure and cladding components to improve design awareness, reduce the time of design-to-production pipeline leading to occupation (Fig. 43). The digital pipeline currently terminates at the reported configuration.
3. **Procedural Geometry**—The geometry of the units, interiors, and materials could be procedurally generated in the software stack. Currently, the system has been developed as an API to receive such methods in the correct data structure, but the content is loaded as static meshes.
4. **Asset Management**—The content database could be dynamically managed, assemblies coordinated during creation, and directories automatically synchronised. Over one hundred content organising directories responsible for the configuration kit components is difficult to maintain and coordinate manually and are not a scalable protocol for more complex game scenarios, or more robust functionalities and selection sets. 3D Scene Descriptions The compiled scene could leverage Universal Scene Description (USD) or GL Transmission Format (GLTF) to capture more information per asset and the relationship between parts. Currently, the software stack utilised UE4 to compile, coordinate, and data enrich objects.

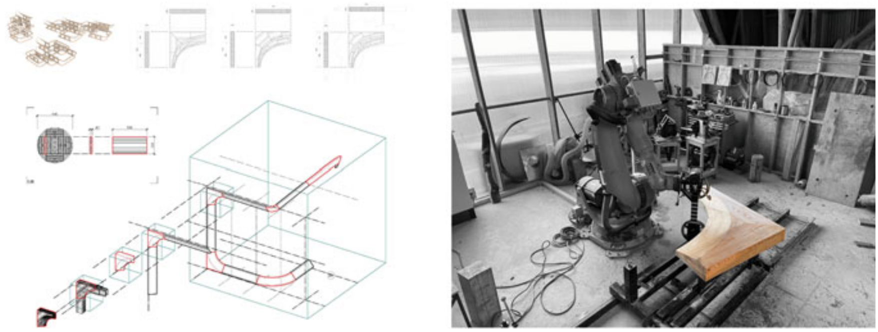

**Fig. 43** Digital supply chain integration via robotic fabrication of timber components. *Image Courtesy* Circular Factory

5. **E-Commerce Features**—The Configurator content could present a local marketplace of digital assets licensed to different regional or local suppliers and artisans who could commercialise their products in the platform. Currently only ZHA-designed content is in the Configurator.
6. **Domain Extension**—The platform framework could be extended to non-residential use domain applications. For instance, urban planning, commercial, retail, and interiors present similar consensus planning and customisation negotiated design problems the platform could be adapted to address.

## 8 Conclusions and Summary

The paper articulates the relevance of game technologies utilisation in the AEC pipeline to achieve a user-centric multifamily residential design. In particular, the contributions as described, demonstrate decentralised buyers can engage in emergent consensus behaviour in property planning and land development. Likewise, the participation of design experts in a self-guided non-expert game environment resulting in construction feasible community is detailed. The resulting session outputs demonstrate mass customisation of components, add-ons, and options each equally exhibits a construction feasible configuration. The timeline required for future configuration outputs is dramatically reduced given the system design principles and engineering aware game mechanics and component creation. Furthermore, bringing together key stakeholders, whether encoded as non-player character rulesets or active gameplay participants, in a shared digital platform can deliver high value, locally relevant, resource effective, supply chain integrated design solutions for residential living.

**Acknowledgements** This research was carried out collaboratively between the authors and with the support of the respective organisations: Zaha Hadid Architects, Epic Games, AKT II, Hilson Moran Partnership, Circular Factory, AADRL Nahmad/Bhooshan Studio, The Manufacturing Technology Center, and Prospera. We would like to thank those in the Computation and Design Group contributing to documentation and design acumen, Jianfei Chu (Truman), Edward Meyers, Cheolyoung Park (Nick), Efthymia Douroudi, Taizhong Chen, with Chun-Yen Chen (James), and formerly Federico Borello, Jackson Bi, Georgios Pasisis, and Leo Bieling.

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# From Debris to the Data Set (DEDA) *a Digital Application for the Upcycling of Waste Wood Material in Post Disaster Areas*

**Roberto Ruggiero, Roberto Cognoli, and Pio Lorenzo Cocco**

**Abstract** The convergence of digital and ecological transition [1] can be crucial in achieving the European Green Deal targets. In this perspective, implementing the Industry 4.0 model in the building sector acquires high value not only for the efficiency of construction processes but also for mitigating the carbon footprint and resource exploitation, traditionally related to the building industry. Considering the circular economy as a paradigm of sustainability [2], the search for synergies between "circular" and "digital" approaches in the building sector represents nowadays a strategic research sector. "Upcycling" demolition material to transform into new building components is, in particular, a topic where digital technologies can play a key role. *«Only by capturing the physical world through data»* [3] there is a real possibility to overcome the limits that have emerged to date in upcycling processes, in particular concerning the control and classification of waste materials. In this context, post-disaster areas represent a remarkable reservoir of available and potentially reusable materials: a "material bank", according to the circular economy vocabulary. DeDa (From Debris to the Data set) is a research work in progress at the University of Camerino, which focuses on reusing waste wood material in post-disaster areas. DeDa represents a new way of applying the principles of the circular economy and Industry 4.0 to debris treatment. This paper describes the aforementioned research work in its cultural and operational aspects, current limitations and future potential.

**Keywords** Digital innovation · Circular building · Disaster area · Data-driven design · Waste wood · Bim · Database

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_41

**United Nations' Sustainable Development Goals** 9. Industry, Innovation and Infrastructure · 11. Sustainable Cities and Communities · 12. Responsible Consumption and Production

## 1 Introduction

In the last 25 years, the advent of digital culture has touched «all aspects of existence, from everyday life to industrial manufacturing, from transport to politics, and from popular culture to the emotional relationship we form with each other» [4]. Architecture—understood as a «permanent process of transformation (…) which contributes to shape the built reality through the use of materials, (…) elements and systems»[1] [5]—has also been profoundly and progressively affected.

Nowadays in the architecture sector, digital tools are made up of a wide ecosystem of innovative technologies that concern the field of design and the industrial production of building systems and components. Parametric and computational design, CNC machines, robotics and other "enabling technologies" are—according to the Industry 4.0 vocabulary—progressively *«changing the ways»,* in many contexts, architects *«communicate and collaborate, analyze and simulate, fabricate and assemble»* [6]. Digital technologies *«not only help us to grasp very complex structures that we couldn't otherwise simulate, they also (…) allow us to gain a depth of understanding about materials, structures and building to predict performances and behaviors»* [6].

Nowadays, in what Mario Carpo called "the second digital turn" [7], digital tools represent much more than *«mere methods that can solve technical problems»*. They provide a "new possibility" *«to change the way we design, build and inhabit our world for a more sustainable future»* [8], or to conceive and produce spaces that are "ontologically" digital, a direct expression of the "digital man", able to overcome the objectives of optimization and efficiency on the one hand, and control complex forms on the other (a feature of the "first digital turn"). Whether *«the task of any architect is not about using computers to replicate or to automate what has already been thought and produced»* [9], the challenge underlying the advent of digital in Architecture is to *«give birth to a kind of architecture that is also beyond our usual capacity»* [9]. Looking at the current scenario and with specific reference to the architectural culture, nowadays we need more than ever "to give birth" to a new "architectural intelligence" that takes into account the "ecological crisis" we are experiencing, or better to say, the ecological crisis: *«the disequilibrium, which has become chronic in the Anthropocene era, between technological cycles (through which human action is expressed) and biological cycles (of nature)»* [10]. For this reason, the digital and ecological transitions can be considered, according to Luciano Floridi, "converging transitions" [1]. Following this vision, the implementation of digital culture in the context of the transformations of the built environment—i.e. the

[1] Original text: «permanente processo di trasformazione» che attraverso l'impiego di «materiali, (…) elementi, (…) sistemi contribuisce a dare forma alla realtà costruita» (translation by the authors).

introduction of the Industry 4.0 paradigm in such processes—can be a key factor in achieving the sustainability goals promoted by the European Green Deal.

## 2 Circular/Digital Approach in Building Processes

Nowadays the topic of the "circularity" of building processes has a strategic value. According to the European Union's Action Plan for the Circular Economy[2] (2020), the circularity of building processes represents a primary requirement to achieve the EU/2050 climate neutrality target. At present, the inefficiency in "environmental terms" of the technological cycles related to the transformations of the built environment is tangible.[3] Just to mention one: about 1900 million tons of construction and demolition waste (C&DW) were generated in 2018 [11]. This huge amount of material represents the largest waste stream in the EU by weight.[4] Against this backdrop, the target of 70% recycling of construction and demolition waste envisaged by 2020 by the EU Directive 2008/98/EC[5] has been largely missed.[6]

Even where recycling practices have found application, the processes of "downcycling" of crushable materials (stone, concrete, etc.) remain privileged compared to the creative reuse of waste and, in particular, of non-crushable material (wood, metal, etc.) (upcycling).[7]

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[2] In line with the EU Green Deal goal of climate neutrality by 2050, in March 2020 the European Commission proposed the first package of measures aimed at accelerating the transition to a circular economy, as announced in the Action Plan for the Circular Economy. The proposals include the enhancement of sustainable products, consumer empowerment towards the green transition, the revision of the building materials regulation and a strategy on sustainable textiles. Cf.https://eur-lex.europa.eu/legal-content/IT/TXT/?qid=1583933814386&uri=COM%3A2020%3A98%3AFIN

[3] With reference to the European context, two data exemplify the dimension of the problem: 3.4 million companies (equivalent to 9% of the EU gross domestic product) engaged in the field of building construction produce 25-30% of all waste generated in the Union (with an expenditure of 45 billion euros for their treatment) and employ 4.3 gigatons/year of materials (of which only 12% comes from secondary sources). Source: "UNEP at 50" Report (United Nations Environment Programme).

[4] Source: European Topic Centre on Waste and Materials 2020 report: "Construction and Demolition Waste. Challenges and opportunities in a circular economy". https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/construction-and-demolition-waste-challenges-and-opportunities-in-a-circular-economy

[5] This EU Directive and the subsequent EU Directive 2018/851 set out measures for the reduction of impacts in waste generation and management. They represent the reference regulatory instruments for the Member States of the Union on waste matters.

[6] Source: Legambiente—https://economiacircolare.com/rifiuti-da-costruzione-e-demolizione-dovremmo-recuperarne-il-70-ma-non-sappiamo-neanche-quanti-ne-trattiamo/

[7] Paola Altamura gives a specific definition of these two terms [12]. Downcycling: *«The process of reworking a product, almost always with high energy consumption, which reduces its quality in terms of performance and/or economic value»*. Upcycling: *«The process of converting a waste material into a new material (...) characterized by better quality, which requires creativity and planning»*.

On the other hand, advanced upcycling practices are at the center of numerous research and experiments (also in the academic field) in which circular processes are triggered through advanced digital workflows ranging from raw-material digitization to the use of artificial intelligence for processing waste materials. Some research that have particularly influenced the work presented in the following pages of the paper are reported below:

- "Cyclopean Cannibalism", carried out at the Massachusetts Institute of Technology. It consists of the automated construction of a wall face using waste materials and, in particular, concrete, rubber and stone[8] [12].
- "Ashen Cabin", carried out by Hannah, an experimental design and research studio based in New York. The cabin reflects how new production methods can help to make useful what we think is wasteful. It uses waste timber through the implementation of high-precision 3D-scanning and robotic-based fabrication technologies [13].
- "Mine the scrap", developed by Tobias Nolte and Andrew Witt from Certain Measures, an international design studio. Part of this project concerns the development of a software tool that can scan scrap elements from demolished buildings and rearrange them into new architectural envelopes [15].
- The research carried out at the Institute for Advanced Architecture of Catalonia (IAAC) called "Material (data) Intelligence. Towards a Circular Building Environment". It is based on the convergence of artificial intelligence and data analysis to generate new strategies for the reuse of building materials from selective demolition [14].

These and other projects demonstrate how the "enabling technologies" underpinning the Industry 4.0 model can be decisive for achieving advanced results.[9] In many of these experiences strongly emerges «*the idea of using digital tools to exchange services and commodities, exploiting inefficiencies and redundancies, making a better use of material resources and physical assets*» [15]. The capacity of the digital to translate the sensible world into a data set constitutes, in particular, «*the technological and operational prerequisite for the application of some fundamental principles of the circular economy applied to the construction, such as "buildings as material bank" and "urban mining", which refer to the built environment as a bank of potentially reusable materials*» [10]. According to Thomas Rau and his studies about the "material passport", «*only by capturing the physical world through data is it possible to organize what is limited so that it remains available indefinitely*»

[8] The authors of this experimentation (launched in 2017) are Randon Clifford, Wes McGee and Johanna Lobdell, researcher at MIT, in partnership with the company Quarra Stone. Cf. http://www.matterdesignstudio.com/cyclopean-cannibalism.

[9] A recent study [18] identified ten specific enabling technologies that can be introduced in the Circular Construction processes in line with the Industry 4.0 paradigm: Additive and Robotic Manufacturing (AM/RM), Artificial Intelligence (AI), Big Data and Analytics (BDA), Blockchain Technology (BCT), Building Information Modelling (BIM), Digital Platforms, Digital Twins, Geographical Information System (GIS), Material Passports and Databanks, The Internet of Things (IoT).

[3]. Likewise, the possibility of "processing" data and transferring it, in the form of instructions, to machines capable of producing artefacts is the sequel to a digital production model that, in the construction field, is still to be explored.

## 3 Circular and Digital Timber Construction

Globally, many countries have set challenging targets aimed at reducing carbon emissions (towards net zero emission) by 2050. In particular, the construction sector generates about 50% of current emissions[10] attributable to the entire life cycle of buildings, including the production and construction phases. The extensive use of concrete and stone as construction materials represents a critical factor in reducing the embodied carbon footprint of buildings.

Nowadays timber is considered a key material for the ecological transition in this sector as *«it is abundant, renewable, possesses good technical characteristics, and can be converted into a host of different "engineered" wood products»* [16]. *«In the context of climate change, the main argument for using wood (…) is the fact that it is a renewable resource and that it stores CO2»* [20]. Among the many qualities of "wood" as material, there is its capacity to store $CO_2$ during the plant's growth process. Extending its life cycle, or postponing as much as possible the moment of release of $CO_2$ into the atmosphere, is a strategy of a circular approach to the use of resources [17]. It is estimated that implementing the reuse of timber as a building material could lead to a 25% reduction in emissions by 2050, especially those of $CO_2$ [18]. That's why timber can be considered "the" alternative to energy-intensive materials like concrete or steel.

Nevertheless, timber's availability is not unlimited. Over the past 20 years, global timber consumption raised by 1.1% per year, due to increasing urbanization and global housebuilding requirements. Global industrial roundwood timber consumption reached figures equal to 2.2 billion $m^3$ in 2018.[11] According to a survey carried out in 2020 by Gresham House,[12] over the next 30 years there will be an almost three-fold increase in timber consumption, from 2.2 billion $m^3$ consumed today to 5.8 billion $m^3$ in 2050.

According to Mark Hughes *«it's time to rethink how we use wood in construction»* [16], considering wood as a renewable but not unlimited resource and also taking into account the environmental costs of the engineering process of wood products. A strategy for the sustainable use of wood resources is the reuse, or "cascading",[13]

[10] Source: International Energy Agency.

[11] Source: FAO (The Food and Agriculture Organization of the UN); Forest Product Statistics 2018. https://www.fao.org/forestry/statistics/80938/en/.

[12] *Gresham House* is a specialist alternative asset management company (https://greshamhouse.com).

[13] The concept of cascading is comparable to downcycling: a building component is reused several times, for iteratively less demanding purposes [16].

of wooden elements embedded in existing buildings. *«Prolonging the life of wood products increases their capacity to store carbon for longer as well as avoiding the use of material with greater impacts»* [16].

In Europe, this material is often burned for energy recovery, with the consequent return of the carbon embedded into the atmosphere. This practice is also fueled by logistic, technical and economic criticalities connected to the transformation of demolition wood into another solid wood compound. Some critical issues concern the manufacturing phase, such as the need to have "clean" (and then "re-processable") wood after the removal of nails, screws or damaged parts. However, the most critical aspects concern the way in which a raw and heterogeneous material can be acquired, traced, stored and evaluated for its intrinsic qualities (firstly geometric and mechanical) and then be transformed into a set of components available for reuse.

## 4 Post Disaster Areas as Material Bank

Disaster causes the damage and collapse of buildings and infrastructures and consequently the production of great amounts of debris. The management of demolished parts and waste material is one of the great challenges after earthquakes. In Italy, for instance, it has been estimated [19] that after the Friuli earthquake (1976), about 188,000 $m^3$ of demolition waste were produced, 2.650.000 $m^3$ after the L'Aquila earthquake (2009) and about 364.000 $m^3$ in Emilia Romagna (2012). For the Central Italy earthquake (2016), according to the extraordinary reconstruction commissioner, public rubble alone is about 2.800.000 tons.

The application of the "Circular/Digital" approach in disaster areas represents a field still subject to little analysis. The treatment of debris is an aspect that often holds back reconstruction processes[14] that are usually lengthy and, especially in Italy, carried out with a low innovation content.[15] However, it has been proven that an effective debris management during the recovery and rebuilding phases has valuable social, financial and environmental impacts [20].

In the areas affected by catastrophic events it is possible to find different kinds of waste and this mainly depends on two factors: the type of event (earthquakes,

[14] In the case of the 2016/2017 earthquake, the reconstruction of private assets is still in a phase of substantial stalemate, especially due to the inability to dispose of the rubble of the destroyed buildings and, for the same reason, to demolish the crumbling buildings. The landfill sites are full and it is still necessary to travel more than 100 km to use a landfill (Source: Osservatorio Sisma, https://osservatoriosisma.it/gestione-macerie/).

[15] Italy is a highly seismic country where catastrophic events have followed one another, requiring almost always long and laborious reconstruction processes. The earthquakes of Belice (1968), Friuli (1976), Irpinia (1980), Marche/Umbria (1997), Puglia/Molise (2002), L'Aquila (2009) and Amatrice (which affected a large area of the sub-Apennine region of central Italy in 2016/17) represent some of the destructive seismic events occurred in Italy in the last fifty years. "Concrete" has been the reference reconstruction material in all these cases, except for L'Aquila. Here, the use of timber for the reconstruction of residential buildings has been undermined by urban planning and typological choices that are still at the center of a strong debate [23].

tsunami, etc.) and the building technologies used for the destroyed (or damaged) heritage. Wood will be the prevailing material in areas where there is a strong presence of trees (that is especially in suburban areas) or where wood was mainly used as a building material. As an example, Hurricane Andrew (Florida 1992) left an estimated 6 million tons of debris in the Greater Miami region, including downed trees and wood debris from 150.000 houses that were severely damaged or completely destroyed. Approximately 500,000 tons of wood waste from the hurricane were mulched and distributed to agricultural areas, parks and residential sites.[16] In Japan, the debris caused by the 2011 Tohoku earthquake (and the subsequent tsunami which damaged the Fukushima nuclear power plant[17]) were mainly composed of wood from the destroyed houses and trees swept away by the force of the tsunami. Following this event, Toyo Ito and other Japanese famous architects[18] realized the "Home for all" project: one of the most iconic projects of wood reuse in post-disaster reconstruction. It focused on a construction system mainly based on cedar trees (widespread in the area). The presence of seawater in the soil (resulting from the tsunami wave) "killed" a large number of plants. A team of botanical experts determined that they could still be used as pillars [21]. The local people cut and processed the cedar wood themselves and the building is surrounded by 19 local cedar pillars, seemingly erected at random.

In Italy, especially in post-earthquake contexts such as the sub-Apennine areas, there are two kinds of C&D (Construction and Demolition) wood waste: the wood coming from buildings that have been destroyed or will be demolished (floors, roofs, etc.) and the provisional structures supporting buildings awaiting restoration or demolition. All these categories constitute a vast and widespread catalogue of potentially reusable material, suitable to be implemented in a "material bank". In particular, provisional structures and temporary works to support the first emergency phases constitute a "reservoir" of wooden material destined to be discarded (in landfills or used as biomass) during the reconstruction phase, further increasing the production of C&D waste and $CO_2$ emissions. In particular, the shoring works [22] consisting of untreated wooden elements for structural use with homogeneous cross-sections (Table 1)[19] constitute a resource of constructive elements, potentially reusable in the reconstruction process as long as they are "processed" and acquire the characteristics identified by the legislation so that they can cease to be waste

[16] Source: United States Environmental Protection Agency EPA, Planning for Disaster Debris, EPA report, December 1995.

[17] With a 9.0 magnitude, the earthquake triggered a tsunami and the meltdown of a nuclear power plant, costing more than 20,000 victims and destroying more than 120,000 homes (about 1 million were damaged).

[18] Along with Toyo Ito, Riken Yamamoto, Hiroshi Naito, Kengo Kuma and Kazuyo Sejima were involved in the project.

[19] Usually solid wood elements are used for temporary works. Depending on the origin of the material (foreign or domestic) there are two different classifications given in UNI EN 338 (material of foreign origin) and UNI 11035 (material of Italian origin). See also UNI EN 460: 1996 and UNI 350: 2016 about the durability of wooden products.

**Table 1** Most used cross section for shoring works [19]

| Cross section (mm) | Width height (mm) | Length (mm) |
|---|---|---|
| 100 × 100 | 100 × 100 | 6000 |
| 130 × 130 | 130 × 130 | 6000 |
| 150 × 150 | 150 × 150 | 6000 |
| 180 × 180 | 180 × 180 | 6000 |
| 200 × 200 | 200 × 200 | 6000 |

and become first-secondary matter.[20] In particular, provisional structures generate a large amount of "temporary object", generally destined to become waste at the end of their employment.

Always in Italy, the inspection of a wooden structure is conducted according to the criteria and procedures referred to in UNI 11,119:2004 regulation: "Cultural heritage. Wooden artefacts. Load-bearing structures of buildings—In situ inspection for the diagnosis of the elements in place", and UNI 11,035:2010 "Structural timber—Visual classification of timber according to mechanical strength".[21] These regulations also concern the assessment of waste wood.[22] The procedure is based on a visual inspection carried out by a forestry professional in order to evaluate the state of conservation and possible uses of the wooden components. It is focused on the identification of basic characteristics of materials such as wood species, geometry, biological and mechanical degradation, humidity and mechanical strength levels.

[20] According to the European Directive (2008/98/EC, subsequently amended by Directive 2018/851/EU), a waste is no longer such after being subjected to a recovery operation that fulfils the following conditions: (a) the substance or object is intended to be used for specific purposes; (b) there is a market or demand for that substance or object; (c) the substance or object meets the technical requirements for the specific purposes and complies with the existing legislation and standards applicable to such products; (d) the use of the substance or object will not cause overall negative impacts on the environment or human health. When all these conditions are met, the waste resulting from the recovery process is no longer "waste" and becomes a "product".

[21] Original text: UNI 11119:2004: "Beni culturali. Manufatti lignei. Strutture portanti degli edifici - Ispezione in situ per la diagnosi degli elementi in opera". UNI 11035:2010 "Legno strutturale - Classificazione a vista dei legnami secondo la resistenza meccanica".

[22] The UNI 11035 regulation only applies to Italian timber and concerns the classification of solid wood sawn timber for structural use of any size and moisture content. The material is classified in different categories (S1, S2, S3 for conifers and S for hardwoods) according to its defects. The UNI 11119 regulation sets objectives, procedures and requirements for the diagnosis of the conservation state and the evaluation of the strength and stiffness of wooden elements through in situ, non-destructive inspections and methodologies. The parameters underlying the inspection phases are: mechanical strength, geometric characteristics, biological degradation (for example: knots, inclination of the grain, density, cracks and onions), presence of chamfers and deformations, biological degradation, mechanical damage (as lesions).

This being the current situation, a question arises: can digital technologies support more effective processes for the reintegration of wood waste into a circular construction cycle? As shown in some recent research,[23] some of these surveying and inspection operations can be conducted through digital technologies related to Industry 4.0 paradigms. The application of such technologies can significantly increase process efficiency and enhance the possibilities of the reuse of waste materials as well as their field of application.

## 5 From Debris to Data Set (DeDa). A Digital Workflow for the Reuse of Waste Wood Material in Post-Disaster Areas

### *5.1 Research Goal and Field of Application*

Following the earthquake that hit central Italy in 2016, the University of Camerino (UNICAM) established coordination of all its staff in order to promote research in the field of reconstruction. UNICAM boasts a long tradition in the sector of innovation technology studies for the built environment and, as it is located in a highly seismic territory, of post-earthquake reconstruction processes.

DeDa is one of the latest studies on this topic. It stands for "*From Debris to Data set. A digital workflow for the reuse of waste wood material in post-disaster areas*". Its development began in 2021 at the School of Architecture and Design (SAAD), a UNICAM department, by a research team composed by the authors of this paper (of which the coordinator is Roberto Ruggiero). Subsequently, it has been tested during the Unicam Master on Circular Architecture titled "Circul-Ar, Shapes and methodologies of the circular architecture".[24] This master, which takes place this year for the second edition, focuses on the application of circular economy principles to the built environment through the use of innovative digital technologies. Like other European masters,[25] Circul-Ar is characterized by a strong propensity for

[23] As an example, the work "Matter Site. Material (data) intelligence" by Garcia et al. [14] investigates the reusability potentials from post and pre-demolitions sites using enabling technology such as Ai, Robotics and Data Analytics. The work was carried out at IaaC (Institute for Advanced Architecture of Catalonia) during the 2019-2020 edition of the Master of Robotics and Advanced Construction and subsequently developed by Driven (startup incubator) and supported by Scaled Robotics as Industrial partners.

[24] Circular-Ar is a second level master directed by Prof. Federica Ottone with the support of an international scientific committee, different companies involved in circular economy and private associations such as Symbola foundation and ANAB (Associazione Nazionale Architettura Bioecologica).

[25] At international level, the Institute for Advanced Architecture of Catalonia (IAAC) is today one of the main references for research in this field, as it uses innovative methodologies involving the integration of research and higher education, as in the case of IAAC's immersive Master in Advanced Ecological Buildings and Biocities (MAEBB).

experimenting with new ideas. For this reason, students are involved in experimenting with innovative approaches to the topic of circular construction. DeDa is a workflow based on digital tools for data acquisition and management. Its main purposes are:

- To implement a sharable cloud-based database of wooden elements, classified according to size and quality parameters: a virtual bank of raw materials;
- To demonstrate the effectiveness of this process for the reuse of waste materials.

DeDa is a digital application for the reuse of different types of waste (wood, metal, stone*)* in post-earthquake reconstruction. The specific background of this work is the sub-Apennine area affected by the 2016–2017 earthquake. This is a large area previously made up of small villages with a high landscape value.[26] In this area, communities are strongly linked to their building traditions and local materials (mainly stone and wood). The reconstruction works are also slowed down by the difficulty of disposal and research of materials, due to the distance from the main infrastructural network and the largest residential centers.

The first DeDa test was carried out during the 2021 edition of the Master. The material examined was the wooden material used as provisional shoring for the buildings damaged by the earthquake. In particular, the case study examined was a three-storey building located in the historic center of Santa Giusta, a small village situated in the province of Rieti. The entire main façade (12 m $\times$ 9 m) of the building was "caged" with steel tie rods and wooden uprights of homogeneous length and sections (Table 1). This kind of intervention presents recurring characteristics compared to the numerous shoring interventions carried out in the crater area.

## *5.2 Workflow Steps*

The workflow is structured in five steps: 1. Data acquisition; 2. Data analysis and organization; 3. Database setup; 4. Database modelling of informed geometries (from Mesh to BIM); 5. Design from Database (Fig. 1).

After the first three phases, the wood components examined are "translated" into "digital objects" catalogued according to various parameters. They are brought together in a database of digital objects/materials informed, defined by qualitative and quantitative parameters and classified according to possible areas of use. According to Thomas Rau [3], this step allows to draw up a "material passport" of the wooden components from provisional structures. Through its "virtualization", this material can be "objectivized" (according to qualitative and quantitative parameters), stored in a virtual database and shared via the cloud (cloud database). The last step concerns a design hypothesis for the reuse of this (now) informed digital object through an

[26] In 2016 and 2017, central-Italy was affected by a destructive seismic event sequence. The crater area is about 8,000 $km^2$ and includes 140 municipalities and 580,000 inhabitants.

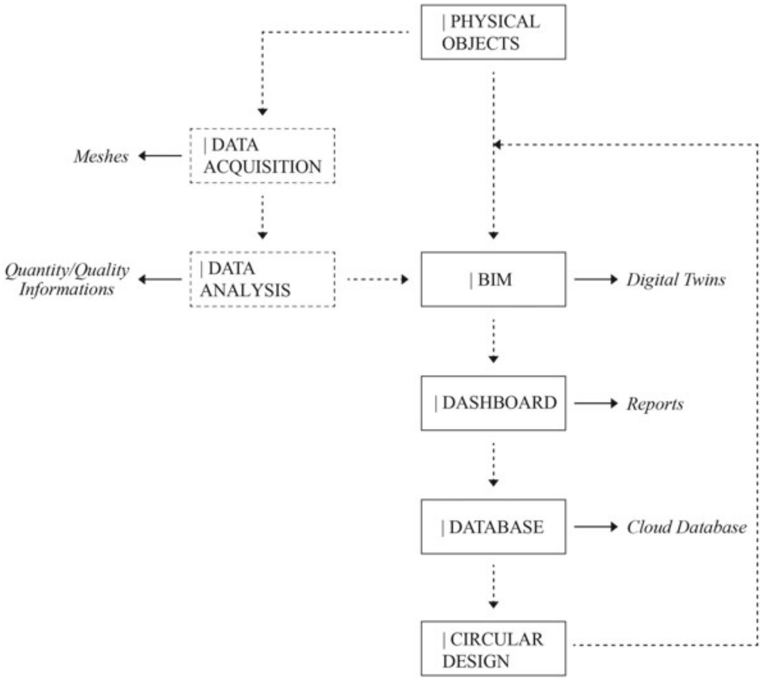



**Fig. 1** The workflow is structured in five steps: 1. Data acquisition; 2. Data analysis and organization; 3. Database setup; 4. Database modelling of informed geometries (from Mesh to BIM); 5. Design from Database

approach that combines BIM and computational design (Data Driven Design).[27] A small pavilion is the subject of this step.

The development of this work will concern further steps focused on the design of new components' families as well as on their production. Regarding the latter, an automated process using a collaborative robotic arm controlled via a mobile workstation is under study (but it is not the subject of this paper).

### 5.3 *Data Acquisition*

This phase focuses on the collection of all the information (at dimensional, qualitative and quantitative level) required to create the digital twin of each previously scanned

[27] The term "data-driven design" refers to a process in which qualitative and quantitative data are processed to guide design decisions [24]. For a concise but effective understanding of this topic, it may be useful to consult Proving Ground, a digital design agency that enables digital transformation with creative data-driven solutions to the building industry. https://provingground.io/.

wood item. Among the different methods of digital surveying available today, "photogrammetric surveying" was used. It is based on the acquisition of metric data (shape and position of an object) through the detection and analysis in a digital environment of photograms.[28] Compared to other systems (i.e. laser scanning) this method offers, through cheaper and more flexible instrumentation, good levels of accuracy as well as the possibility of acquiring high-resolution images.[29] In particular, two photogrammetric methods were employed at this stage with a dual purpose: a. to catalogue the wooden elements; b. to acquire more accurate images and geometries:

a. Tool: drone; model: Dji MavicMini[30]; method: automatic flight parallel to the facade of the "caged" building; distance: approx. 2 m from the façade, with height increments of 1.0 m and shots every 0.5 s for a total of approx. 100 frames. The images were processed and the point cloud was extracted through Agisoft Metashape, a photogrammetric processing software which uses structure from motion algorithms. Then the point cloud was segmented using the Cloud Compare software to isolate the supporting elements protruding from the main façade by identifying the main planes of the geometries to be isolated, using "fit-plane and RANSAC algorithms" [26]. The identified portions of the cloud were exported and used for the reconstruction of the main geometries (Fig. 2).
b. Tool: digital camera Lumix DMC-lx100.[31] Once the process of partial demolition of the building and removal of the provisional structures was completed, the second photogrammetric survey was carried out on individual wooden elements (Fig. 3), using a digital camera in a controlled light environment (2 flash studio, white backdrop). This step allowed to achieve ideal and repeatable shooting conditions for each individual element. The shots were taken using a fixed camera by positioning the element on a rotating platform (one shot every 15°). The coded targets allowed to use the images for the "structure from motion" process using Agisoft Metashape software. The high-definition images with ideal lighting conditions allowed to generate both a point cloud with very high resolution and accuracy (error < 3 mm), and an accurate texture to be applied to the detected geometries.

[28] Photogrammetric surveying is based on "structure from motion" algorithms, i.e., a calculation method allowing the reconstruction of the three-dimensional shape of objects by the automatic collimation of points from a set of pictures [25]. This is how the procedure works: the algorithm extracts the remarkable points from the individual photos and (by cross-referencing the recognizable points on several frames) calculates the spatial coordinates of the single points. The result of this calculation is a scattered cloud of points to be, subsequently, employed to determine a dense cloud of points in space. Each point is characterized by spatial coordinates and a color.

[29] In this regard, cf. https://www.agisoft.com/ and https://www.danielgm.net/cc/.

[30] Cf. https://www.dji.com/it/mavic-mini.

[31] Cf. https://www.panasonic.com/it/consumer/fotocamere-e-videocamere/compatte-fotocamere/professionali/dmc-lx100.html.

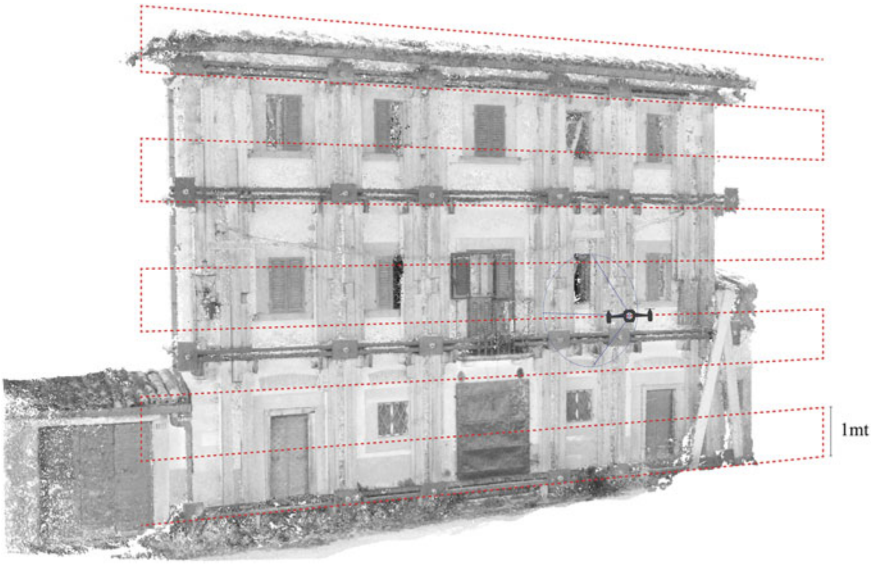



**Fig. 2** Drone automatic flight parallel to the facade of the "caged" building; distance: approx. 2 m from the façade, with height increments of 1.0 m and shots every 0.5 s for a total of approx.

**Fig. 3** Studio setup (rotating platform with coded targets) for individual wood elements photogrammetry survey


**Fig. 4** Façade survey point cloud post-processed. N.points 1701997

### *5.4 Data Analysis and Organization*

For the reconstruction of mesh geometries from point clouds, two methods were employed. The first is based on the use of the CockRoach, a Grasshopper3D[32] (Mcneel Rhinoceros) plugin[33]: a tool aimed at managing point clouds and reconstructing mesh geometries directly in the CAD environment. This tool is particularly useful in managing point clouds. The tool offers various options, including: 1. the reduction of the points number, the clustering and segmentation of the cloud (i.e., the definition of the main planes using RANSAC—RANdom SAmple Consensus—algorithms) (Figs. 4 and 5); 2. the management of addition and subtraction operations (Boolean) between mesh geometries. One of its current limitations is the calculation time, which is directly proportional to the number of points to be processed. For shorter calculation times, the textures obtained will be less accurate than dedicated software.

Once the outline geometries were reconstructed, it was possible to estimate (within Grasshopper3D) the volume of materials detected and the number of elements and their dimensions, providing the necessary data for the construction of an initial database (Fig. 6).

The second method used for the reconstruction of detailed mesh geometries still refers to the use of Agisoft Metashape, a software that performs photogrammetric

[32] https://www.grasshopper3d.com/.

[33] P. Vestartas and A. Settimi, Cockroach: "A plug-in for point cloud post-processing and meshing in Rhino environment", 2020. Cfr: https://github.com/9and3/Cockroach.

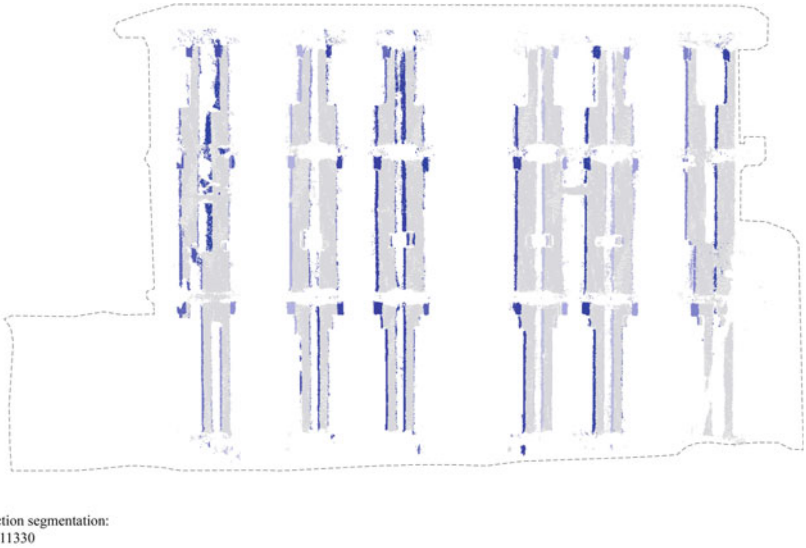



**Fig. 5** Plane detection point cloud segmentation (RANSAC) for beams extraction from façade. N.points 311330


**Fig. 6** Elements numbers, dimension and material quantity evaluation with Grasshopper 3D

processing of digital images and generates 3D spatial data to be used in a digital environment. Like the previous one, also this workflow involves the automatic construction of surfaces composed of polygons whose sides are the segments connecting the points of the cloud. This procedure allows to get surfaces consistent with the

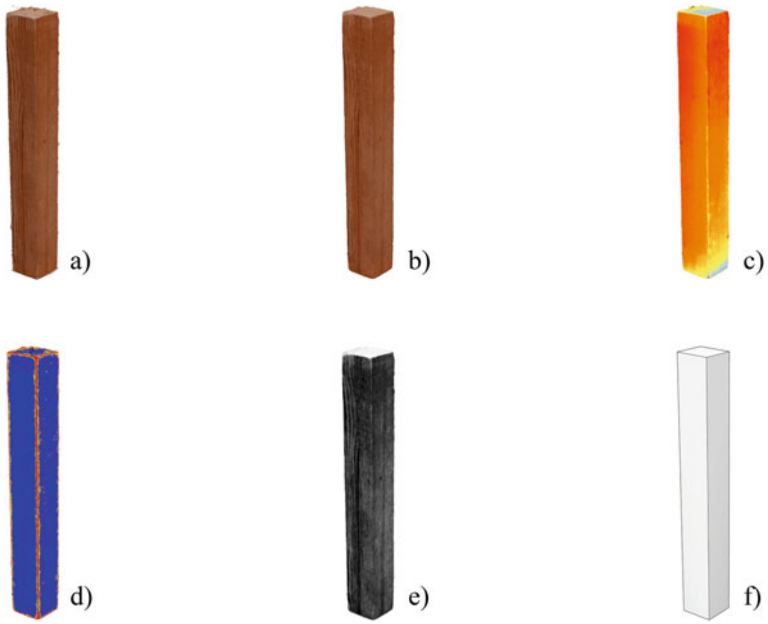



**Fig. 7** Surveyed geometries and textures of the wooden elements analysis with Grasshopper 3D. **a** Point cloud; **b** Mesh geometry; **c** Deformation analysis; **d** Mesh curvature analysis; **e** Texture analysis; **f** Bim model

shape of the surveyed objects and also to construct interpolation surfaces to cover any defects or missing parts in the point cloud. The software also contains various presets and parameters able to determine the accuracy of the reconstructed geometries and manage calculation times (quality, quantity of faces, etc.). The "build texture" command allows to start of a subsequent step, obtaining a high-resolution texture (from the photographic sockets used to extract the point cloud) to be applied to the reconstructed surfaces (Fig. 7a, b).

The surveyed geometries and textures of the wooden elements are analyzed (in Grasshopper) to check their quality and performance condition and the presence of any defects or foreign bodies, by considering the parameters provided by the aforementioned UNI 11,035 and UNI 11,119 regulations (cf. note n. 21). Below are some of the main analyses undertaken:

- *deformation analysis*: aimed at quantifying the presence of excessive deformations (embossing, bowing, warping, etc.) in the surveyed elements, the method consists of evaluating the deviation between each vertex of the 3D scanned mesh and an ideal perfectly straight geometry of the building element identified by an evolutionary solver. A greater distance from the reference axis corresponds to the main deformations of the element (Fig. 7c);
- *mesh curvature analysis*: aimed at checking for structural defects (lack of material, holes, surface inhomogeneity, etc.), using the analysis of the change in the

curvature of the surfaces of the surveyed geometry. Any surface irregularities are highlighted by mapping the relative changes of direction in the perpendicular mesh faces (Fig. 7d);

- *texture analysis*: aimed at identifying any potential defects in the wood (fungi, knots, holes and, in general, inhomogeneity in the coloring of the material), manipulating the images to obtain a two-color mapping (black, inhomogeneous surface; white, homogeneous surface). By extrapolating the percentages of the two black/white values using Grasshopper 3D, it is possible to quantify the homogeneity percentages of each element (average between the values of the different faces of the element, (Fig. 7e);
- *material analysis*: aimed at obtaining a reliable indication of the wood species, average hue values, saturation and brightness by extrapolation from the detected textures and comparison with sample images of the most common wood species;
- *volume and specific weight evaluation*: aimed at assessing the presence of any defects that could alter the weight of the single element (such as the excessive presence of water or the presence of deteriorating internal parts). The digital model provides information on the volume. The multiplication of the volume thus obtained for the specific weight of the wood (variable from essence to essence) gives an indication of the expected weight of the element. Based on an empirical method, the expected weight is compared with the actual weight (measured by means of a dynamometric balance). This made it possible to obtain the first quantitative parameter to establish the material quality. For example, a ratio greater than 1 could indicate the presence of excessive humidity, and a ratio lower than 1 the internal deterioration of the material.

Following these analyzes, each element was assigned a score for each performance in order to identify and group elements with similar characteristics, drafting a classification based on possible reuses: biomass for elements with the lowest score; decorative or in any case non-structural uses for elements with average scores; structural uses for elements with higher scores according to the resistance class determined by the already mentioned standards (see note n. 21).

## 5.5 Database Setup

The digitization of physical elements and the systematization of the related data (at qualitative and quantitative levels) allows the creation of virtual stores. They can be shared and updated over time. Once the data collection of the shoring elements is completed (Paragraph 5.4), the DeDa workflow allows their organization into lists within Grasshopper 3D. The latter allows the simultaneous handling of heterogeneous data and their association with geometric entities (mesh). Lunch Box, a Grasshopper

**Table 2** List of elements information in csv format

| Element ID | Width (mm) | Height (mm) | Length (mm) | Material | Deformation factor | Quality factor |
|---|---|---|---|---|---|---|
| Element 00,000 | 180 | 180 | 4100 | Pine | 0.775 | 0.931 |
| Element 00,001 | 180 | 180 | 4100 | Pine | 0.733 | 0.821 |
| Element 00,002 | 180 | 180 | 4100 | Pine | 0.84 | 0.75 |
| Element 00,003 | 180 | 180 | 4100 | Pine | 0.931 | 0.996 |
| Element 00,004 | 180 | 180 | 4100 | Pine | 0.897 | 0.733 |
| Element 00,005 | 180 | 180 | 4100 | Pine | 0.83 | 0.792 |
| Element 00,006 | 180 | 180 | 4100 | Pine | 0.806 | 0.941 |
| Element 00,007 | 180 | 180 | 4100 | Pine | 0.983 | 0.834 |
| Element 00,008 | 180 | 180 | 4100 | Pine | 0.73 | 0.767 |
| Element 00,009 | 180 | 180 | 4100 | Pine | 0.893 | 0.703 |
| Element 00,010 | 180 | 180 | 4100 | Pine | 0.709 | 0.93 |
| Element 00,011 | 180 | 180 | 4100 | Pine | 0.774 | 0.709 |
| Element 00,012 | 180 | 180 | 4100 | Pine | 0.796 | 0.702 |
| Element 00,013 | 180 | 180 | 4100 | Pine | 0.997 | 0.853 |

3D plugin, allows the creation of lists in.csv format[34] (Table 2), a file format that can be interpreted and edited by several commonly used applications (Excel, Open Office, Notepad). The interoperability of this format facilitates the integration of the database with data from other sources, providing the possibility of managing all information in a single software environment. This opportunity is decisive to work in the Building Information Modelling environment and to create a Material Passport dedicated to scrap materials. At the conclusion of this process, the.csv files are finally treated using Power Bi (a Microsoft software for the Data Visualization) in order to create an intelligible and more friendly interface (Fig. 8).

[34] A CSV (comma-separated values) file is a text file characterized by a specific format which allows to save the data in a table structured format. CSV is a common data exchange format that is widely supported by consumer, business, and scientific applications.

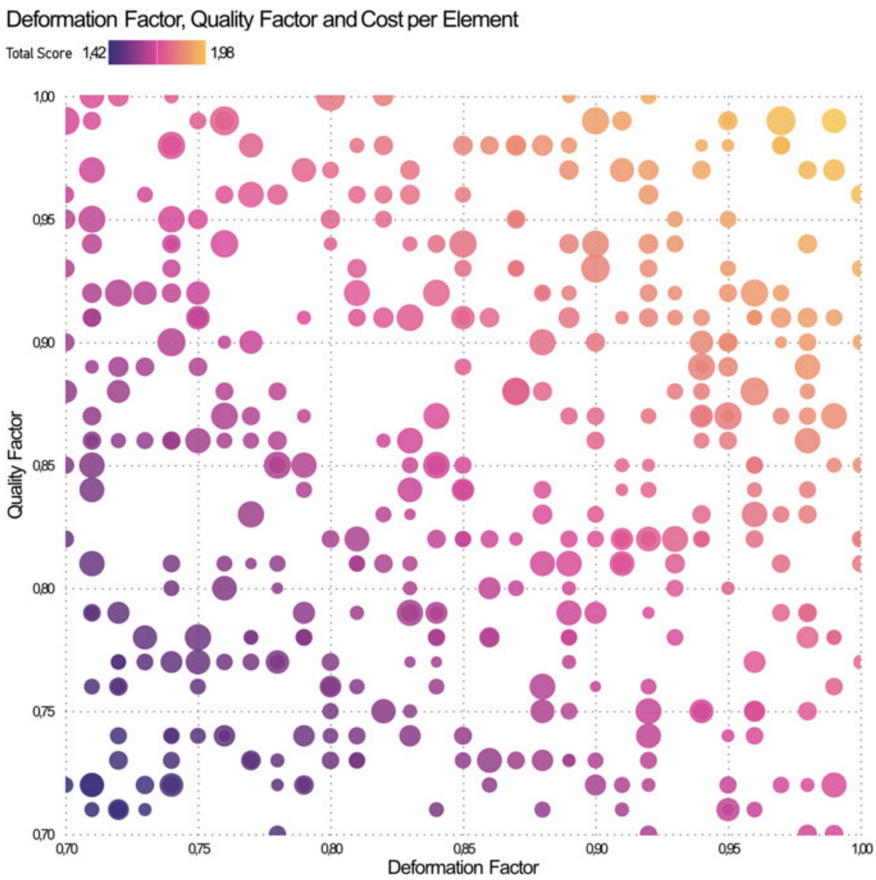



**Fig. 8** Data visualization using Power Bi

## 5.6 *Database Modelling of Informed Geometries (from Mesh to BIM)*

Using current technologies, the product of a three-dimensional scan is returned in the form of a *mesh*: a network of interconnected points (vertices). The way this network of points is organized determines the "topology of the mesh" [27]. The mesh allows the digital restitution of the morphology and texture of a real object. However, the use of meshes in the BIM environment is computationally burdensome [28]. If the goal, as in the DeDa case, is the creation of the digital twin of wood waste elements and, subsequently, the organization of a material bank of all the (digitally acquired) elements, the transformation of the meshes from the scanning process into parametric objects (objects with associated information) still requires various steps using current technologies [29]. In the lack of automated (via artificial intelligence) "mesh/parametric object" conversion strategies, it is now possible to use computational software such as Grasshopper3D, able to "interface" with BIM software. Such a procedure still requires a "crafted" approach, where the choice of software and procedures strongly depends on the morphological characteristics of the object [30]. This implies a cumbersome workflow and the impossibility of defining a single method repeatable in different applications. In fact, the main BIM authoring software does not support the automatic modelling of meshes (except for special cases, such as topographic surfaces) as these are not recognized as native geometries.[35] This results in the absence of qualitative and quantitative information and parametric behaviour, typical characteristics of native BIM objects [31]. The workflow is divided into the following steps:

- *Identification of the parallelepipeds that best approximate the mesh.* Tool: Grasshopper3D. For this step, the potential of evolutionary and genetic algorithms has been exploited.[36]
- *BIM modelling* from *Grasshopper*. Tool: *Rhino.Inside*.[37] Rhino.Inside is employed to connect Rhino and Grasshopper via the API (Application Programming Interface) of the Autodesk Revit BIM authoring software.[38]
- *Conversion of modeled objects into parametric objects.*
- The following parameters are detected and attributed to the digital twin of each scanned and modeled wooden element: morphology, weight, essence, deformation, density, discontinuity, presence of foreign bodies, need for machining to eliminate unusable parts and origin concerning the original location in the building. This information was implemented and automated using Rhino.Inside Revit technology, with particular attention to data matching within Grasshopper.

The result of these three steps is a database of computerized, modelled and classified BIM components of the wooden elements taken as an object of experimentation. Despite the limitations deriving from the software technologies available today (highlighted above), this workflow actually achieved its goal thanks to the complete "interoperability" [33] of the software used, able to exchange information in real-time (Fig. 9).

[35] BIM software uses a B-Rep (Boundary Representation) method whereby each object can be represented by a curve governing its course (directrix) and by a curve defining its profile (generatrix) [27].

[36] These algorithms allow to find solutions to the problems described through a system of constraints and targets, expressed using a fitness function and the continuous recombination of design variables known as "genes" [32]. In this case, the algorithms control the orientation in the three dimensions of the reference planes (genes) for the construction of the parallelepipeds. They allow to minimize the difference between the volume of the starting mesh and its boundary parallelepiped (fitness function).

[37] Rhino.Inside is an open-source software that allows Rhino and Grasshopper to run within other 64-bit Windows applications (such as Revit or AutoCAD).

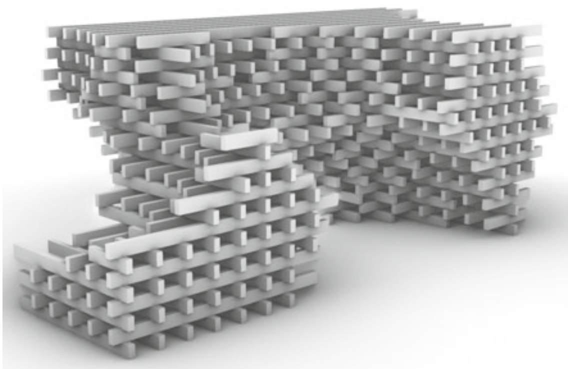
[38] Through direct communication with the Revit API, Rhino.Inside allows native Revit geometries (each characterized by a unique GUID—Globally Unique Identifier) to be modeled from Grasshopper's computational environment. Cf. https://www.rhino3d.com/inside/revit/beta/guides.


**Fig. 9** Visualization of the set of design solutions, optimized on the basis of the objectives and consistent with the system of constraints

## *5.7 Design from Database*

The outcome of this first experimentation is the realization of a pilot project of a wooden pavilion (Fig. 10) made with the materials contained in the virtual storage of "informed wooden components" obtained by following the previous steps. The design phase was performed using evolutionary and loop algorithms. These algorithms allowed continuous recombination of the design parameters, generating different design solutions for different design goals. The result of this process is a set of design solutions, optimized on the basis of the objectives and consistent with the system of constraints (Fig. 9). Loop procedures were used to select the most suitable elements from the database (in relation to their geometric, mechanical, conservative properties, etc.) to perform a given "task" in the pavilion construction system.

**Fig. 10** Wooden pavilion made with the materials contained in the virtual storage of "informed wooden components"



This step is still in progress. It is planned to progressively increase the complexity of the design application (in order to obtain the design of a more complex object), but also to implement the database with new wooden elements. A further objective is to move from the design phase to the construction phase, i.e., to realize the artefact. This further step involves an upgrade of the database, once the hall has been assembled and subsequently dismantled. In fact, at the end of this process, some wooden components will have suffered damage or changes in some parameters due to assembly and disassembly and the operating time of the pavilion. This upgrade—which will involve the repetition of the entire workflow—sets up an infinitely circular process that, through the "virtualization" of waste wood, allows more than its simple one-time reuse and implies its re-introduction into an infinitely circular manufacturing process inspired by the "Design for Disassembly (DfD) principles" [34].

## 6 A Master Course as a Place for Research and Experimentation

What Mario Carpo defines as "the second digital turn" [7] represents for architecture an irreversible process meant to modify many consolidate rules in the professional practice. If there is no advancement in methodologies, tools and skills, in the next future training in architecture will prove to be inappropriate [35]. *«To create the ethical and scientific basis to allow the architect to play a leadership in a future that is announced as increasingly "digital", a radical re-thinking of the educational paths in architecture is necessary, as well as the testing of innovative methods and models based on the prefiguration of future (medium and long-term) scenarios»* [35].

As some experiences in international contexts demonstrate, the quality of educational offer requires a close relationship between training, experimentation and research. From Buckminster Fuller's experiments with geodesic structures in the 1950s with students from Black Mountain College [36] to more recent experiences such as the immersive Master in Advanced Ecological Buildings and Biocities (MAEBB) of the Institute of Advanced Architecture of Catalonia (IAAC),[39] research in architecture has often used educational environments as a place for experimentation. Mention one, the Voxel Quarantine Cabin, built during the MAEBB 2019–2020 Master's degree, represents an inspiring example of the overlap between education and advanced research.[40] In particular experiences like this are based on the use

[39] The MAEBB is a good example of an innovative educational format that offers interdisciplinary skills through an experimental activity focused on new categories of projects, technologies and solutions related with the design, prototyping and fabrication of ecological buildings.

[40] The project is the result of an innovative digital workflow realized with the co-partnership between the Master's students and teachers and external specialists. The Voxel is an autonomous 12 $m^2$ cross-laminated timber (CLT) structure clad in a parametric rainscreen, exemplifying an advanced ecological approach to architectural production. Every timber element can be traced back to its exact point of origin, and all building components have been rigorously quantified in terms of geographic

of advanced digital tools for research goals starting from the circularity of production processes. In this and other areas of research, the creation of manufacturing workshops and the offer of advanced tools such as parametric/generative software and prototyping/manufacturing machinery would become a priority for architecture departments to implement a "learning by experimenting" approach, to guarantee what Alvin Toffler already defined as an *«education in the future tense»* [37] and allow the architects of the future to meet the social, technological and, above all, environmental challenges of the coming years.

At the same time, the participation of students in research experiences can represent an added value in terms of human resources and opportunities for achieving the objectives. Especially where "digital technologies" are the basis of experimental activities, the involvement of young, open-minded, digital native people still in training could represent an added value to be achieved.

Inspired by this idea, the Master course "Circul-Ar, Shapes and Methodologies of the Circular Architecture" held at the University of Camerino represents an opportunity for connection between the educational and research sectors. Integrating multidisciplinary competencies ranging from architecture to design and engineering, the Master course proposes an innovative approach to the theme of circular architecture [15] based on the creative use of new or used, renewable, natural, biodegradable, recyclable and reusable materials. This approach is pursued through the use of advanced digital tools and the experimentation of workflows dedicated to the theme of upcycling, intended as *«creative reuse of materials»* [12]. DeDa is an experimental work developed, in its application part, within the Master's course. In particular, during the first edition of the Master (2020/2021), part of the process described so far was developed in order to experiment with different workflows, according to DeDa goals (already discussed in Chap. 5). The interaction between research and educational contexts achieved excellent results. The continuous feedback between students and teachers, the interest aroused in students by digital applications as well as the combination of social issues (such as the reconstruction in post-disaster areas), environmental issues (such as the circular building) and innovative technology created the right combination for the achievement of teaching objectives (an advanced digital training at the service of the circular economy) and research goals (the integration of digital tools to overcome the limits of software interoperability).

source and carbon content, taking into account any fuel or energy inputs during the entire associated life cycle. Cf. https://iaac.net/maebb-voxel-quarantine-cabin/.

## 7 Research Limits and Opportunities

DeDa is a methodology that could also be extended to other types of waste material. For its further development, it will be necessary to overcome some limitations that the work done so far has highlighted and which can be summarized as follows:

- *Limits of technologies*—As reported in Sect. 5.6, the transition defined "from mesh to BIM" is excessively articulated in the lack of tools enabling automatic conversion. The digital chain proposed in Chap. 5 is still improvable through either the development of a specific tool, or optimizing the procedure here proposed. Both options require the introduction of automatic design and IT (Information Technology) skills into the research group.
- *Limits of design application*—Choosing a small pavilion as design test case (with a limited number of components), helped us to have the right degree of simplification at this stage of the work. Starting in October 2022, a second test has already been planned. An existing temporary single-storey timber building will be the object of a virtual selective demolition process. It is located in the crater area of the 2016 Italian earthquake. It will be dismantled when the reconstruction of destroyed buildings will be completed. Its components will be organized in virtual storage through the DeDa workflow. With a larger quantity and quality of components than those used in the first application of DeDa, it is planned to develop a second design application focused on the production of small wooden building components to be integrated, as cladding, into façade systems.
- *Production limits of discrete systems*—For each wooden component examined, the level of degradation is recorded and any parts to be removed is precisely identified and faithfully reported in the dataset (cf. paragraph 5.6). Usually, wood waste material includes parts that are irreparably damaged. Consequently, form the original to the reusable piece a "reduction in size" (due to the removal of excessively degraded parts) is likely to be. Therefore, the reusability of these components requires, as a privileged field of application, the so-called "discrete systems". The "discretization" of building systems constitutes one of the paradigms of so-called digital fabrication [38]. It can be said that discrete systems (in building construction but also in the production of objects) count flexibility, reversibility and versatility among their advantages. At the same time, they require a great number of connections with a complexity of assembly work.

In connection with this last consideration and as a medium- and long-term goal, the research group is in parallel working on a second line of research focused on an automated process of recycled wood material. For the re-employment of the "stored components" (according to the DeDa method), a second workflow is being developed. It is focused on a mobile workstation and the use of a collaborative robotic arm. This additional work module would allow to produce, in situ, artefacts made by discrete parts from wood waste material. Arm activities range from the removal of metal elements, to repair, to the assembly of discrete parts. This second phase is not the subject of this paper (Fig. 11).

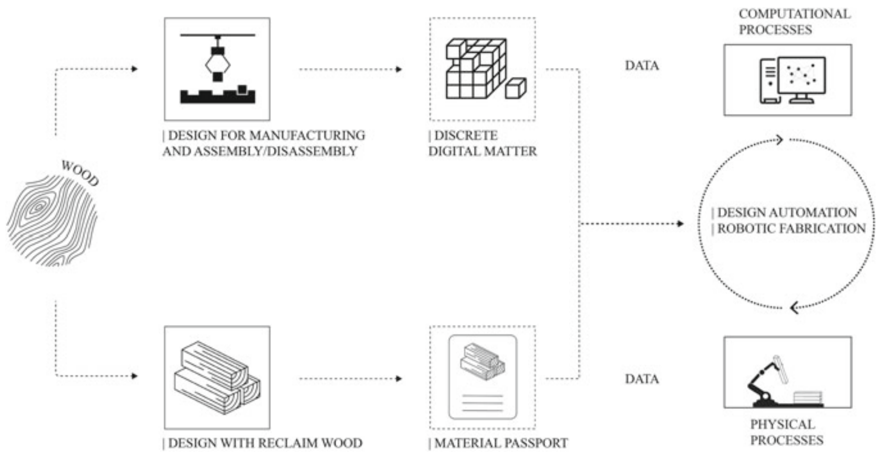



**Fig. 11** Digital circular timber construction workflow

## 8 Conclusion

The current "environmental crisis" is an "ecological crisis". Meaning by ecology *«the exosystemic relation between something or someone and its environmental context»* [15], it can be argued that, since the first Industrial Revolution, the relationship between man and the natural environment has gone into crisis. Since that time, human actions on the environment have become more aggressive and increasingly based on linear production processes. Those processes are responsible for what we now call "climate change", which is nothing more than the progressive reaction of the natural environment (whose transformations take place through circular processes) to human actions[41] [39]. This conflict cannot be resolved by pursuing the (simplistic) idea of a "return of man to nature". According to Bruno Latour, *«the human being (…) is first and foremost a cultural being distinct from nature»* [39]: that's why any definition of ecological crisis as a "return to nature" results rhetorical and without foundation. Therefore it seems more realistic to attempt a realignment between human technological cycles and the biological cycles of nature. Nowadays, moving from a linear to a circular model of production and consumption is a condition that no longer appears questionable.

[41] The currently most human-driven technological cycles are still "linear". According to the Ellen McArthur Foundation, *«in our current economy, we take materials from the Earth, make products from them, and eventually throw them away as waste»* (https://ellenmacarthurfoundation.org/). In the future, the scarcity of resources will require more and more to focus on new techniques and methodologies in order to replace the principles of the linear economy with those of the circular economy, in which waste products are reused as inputs for the creation of secondary products [44]. The Ellen McArthur Foundation is a charity foundation whose core business is promoting circular economy i.e., eliminating waste and pollution and boosting the spread of circulate products and materials. Cf. https://ellenmacarthurfoundation.org/about-us/what-we-do.

This transition, as ambitious as it is necessary (given the dramatic effects of the current ecological crisis), must and will have to be *«driven by design»* [40]. Nevertheless, design needs appropriate technologies to be effective and creative as the situation requires. Digital technologies linked to the Fourth Industrial Revolution constitute, in particular, a "new opportunity" to redeem technology against the environment and help design fulfill its purpose. *«Where the danger is, also grows the saving power»* is the famous aphorism by the German poet Friedrich Hölderlin (1770–1843). If the current climate crisis has its roots in the industrial development and the first three phases of the industrial revolution [41], the advent of the Fourth Industrial Revolution (the digital revolution) gives the opportunity to face the environmental challenge with new weapons and possibilities. Technology, which has so far contributed significantly to the current environmental crisis, can therefore represent a way out in its digital form.

Some recent experiences of a "circular/digital" approach to building construction (see Paragraph n. 2) demonstrate the effectiveness of design approaches based on the interconnection of information between the physical and digital world. This approach must be placed in the context of a "digital ecosystem" that *«encompasses the technologies that enable the creation and use of digital information, following a set of data standards and interoperability. These technologies enable reality capture, computational design, data acquisition, data analytics, artificial intelligence, simulation and analysis»* [42]. However, the level of interoperability between some digital environments is still inadequate and there is a lack of "bridging tools" able to facilitate the interconnection between software [43]. These limitations have also been experienced in the application of DeDa.

DeDa is a workflow focused on the transformation of waste materials into new materials, ready to have new uses and a new life expectancy. Such a "transformative flow" requires a substantial intermediate step: the virtualization of waste material in terms of both digital twin and data set. This temporary condition of "digital object" is the prerequisite for the waste material to be framed in its performance futures. This "migration" of the physical world into a virtual world is in the middle of the current debate about "digital". In the book "Non-things: Upheaval in the Lifeworld", the South Korean philosopher Byung-Chul Han states that the "things of the world" (physical world) *«have the task of stabilizing human life by giving it a foothold»* [45]. When *«the earthly order is succeeded by the digital order»*, the latter *«dematerialize the world by computerizing it»* [45]. In Han's criticism, the ongoing process of dematerialization of the world has a negative meaning: *«it is now data and no longer concrete things that influence our lives. Non-things are taking over from the real, from facts and biology. And so, reality appears to us more and more elusive and confusing, full of stimuli that do not go beyond the surface»* [45]. In complete agreement with Han's critique, the dematerialization process at the basis of DeDa is a key requisite—*a conditio sine qua non*—so that the practices of reuse and upcycling of waste materials "come into reality" in a systematic, repeatable and scientifically controllable way. This is a paradox compared to Han's vision. In this case indeed, "computerizing" pieces of the real world in digital environments—i.e. converting scrap things into "non-thing"—is a necessary practice to redefine the "earthly order of things" called into question by the current ecological crisis.

Finally, the purpose of this work (and its future developments) is to explore a 4.0 approach to building processes from the perspective of rethinking the way we use resources in view of the current environmental crisis. If we consider post-natural disaster areas as great "material banks", the "material/data/material" approach proposed here could support new and desirable policies for the reuse of waste, transforming scrap material into a *«new raw material»* [46]. Policies and technologies need each other to achieve these goals. In the absence of effective technologies and operational chains, the ecological transition of construction processes will not take place and inefficiencies and waste of resources will continue. In the specific context of post-disaster recovery, drawing up appropriate technologies for the reuse of debris could be a key strategy to make such processes more efficient and sustainable. However, there is still a long way to go in terms of research on this topic, even if today's digital technologies open up new scenarios that were unthinkable until a few years ago.

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# From DfMA to DfR: Exploring a Digital and Physical Technological Stack to Enable Digital Timber for SMEs

**Alicia Nahmad Vazquez and Soroush Garivani**

**Abstract** Design for Manufacturing and Assembly (DfMA) and Digital Manufacturing (DM), particularly as related to Timber construction, is expensive. DfMA is costly due to the costs related to skill acquisition—Computer-Aided Design (CAD), Building Information Modelling (BIM), knowledge about robotic production etc. Digital Manufacturing is expensive due to the initial capital costs related to digitally able machines and robots. This entails that the segment of the construction sector that is rapidly adopting these technologies to meet the productivity and ecological goals of the Construction Sector is largely restricted to large businesses—large Architectural, Engineering and Construction (AEC) firms. More importantly, it entails that the Small Medium Enterprises (SMEs) are unable/unwilling to participate in the rapidly digitizing economy. This forms the driving motivation to propose a design and fabrication paradigm based on Design for Robofacturing (DfR), a technology stack based on affordable, multiple-use machines. To enable DfR for SMEs, the research follows three main avenues: (1) the design of an easy-to-deploy micro-factory based on industrial robotic arms for timber to produce complex carpentry products; (2) a digital-management software and sensor package; (3) worker training modules and micro-credentialing. The aim is to develop a comprehensive package that brings several advantages of digitalized construction at a lower initial capital interest to SME contractors. Finally, a case study and micro-factory prototype currently being developed is presented and analyzed. An initial prototype and proof of concept of the research, is currently being developed. The researchers are taking the challenge to create a DfR-enabled digital timber factory on a remote island, to produce in situ a housing complex. The project has the particularity to offer future clients the possibility to modify and customize the design using a digital app, requiring the micro-factory to handle and produce mass-customized, geometry complex parts in a flexible yet controlled process.

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_42

**Keywords** Micro factory · Cyberphysical app · Democratization of digital manufacturing · Design for robofacturing · AEC entrepreneurship · Digital and robotic fabrication · Digital craft · Digital timber

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns

## 1 Introduction

Timber is one of the most traditional building materials, and societies have used that for thousands of years. Contemporary construction practices suggest a growing interest in building with timber, due to its sustainable credentials and novel technologies, at a scale not previously attainable [1]. The solid timber industry continues to grow in America, Europe and globally. New production plants are opening for business all over the world, while existing plants are increasing their capacity by extending and opening new sites. Design for Manufacturing and Assembly (DfMA) has become the standard of the mass timber industry, allowing them to build with high quality, faster, efficient and more sustainable [2]. Buildings are produced offsite following a 'kit of parts' organization and then transported to their final sites. However, the advantages of this building method with timber are concentrated in large-scale manufacturing firms. SME-friendly timber technologies are behind [3, 4]. This means that SME contractors cannot participate in the digital economy, resulting in the construction industry has one of the lowest indexes of digitization [5]. SMEs represent 98.9% of all contracting firms in the Canadian construction industry and a turnover of more than 50% of the total annual business [6]. In the UK, SMEs represent 99.9% of all contracting firms and turnover more than 63% of the sector business[2]. Migrating towards offsite fabrication is causing construction skills to be lost as construction jobs shift to manufacturing jobs [7]. Young people are not entering the field with revies predicting that the industry's workforce will decline by 20–25% in the next decade [5–7]. Thus, transferring the advantages of digital timber construction to the broader industry is critical. DfMA and DM have to be made appropriate for SMEs, and benefits of offsite construction have to be democratized to all the players on the industry.

## 2 Design for Manufacture and Assembly (DfMA)

Digital timber manufacturing relies on using high-accuracy gantry and joinery machines such as 5-axis gantry machines and CNC joinery machines. These machines require a large initial investment for the purchase of the equipment, setup and proprietary CNC software to operate them and for the size of the facilities to host them and are better suited for high-volume production and less suited for flexibility, operation in small spaces or make-to-order manufacturing of unique pieces [1, 4]. These last three scenarios are more common to an SME contractor than a large-scale manufacturer. Additionally, SMEs are more likely to be found in a more extensive set of scenarios such as: retrofitting or upgrading existing building stock, low-volume housing, and housing in smaller towns and remote locations, which are not always accessible for volumetric components.

The use of industrial robots to manufacture wooden structures as a field has seen a significant amount of research contributions. During the last five years, roboticists from creative and architectural backgrounds have focused on several areas such as (1) the fabrication of wood panels, wood frames and spatial structures [3, 8–14]; (2) traditional timber joints and differentiated timber joints using both robots and CNC joinery machines [3, 4, 15–17].

Robots' compact size and flexibility allow for onsite or near-site manufacturing, which is impossible for joinery CNC machines [17]. Industrial robotic arms are flexible in their applications, require a lower financial commitment and allow for decentralized fabrication [18]. Their potential to feed stacks of the wood material to cutting and milling machines has also been a field explored by architects as means to increase speed and accuracy and streamline digital flows of information over manual CNC production workflows [17, 19, 20]. These efforts have proven great potential for the robot as a mediator between the digital files and the machines used to cut and process the wooden elements. However, their focus has been mainly on processing long wood elements picked from a loaded pallet and translated back and forth for processing.

## 3 Design for Robofacturing (DfR)

Design for Robofacturing (DfR) is a fabrication paradigm in which flexible robotic cells can robofacture a range of high-quality timber products by integrating different fabrication processes [21]. DfR represents a shift towards localized, configurable spaces equipped with a broad range of flexible digital fabrication processes enabled by low-cost machines such as industrial robotic arms. The research presented in this paper aims to capitalize on industrial robotic arms' characteristics, flexibility and potential to extend their capabilities for integrated timber production. It proposes the Design for Robofacturing (DfR) paradigm to develop a specialized timber micro-factory with its corresponding hardware, software integration, communication protocols and micro-credentialing program. The research involves both the creation and adoption of bespoke timber-based DfMA software to produce and adapt architectural designs for DfR.

The developed DfR software toolbox consists of a set of principles to produce complex architectural timber products with their accompanying custom-designed physical robotic fabrication facility. The DfR communication platform connects different fabrication devices, including human tasks required throughout the fabrication process. The DfR platform also works as a communication system between the various stakeholders on the project, from designers, shop managers and fabricators to the trades and product finishing the pieces. It enables providing feedback on time, material, production times and costs to the designers. Finally, the UI is specifically developed to be used by trades allowing them to participate in the digital economy and learn novel fabrication methods. DfR positions itself within the paradigm of digital craftsmanship [22]. It integrates traditional construction trades, crafts and skills with digital manufacturing and digitally produced materials. DfR considerations, in this case, are focused on onsite and near-site fabrication utilizing local resources. The design keeps a low-entry point on space, cost and software skills. It aims to make the hardware and software accessible for SMEs, establishes hybrid human–machine work models and ultimately allows them to understand the benefits that adopting novel technologies can bring to their workflows [23].

## 4 Development of the Research Project

For construction to work as mobile manufacturing and evolve as a democratic, accessible solution for SMEs and all the players in the construction industry, three avenues of research are explored: Physical setup, digital communication platform and a micro-credentialing program.

### *4.1 Physical Setup*

For the design of the fabrication facility, five predefined design principles with their quantifying and guiding parameters were researched and established:

**Flexibility**: measured by using generic, multifunctional tools instead of specialized single-purpose equipment in the machines. Allow interchangeability of tools between machines. The floor plan should remain as open as possible, and machines to be mobile to encourage reconfigurability.

**Efficiency**: focus on using local materials and minimizing waste. Design the machine configurations to allow the maximum variety and range of processes to be done utilizing the digital fabrication machines and tools. Keep the remaining manual works to those requiring higher skills while looking for a high level of integration between the DfR facility and the SME workflows.

**Legibility**: SMEs require to be doing many similar yet different parts with the same tools and machines. The system should be legible and provide information to workers, managers and stakeholders as directly and accessible as possible.

**Safety**: the facility should minimize risks to the workers whilst maximizing their comfort (i.e. avoid heavy lifting and repetitive movements, allow swapping between tasks and avoid monotonous jobs; maximize visibility and keep the environment as open as possible)

**Robustness**: keep a low maintenance and service workflow while providing redundancy that allows swapping between machines and amongst workers.

After defining the design criteria, a timber housing project by Zaha Hadid Architects was analyzed and benchmarked for the design of the fabrication facility (Fig. 1). The project was selected due to the complex geometry, its requirement for customized components and its remote location near to natural resources and SME cotractors.

A basic unit of the ZHA project was analyzed to identify how a DfR approach could be implemented and target the capabilities and dimensions of the proposed facility. The unit was broken down into its constituent parts. The complex carpentry components will be the target products for the fabrication and assembly activities in the proposed fabrication facility. The unit was split into different components: First the "cassette" -style timber frame modules for floors, walls and roofs, containing structural and functional components that can be made using traditional carpentry tools and machines (Fig. 2).

Second, the parts that contain single and double curvature, which require specialized processes and robot end effectors (Fig. 3). The units also have vault-style roofs, requiring specialized fabrication processes. To start defining the machine and human processes that transform raw material into these desired products, specific production tracks were defined (i.e. a material and processing sequence).

After identifying all the processes that could be performed using robot end effectors and the processes that require additional machines, the machinic processing tracks were transformed into a functional spatial configuration with maximum flexibility and minimal footprint. The different activities required, materials and machinic sequences—including human and material—were laid out over time and in several states to define the spatial distribution (Fig. 4). The main areas are stocking,

**Fig. 1** Beyabu project by Zaha Hadid Architects (© Zaha Hadid Architects)

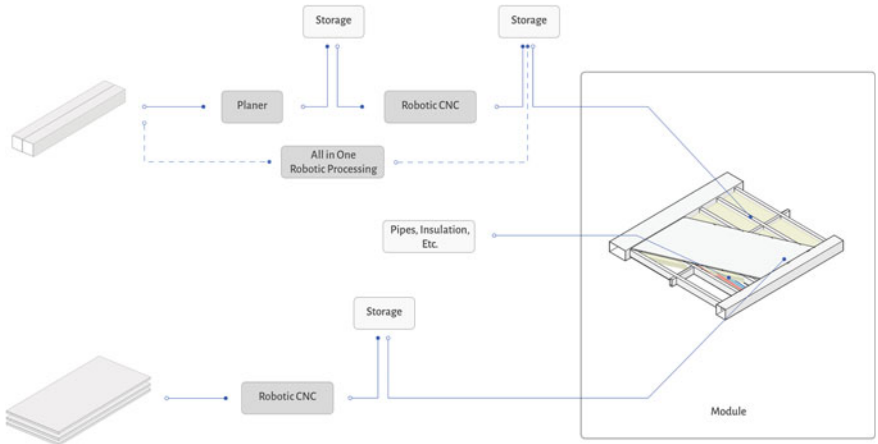


**Fig. 2** Production track for a planar module (©CF in collaboration with IAAC)

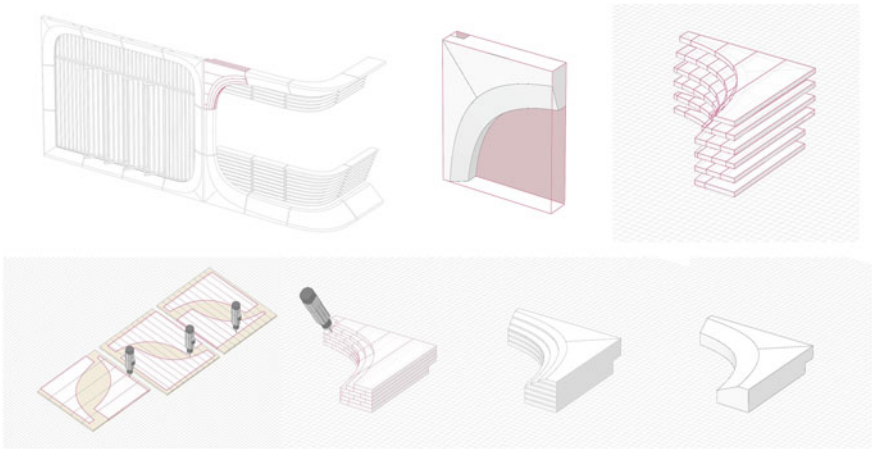

**Fig. 3** Production track for a curved component. (1) design received from the architects; (2) Principal Component Analysis (PCA) for orientation on the stock material; (3) lamination strategy based on the properties and dimensions of the local available material; (4) Nesting for milling of the laminations; (5) stacking of the laminations; (6) layered stack and bandsawing; (7) final piece (© CF)

robotic fabrication, assembly (human-based), finishing area and storage before the components go out to the site.

To enable a system of low capital investment with maximum flexibility, the equipment of the fabrication facility and machine setup are critical decisions. Production scenarios based on industrial robotic arms were studied and analyzed. Machining operations such as routing, drilling and cutting require rigid and precise devices that

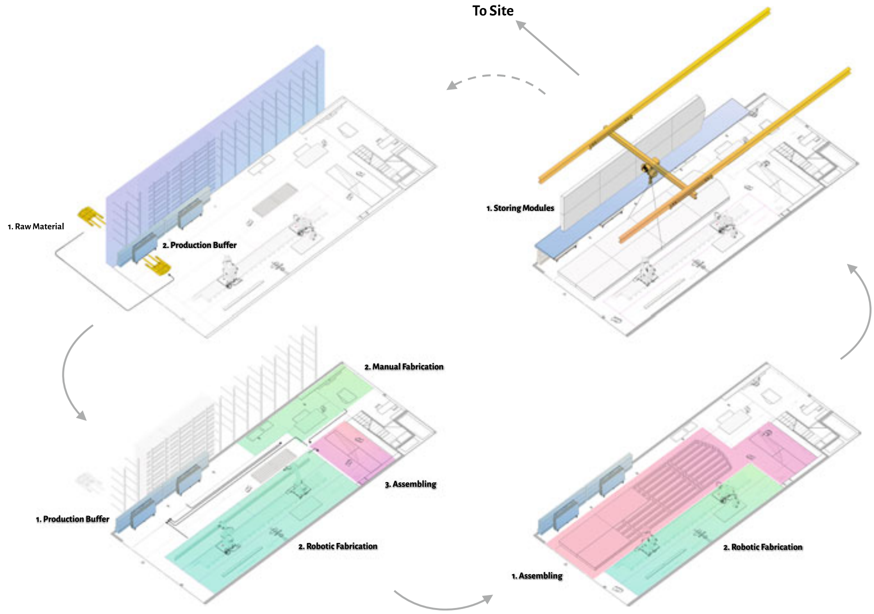


**Fig. 4** Overview of the different processes (©CF in collaboration with IAAC)

provide the stiffness needed for vibration-free and dynamic processes. Additionally, they require high repeatability to ensure dimensional accuracy and high-quality finish of the machined parts. CNC machines have been developed specifically for these functions, making them the industry standard for timber operations. However, specialized woodworking and milling CNC machines are more expensive than industrial robotic arms. The technically ideal 5-axis gantry machines require an even higher investment cost. Hence, the focus is on robot-based setups that allow for the same workability at a comparable scale. The robots provide greater flexibility at a lower investment cost. However, their inherent kinematic disadvantages for machining applications need to be compensated using oversized robots [17].

The adaptability of the industrial robot for different applications makes them an extremely versatile, generic tool but also demands additional effort to set up and integrate all the components needed for specific machining applications. Purpose-built tools like piece holders, end effectors, tool changers, safety light guards, tool and workpiece probes and additional linear axis must be designed and considered.

Four different setup scenarios are designed that satisfy all the considerations: (1) 2 robots on a shared, floor-mounted linear track (Fig. 5); (2) 2 robots on a shared elevated linear track (Fig. 6); (3) 2 robots on individual rails (Fig. 7); (4) 1 stationary robot and a 5-axis CNC machine (Fig. 8).

Setup 1, which considers two identical ABB robots in a shared linear track, allows creation of a large elongated combined working envelope. This setup would allow the processing of the entire length of the largest edge beams. Since they share the same

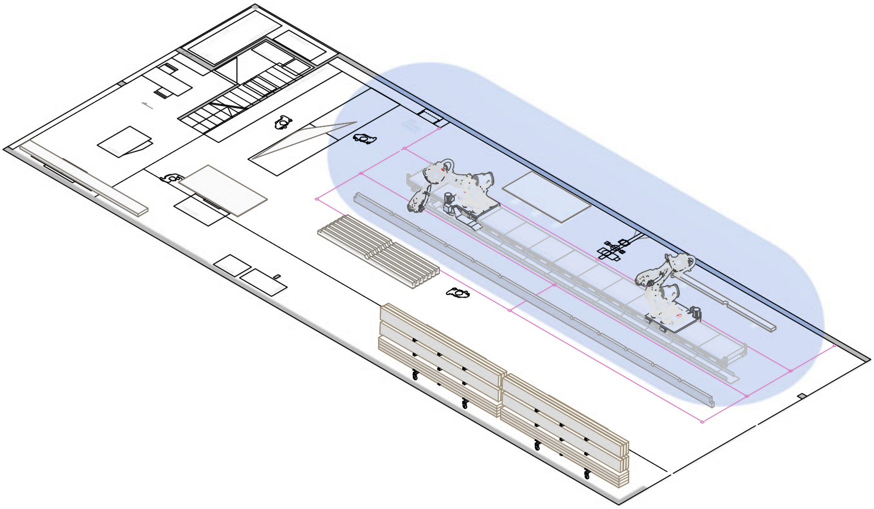

**Fig. 5** Two identical ABB IRB6700 robots share a linear track (©CF in collaboration with IAAC)

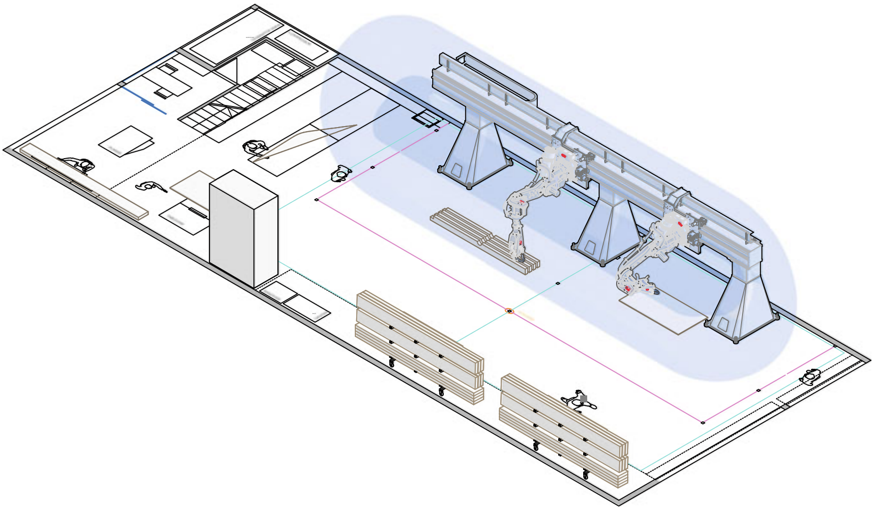

**Fig. 6** An elevated GÜDEL linear track of 13 m in length is shared by two ABB IRB6700 robots (©CF in collaboration with IAAC)

rail, applications in which their working envelopes need to intersect are possible, creating the flexibility to share handling and machining tasks between both of them, but also to act as 2 independent robots that are working in parallel or on one large workpiece simultaneously.

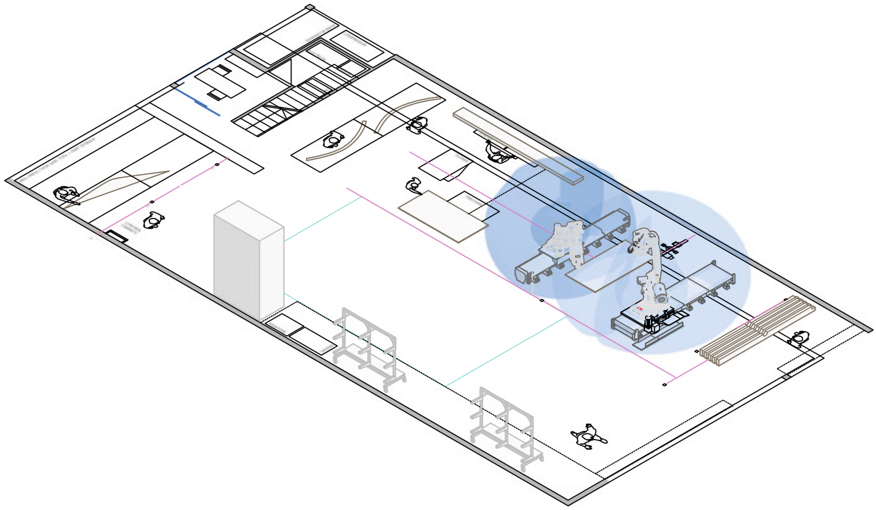

**Fig. 7** Two robots in individual rails (©CF in collaboration with IAAC)

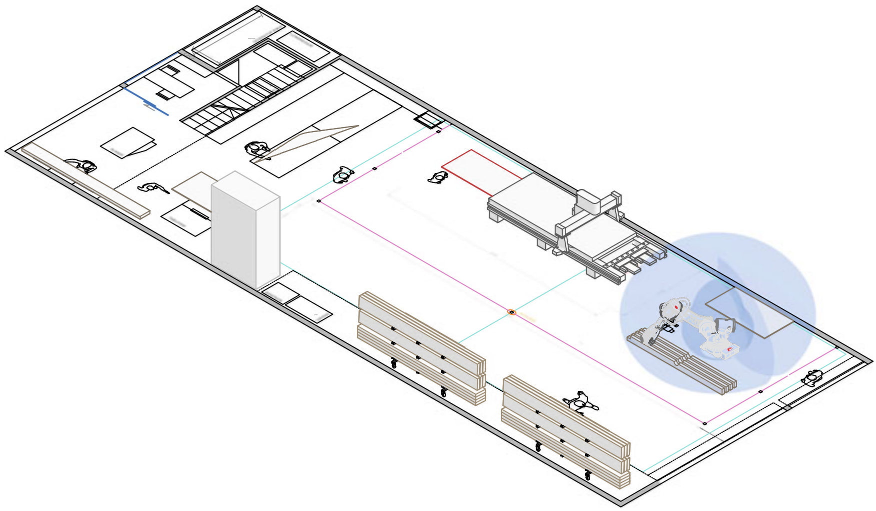

**Fig. 8** One floor-mounted robot with a 5-axis CNC machine (©CF in collaboration with IAAC)

Setup 2, an elevated GUDEL track with two ABB robots on an inverse mount, also provides the capability of processing long beams like the previous one, but its floor mounted. This means that support columns occupy a smaller area of the factory floor than the floor-mounted track. The sideways-hanging configuration also allows for better utilization of the robots' theoretical maximum working envelope, as it is not intersecting with the building floor and walls. The considerable upcharge, the introduction of an additional supplier and extra integration effort (tracks being produced in Switzerland by GÜDEL) make this option less attractive from an economic standpoint. If large format 3d-milling of freeform surfaces is really needed, it might still be a viable option but will only be justifiable if the requirements actually match the theoretical workspace of this setup.

Setup 3 considers one ABB IRB6700 for machining and one ABB IRB6620 as a handling robot mounted on individual linear rails, facing each other with partially overlapping working envelopes. Here, the robots have a limitation in the task assignment. The ABB6620, while cheaper, is not appropriate for milling applications (ABB). While providing a small advantage in investment costs, this comes at the expense of flexibility and robustness, as the most critical tools cannot be shared between the machines. Furthermore, the more equally-sided footprint of this setup suggests a less elongated floorplan, which is less beneficial for the production of the long elements on this project.

Setup 04 considers one floor mounted ABB IRB6700 accompanied by a Laguna 5X CNC router. The router can be custom built to have a large table (4,27 m) for a limited surcharge, potentially enabling it to machine both ends of the longest timber elements used in the current design.

In addition to these four robot scenarios, a system for the clamping and registration of curved elements was studied. To allow precise, flexible clamping, it is important to set up a reliable method that obtains the actual piece configuration and feeds it back to the system in an adaptive way. Four possible solutions (Fig. 9) are analyzed to obtain the workpiece configuration: (1) a mechanical, robot-mounted workpiece probe; (2) using motion-tracking sensors and targets; (3) a robot-mounted depth camera; (4) a laser probe on a linear rail.

An assembly and multifunction space were considered for the pieces' assembly, drying and finishing. These areas will be used mainly by humans doing those activities

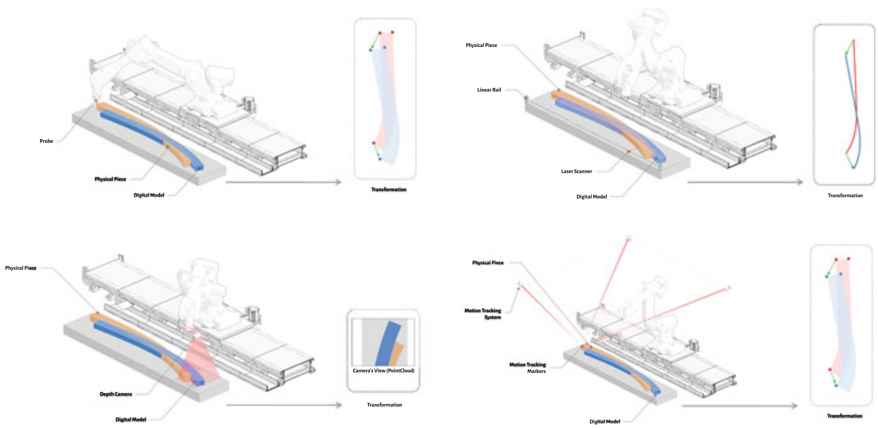


**Fig. 9** Registration methods for machining of curved beams (©CF in collaboration with IAAC)

and configured with assembly tables. Finally, three internal storage areas with the ability to fit a forklift are considered. A production buffer that provides dynamic, hand-accessible storage space during production. Small-parts storage in the vicinity of the pre-assembly area and a high-load cantilever shelf for finished modules, located above the production buffer.

## *4.2 Digital Workflow and Communication Platform*

Digital workflows from design to fabrication are segregated, as they are composed of multiple actors and stakeholders that work in isolation in various software platforms to complete different tasks [24]. Current product development cycles for architectural elements go through the design team, DfMA engineers, and constructors in separate packages (Fig. 10). While this entire team is part of one unified system, each member is in a different location, using different tools and file formats [25, 26].

For DfR to be effective, a communication system is a key to connecting the different machines of the production process into a network. The digital platform aims to provide a unified and transparent overview of the process, leading to a more productive design to fabrication approach. The developed web-based communication workflow is built mostly using existing open-source tools, which can enhance the

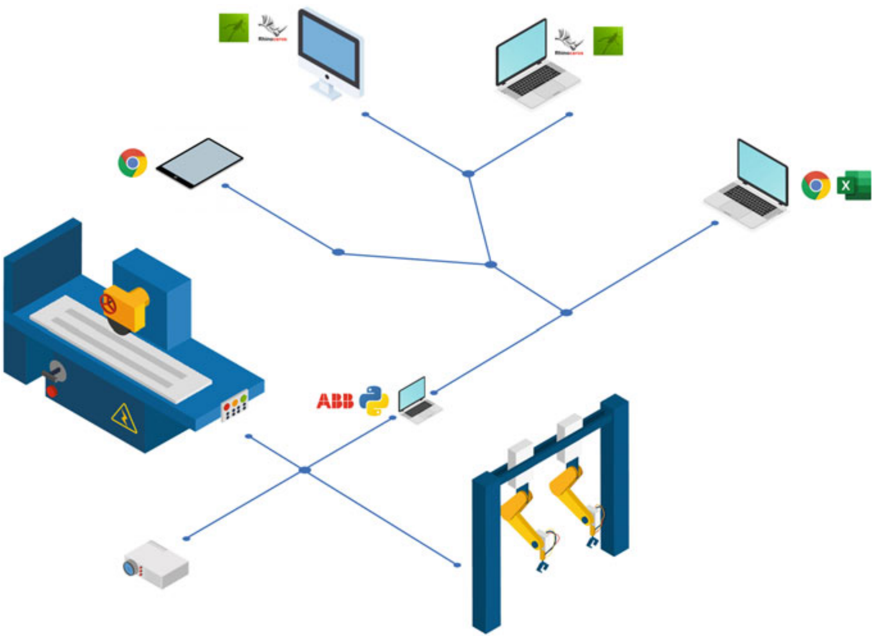

**Fig. 10** Data connections between different Machines in the fabrication process

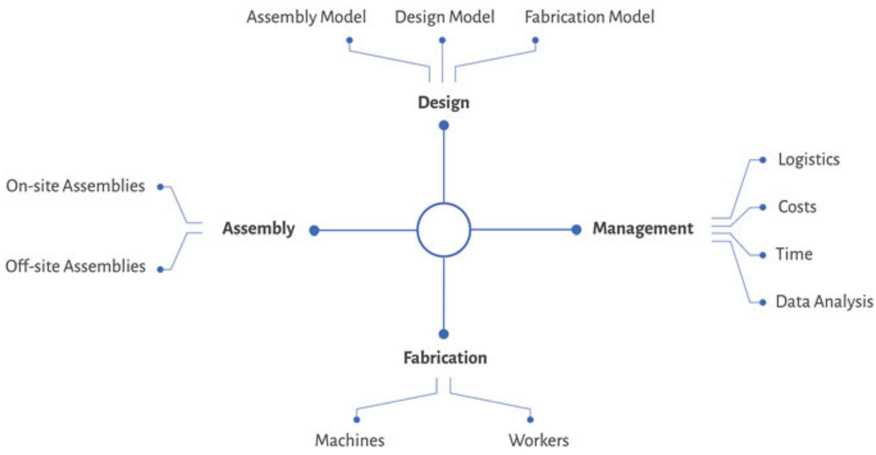


**Fig. 11** Data connections between different Stakeholders in the fabrication process

project's overall management and better understanding and data exchanges between different stakeholders (Fig. 11).

The information management system is based on a database that contains rich data embedded geometry and the files required for different processes such as fabrication, visualization, management, etc. In this approach various stakeholders of the process build together a holistic model. The database allows users to query and access only the required information. Therefore, this information will be easily accessible for the various stakeholders' requirements during the fabrication process. Some of the key features of this communication platform are listed below [27] (Fig. 12).

### 4.2.1 Parts Information

The metadata stored in each part consists of 6 sections (Fig. 13).

- Identification: includes the name and description of the part to help identify the piece.
- Geometry: includes important geometrical data which facilitates further processes during fabrication and planning, some of this information include dimensions, curvature, and important features such as axis line, holes, important curves, etc.
- Fabrication: includes fabrication related information for the piece; The sequence of processes that needs to be performed on the material, as well as instructions and simulation files for these processes.
- Assembly: includes assembly instructions, assembly order and other information regarding the assembly process.
- Logistics: includes information that can help the production manager to optimize the fabrication process. This includes time estimations for fabrication and assembly, raw materials needed for the production of the piece, etc.

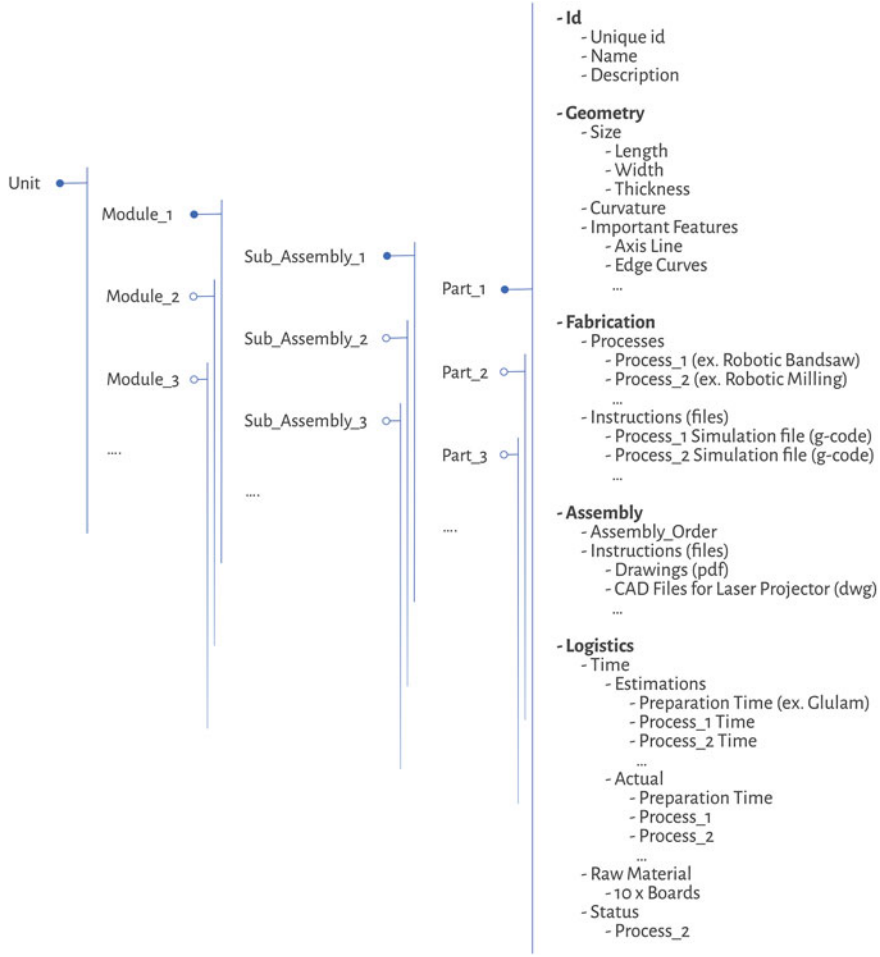


**Fig. 12** Metadata stored for each part

- Quality Control: includes as-built information after the fabrication. Which can be used for further documentation of the construction process. It can contain images, and 3d point cloud data.

### 4.2.2 Fabrication Schedules

For each piece, there are several processes required in the production pipeline to manufacture the part. DfMA engineers rationalize the design and define the fabrication details, such as joineries and other details. Then, fabrication experts define the processes required to fabricate the piece with such details. For each piece to be fabricated, several processes happen on manual and digital fabrication machines, from

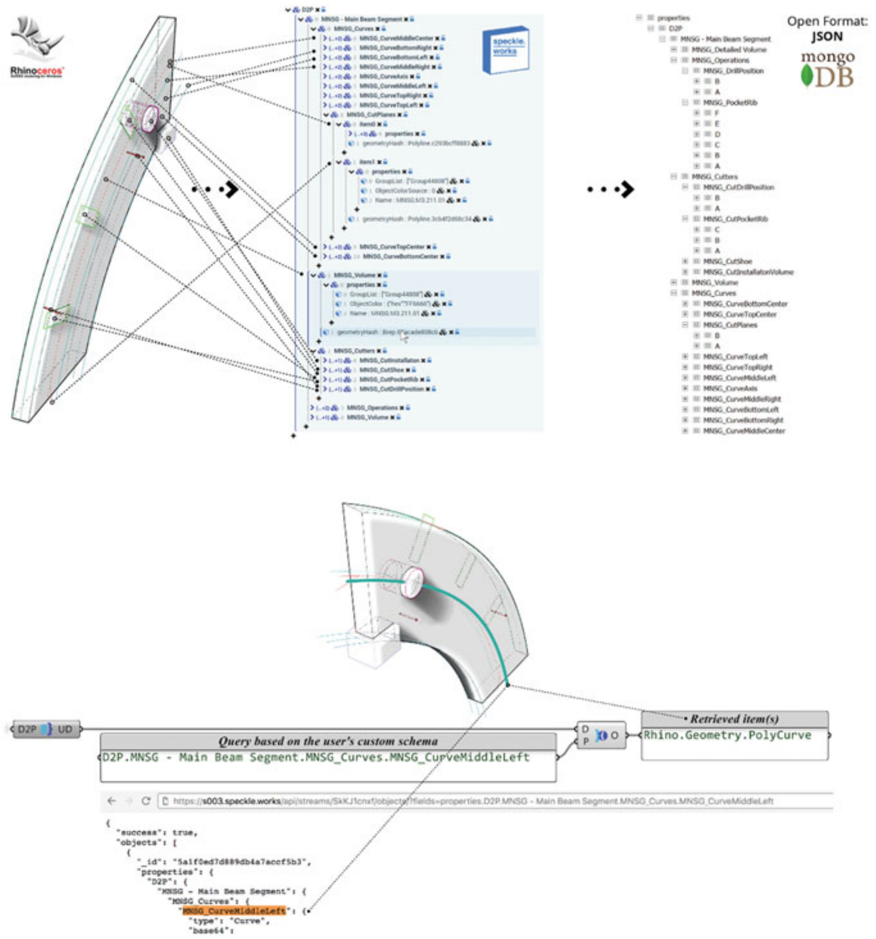


**Fig. 13** Meta-data stored in the database for each part: A "MainBeam" modeled by Design-to-Production containing a hierarchy of different objects and sub-objects translated successively into a UserDictionary and a JSON string. (top) Querying process for specific information from the database (bottom) [24]

planar and table saw to robotic milling cells. Each process needs to be scheduled and communicated to the specified operator in the production workshop (Fig. 14).

The scheduling process is based on the *job shop* scheduling problem, in which multiple jobs are processed on several machines. Each job consists of a sequence of tasks, which must be performed in a given order, and each task must be processed on a specific machine. The problem is to schedule the tasks on the machines to *minimize the total length of fabrication*—the time it takes for all the jobs to be completed. There are several constraints for the job shop problem:

- No task for a job can be started until the previous task for that job is completed.

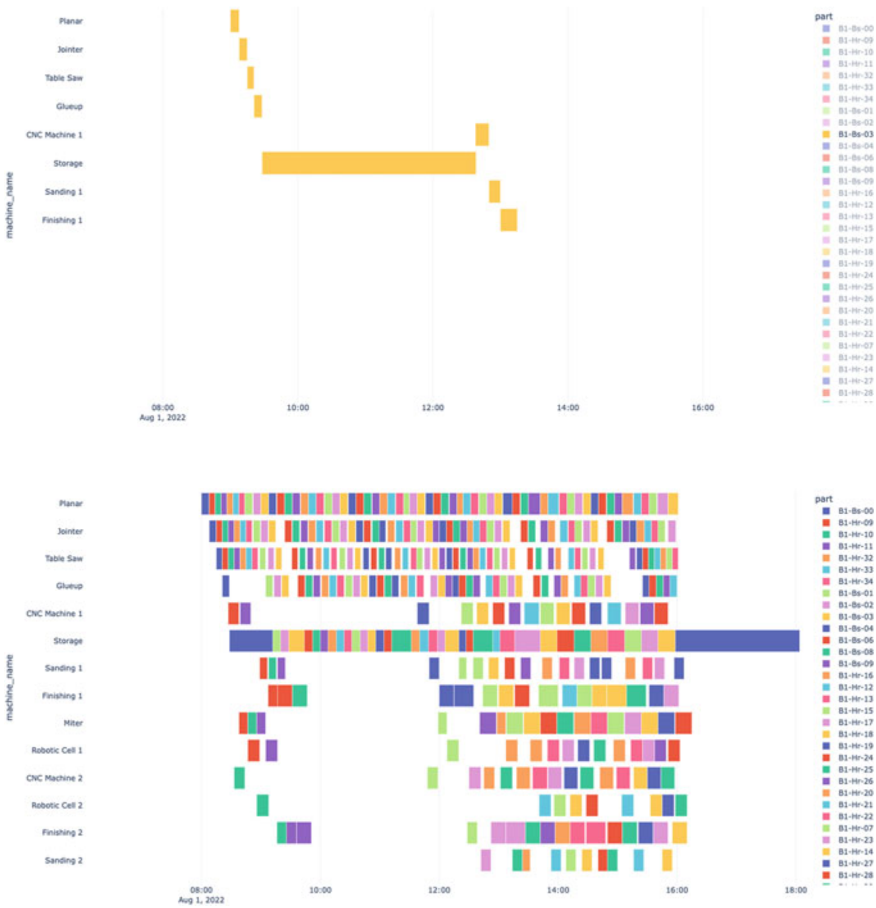


**Fig. 14** Schedules: daily plans for the fabrication of pieces

- A machine can only work on one task at a time.
- A task, once started, must run to completion.

We leverage Google's OR-Tools library, open-source software for *combinatorial optimization,* which seeks to find the best solution to a problem out of a very large set of possible solutions. Below is a snapshot of a daily schedule for production and the processes for one part within that day.

By defining the schedules, the manufacturer can easily input their product data into the network database and quickly download the appropriate work materials, tools, machine tools, and fixtures based on the fabrication requirements.

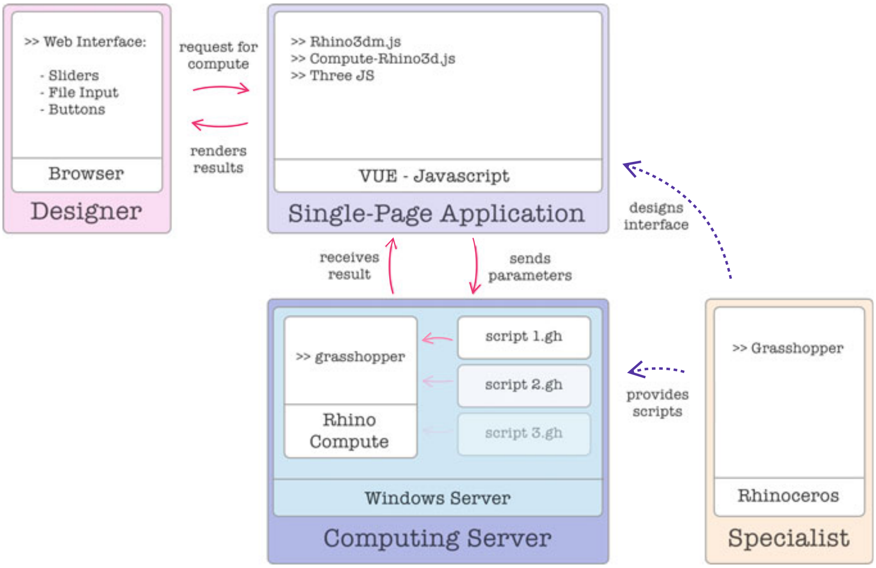


**Fig. 15** Geometrical cloud computing (Rhino Compute) Interface between designer and engineer

### 4.2.3 Feedback for Product Development

Integration of this platform with server-side computing enables the specialist construction team to provide an interface/tool for the designers to assess their design in real-time using the scripts provided by the specialist.

For example, in geometry calculation and analysis, solving a process on a cloud-based Rhino Compute instance; Users can input a local design file and process analysis (CAA) and CAM workflows for the input, getting estimates of fabrication time, cost, waste, and materials needed. Other use-cases can be regenerating a CNC tool path or updating the fabrication schedules based on onsite modifications needed during the construction (Fig. 15).

Providing a web-based interface for solving different CAM and CAA workflows enables users with little or no knowledge of scripting to use a complex script in a fast and simple manner.

### 4.2.4 Interoperability

Leveraging the Speckle database system and cloud computing services like Rhino-Compute, the platform can connect with most of the software used in the AEC industry, such as Unreal Engine, Rhinoceros, etc. It can also integrate with database systems such as graphQl, or blockchain databases (Fig. 16). The interface is accessible through CAD software and programming languages for developers and Web-based access (Browser) for less technical users.

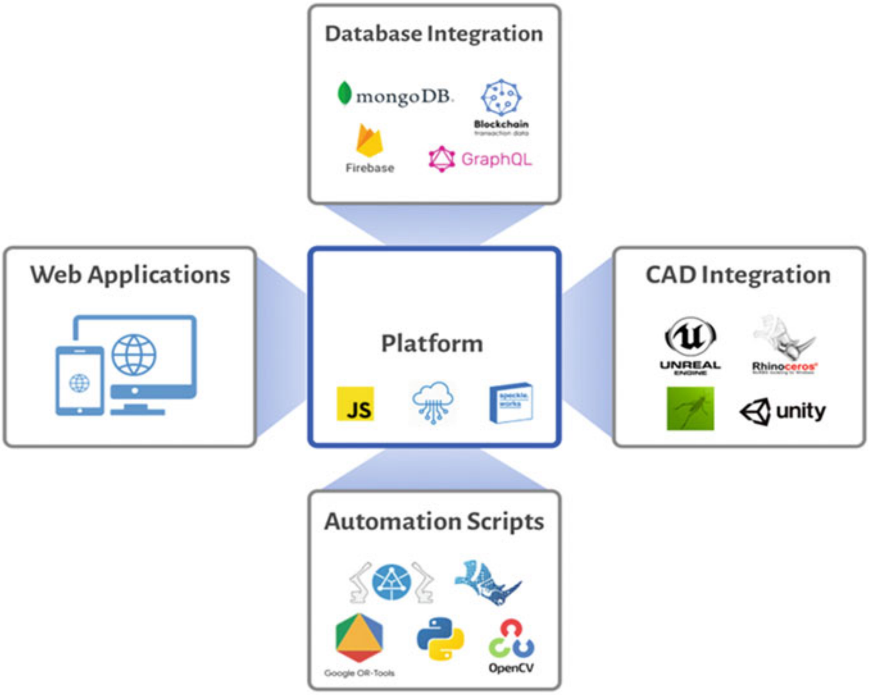


**Fig. 16** Interoperability of the platform interface with Web Apps, CAD softwares, Databases and other Scripting libraries

### 4.2.5 Activity Logs Database

While this communication platform provides tools for communication and real-time computing from different design to construction stages, it also enables the SME's team to log different interactions and information about the design to the fabrication process in a database. Some of the information includes the stock of materials needed, the actual time for fabrication, usage of tools, the performance of the machines and construction team, quality prediction and control, etc. This database can be used for further studies on the process to reduce the gap between estimations and simulations with reality in terms of material use, fabrication time, etc.

## *4.3 Upskilling and Microcredentials*

A DfR paradigm requires promoting and developing a trained and well-informed workforce that can take advantage of the digital processes while maintaining traditional skills and crafts required by the construction industry (Fig. 17). The objective of the micro-credentialing program is twofold: (1) to keep the construction skills and jobs within the sector by introducing digital fabrication skills, and avoiding construction jobs going to manufacturing professionals. (2) to attract new and young talent to the industry through a digitized onsite/near-site offering.

Modern Methods of Construction (MMC) traditionally refers to offsite prefabrication tools and techniques. In the context of DfR MMC is extended to include onsite and near-site digital fabrication techniques. The micro credentialing course is intended to address specific training needs in digital carpentry and focuses on the fabrication of curved façade components. The pieces selected for training require from material preparation, lamination, and several robotic processes such as routing, bandsawing and milling. Participants are also introduced to the digital workflow and communication platforms for preparing a design for DfR. Based on the research of various micro-courses on the construction sector [28, 29] two courses are proposed:

(1) A full-time 9-week course combining practical and classroom activities is envisioned for technicians with construction experience. The program will teach technical skills (knowledge of tools, equipment and processes). Safety training and essential skills are embedded throughout the program, including using 3D models, measurements, calibration, communication protocols, physical dexterity and working with others. This course is designed for technicians with construction experience.
(2) A two-part full-time 9-week course (total of 18 weeks) for technicians willing to train, do a career change and those who don't have experience in the construction industry. The first part of this course focuses on identifying components, processes and procedures to demonstrate an awareness of best practice standards before moving to the second course.

The first iteration of both curriculums will be deployed after the micro-factory completion. The construction of the technology demonstrator is envisioned using local trades that undergo the training curriculum.

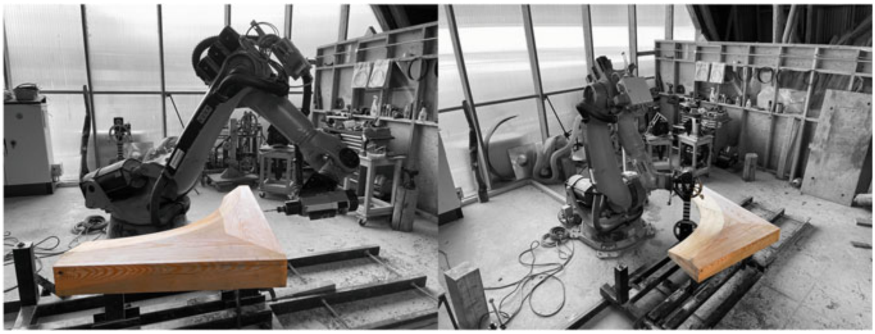

**Fig. 17** Laminated timber prototypes produced using hybrid methods

## 5 Discussion

The digitization of the construction industry faces many challenges—the digital fabrication machines' financial, skill and space requirements limit the advances to large companies able to afford them. Through applying innovation in computational design within a DfR workflow, the research aims to enable SME contractors access to digital machines and tools, upskilling them and making them active participants both onsite and near-site in the digitization of the construction industry. In the current stage, local contractors have expressed interest in going through the training and micro-credentialing program. They also see the potential for renting or buying the facility. The engagement of the local people and results will be analyzed. However, this is a step towards sustainable digital craftmanship [22] in the construction trades. DfR for timber advocates for the democratization of digital manufacturing tools and techniques. It aims to upskill local labour by disseminating the use of digital fabrication machines with their efficient and sustainable credentials**.**

Different stakeholders in the design to fabrication process include the design team, the engineering team and the fabrication team. The fabrication team involves from fabrication experts and production managers to the workers in the factory and the machines processing the materials. The DfR platform presented in this research allows for communication between stakeholders. Connecting the design process to fabrication parameters that include material layout, machine time, human time, laminations and ultimately GCode generation. This interoperability would allow SMEs to be more precise on their estimates but, more importantly, designers and other stakeholders to have a higher degree of transparency, similar to the one that offsite manufacturers offer.

Furthermore, the feedback provided to designers and stakeholders would allow them to understand the implications of their decisions to each of the different parameters (i.e. machine time, human time, bill of materials, etc.) and make informed decisions with confidence using local trades. The platform collects information once the work starts to identify discrepancies between time estimates and actual working times and iteratively refine its calculations. The data collected from the working pieces will help the designers and stakeholders understand limitations and bottlenecks and better plan their designs and schedules using quantifiable information. The lack of For the future development of the software platform, integration with blockchain and smart contracts is considered. Blockchain can enable SMEs to get paid as processes are finished adding more transparency to trades and processes often considered opaque on their inner workings, cost calculation and timeframe delivery. Another consi.

The developed digital and physical DfR framework contributes to promoting inclusivity by enabling a sustainable approach to industrialization. It makes advanced digital fabrication available to a sector often overseen by the construction industry, SMEs (UNsdg 9). The technology demonstrator is purposely built in a country under development. The financial requirements to acquire the machines and the corresponding digital fabrication process were iterative research during the design of the micro-factory. Packing as many processes as possible within a DfR workflow enables a financial model in which SMEs can engage. The technical platform aims to encourage 'building sustainable and resilient buildings utilizing local materials' (UNsdg 11). The DfR cyber-physical platform is a step toward supporting developing countries to strengthen their scientific and technological capacity. Skilled workers must have access to resources in their toolkit that can move them towards more sustainable production patterns (UNsdg 12), such as access to digital fabrication tools.

## 6 Conclusion

The paper presents the author's entrepreneurship and efforts to construct a DfR fabrication facility in a developing, remote location—rich in resources. It offers a digital and physical strategy to upskill and digitize the local trades. The authors will produce a housing complex using the hardware, software, and training program in situ as an initial project. The project has the particularity to offer future clients the possibility to modify and customize the design using a digital app, requiring the DfR workflow to handle and produce mass-customized parts in a flexible yet controlled process. The paper presents the development of the corresponding cyber-physical DfR fabrication platform for complex timber products with its upskilling and training program. The micro-factory facility can subsequently be acquired by the local trades trained in the use of the machines and software. More construction companies are moving towards adopting manufacturing processes in a bid for digitization and in response to problems attracting more workers onsite [5]. This research envisions democratic digitization of the construction industry by providing existing trades with a digital toolset, new talent will get interested and onsite/near-site skills, and construction knowledge will be continued and augmented.

The DfR framework, with its SME-friendly components, aims to enable them to: reduce construction costs by being able to engage with material-reducing design technologies; reduce total construction times by using a low-capital investment, flexible digital micro factory; enabling more transparent processes on time and costs between stakeholders that work with SMEs; reduce the ecological impact by using local materials and processing elements on/near site as opposed to transporting large volumetric materials. Finally, it aims to contribute to the democratic digitization of the supply chain in the construction industry.

**Acknowledgements** Phae 1 of the research presented in this paper was developed in collaboration with the Insitute of Advanced Architecture of Catalunya (IAAC) and their external consultants with expertise in wood manufacturing and architecture, robotic fabrication and fabrication laboratory setup. In particular Raimund Krenmueller, Alexandre Dubor, Shyam Zonca, Lana Awad, Tom Svilans and Daniela Figueroa. Their contributions and work during phase 1 of this project shaped the initial configuration of the fabrication facility and the skeleton of the digital and communications platform. Additionally, Jean-Nicola Dackiw (CF) is part of the team working with the authors

to refine the digital workflow related to the physical fabrication processes. He has been instrumental in refining the factory layout from initial studies to its final configuration—currently under construction- and towards its final physical setup.

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# Spatial Curved Laminated Timber Structures

**Vishu Bhooshan, Alicia Nahmad, Philip Singer, Taizhong Chen, Ling Mao, Henry David Louth, and Shajay Bhooshan**

**Abstract** The paper describes the physical realisation of a demonstration prototype produced by mouldless wood bending of discrete laminated timber elements which are interconnected to create a predominantly compression only spatial structure. Integrated design to production pipelines is increasingly valued in Architecture, Engineerinng and Construction, as it has contributed to developing methods of generation of the so-called architectural geometry and in bringing the various disciplines in the industry closer together. The research presented is motivated by the application and use of timber in such a realm. It details a design to production toolkit along with development of custom actuator-based tool to deliver sustainable benefits of reduced material usage and wastage in addition to efficient production of bent wood structures. Furthermore, the paper proposes an alternative procedure for polyhedral

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_43

reconstruction of disjointed force polyhedrons from an input graph, which enables the creation of spatial structures in static equilibrium.

**Keywords** Digital timber · Laminated timber · Computational parametric design · 3D graphic statics · Fabrication aware design · Digital robotic fabrication · Mesh modeling environments

# 1 Introduction

The research presented in this paper is motivated by the resurgence of timber as a construction material and the current lack of publicly available integrated design, structure and fabrication aware toolkits especially in the domain of timber spatial structures. The paper details the development of such a tool chain that enabled the production, fabrication and assembly of a demonstrator spatial structure made up of 24 nodes of curved laminated timber (Figs. 1 and 2). The objective was to create a toolkit emphasising on knowledge capture and reuse instead of an individual stand-alone solution [1].

## 1.1 Digital Timber

Timber is one of our most traditional construction materials, but its resurgence has come out of recent technological advances in digital production techniques, processing technologies, digital design tools etc.; as well as a ecological factor of timber being environmentally friendly as compared to other construction material

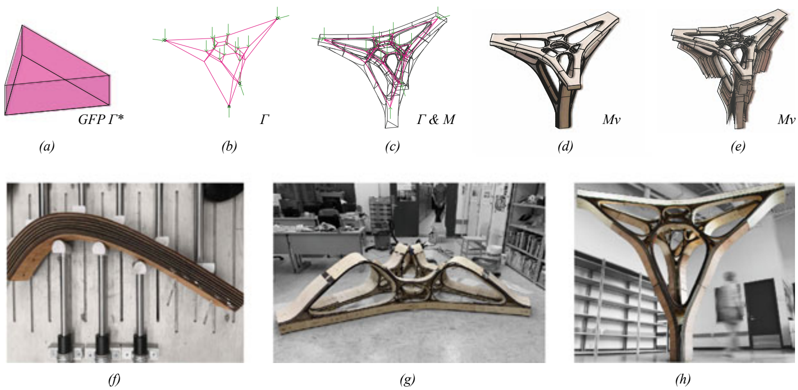



**Fig. 1** Design to production tool chain and physical demonstrator. **a**–**e** procedure to design a spatial curved laminated timber structure, **f** pneumatic bending multi-layer laminates, **g** on site assembly, and **h** finished structure

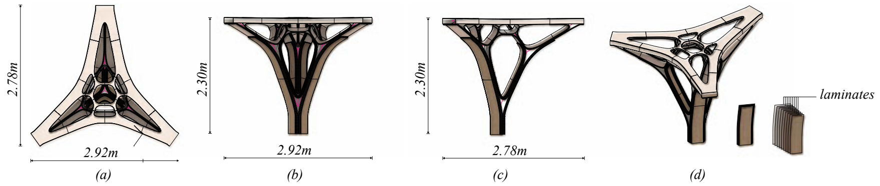



**Fig. 2** Schematic drawings—**a** top view, **b** sections, **c** front elevation, **d** right-side elevation, and **e** perspective

such as concrete or steel. Timber is believed to have a key role to play on creating a net zero built environment [2–5].

The recent and rapid advancements in robotic and digital fabrication systems (RDF), have become extremely useful as they are not only leading to considerable time saving but can directly transfer computational design data directly to manufacturing and assembly operations which are enabling construction of non-standard timber structures. These advancements have also brought about bidirectional feedback of production back to the design conception—the so-called design for manufacture and assembly paradigm (DFMA) [6–9]. The robotic assembly of spatial structures with timber elements have also been researched and documented [10–12].

The benefits of aligning of geometry to structural principals and static equilibrium shapes have been well established especially in the domain of large span timber shells [13–15] etc. Furthermore, albeit not specifically on timber as a material, the benefits of structure aligned geometry paradigm to improve recyclability, and the repair and reuse of material and structural components due to dry assembly have also been recently highlighted [16–19].

The delivery of timber architecture, once endowed to the architect-builder or "master craftsman" must evolve into a collaborative model of specialised skill sets in various trades and "digital craftsmanship" to build the promise of environmentally friendly, sustainable built environment [20–22].

## *1.2 Key Contributions*

The main contribution of the paper is the development of a design to production toolchain that enabled the design and build of a spatial structure in timber. Specifically, it enabled:

- to reduce the amount of material required by precisely computing the number of cross section laminates required based on the compressive and tensile forces acting on the structure;
- to reduce complexity of node connection, a typical issue for high valence spatial structures, by having the timber joinery away from node;

- the development of an actuator-based machine for bending of glulams which used electric linear motion over pneumatic actuation, allowing for less waste and tighter tolerances in comparison to its precedents;
- to register real time and efficiently bend the multiple varying curvature elements in a short period of time via a physical and digital configuration of linear actuators on a bed-like table.

In addition, the paper proposes an alternative procedure to the *extended Gaussian image-based* method detailed in [23], to create a polyhedral force diagram from an input graph—which are amenable for quick design manipulation in commercially available Mesh Modeling and CAD Environment's.

## 2 Prior Work

The prior work stems from domains which are relevant to the main contributions of the paper, which are expanded in the sections below.

### *2.1 Geometry Representation and Architectural Geometry*

Discrete geometry representations—graphs, meshes, volumetric meshes etc. aided by rapid development in applying discrete differential geometry to architectural problems such as planarisation, developability, cylinder fitting of panels etc., have become the preferred geometric representation for both the conceptual design and downstream production stages of the design workflow [24–27].

Coupled with an interactive mesh modeling environment (MME) as detailed in [28], it presents a significant opportunity for a holistic mode of design exploration. They are increasingly valued as it facilitates.

- use of contemporary paradigm of edit and observe interactive modelling [29–31];
- exploration of static equilibrium shape design [31–36]
- greater design control in the production and delivery stages [8, 11, 16, 34, 37, 38]
- and provides a feedback loop between the various stages of the design workflow [8, 11, 16, 20, 28, 37, 39].

Such workflows have contributed to developing methods of generation of the so-called *architectural geometry* [40] and bringing disparate disciplines within Architecture, Engineering and Construction (AEC) industries closer together [37]. For further readings on the use of discrete representation for architectural applications we refer the reader to [16, 31, 35, 36, 38, 39, 41–47] etc.

### 2.2 Polyhedral 3D Graphical Statics

Polyhedral 3D graphical statics (3DGS) is a recent development of graphic statics in three dimensions based on a historical proposition by [48, 49]. The construction of the dual and reciprocal form and force diagrams, the design exploration and structural form-finding via manipulation of the diagrams have been thoroughly explicated by [23, 32, 50–53].

The procedures have been fully extended to computational frameworks and made into publicly available toolsets for CAD application by [54, 55] etc.

Various materialisation strategies have been explored for the realisation of 3DGS structures—concrete, mycelium, glass etc. [18, 19, 56]; However, its exploration in timber is very recent and in early-stages of research and development [57–60].

### 2.3 Wood Bending

Wood bending methods date back to antiquity. Bending started with the use of fresh twigs, which can be easily bent into almost any shape. Dried wood is more difficult to bend as it becomes rigid and breakable and hence relies on the use of heat and water. They were specially developed in the shipbuilding industry in which lamella were turned into boat hulls and bark ribs into canoes [61–63]. These mechanisms relied on using nature found (i.e., tying the wood around a tree after pouring boiling water over it) and purpose-made moulds (Fig. 3a) around which wet, thick sections of wood would be tied and dried to hold the curvature—predominantly single curvature.

In addition to the different steam bending methods for dry wood, other bending practices have emerged and evolved. Glue-laminated timber—abbreviated to *glulam*—the technique of gluing together a slack of thin rectangular-section wood elements to create a larger section element that is typically used as a column or beam. This along with development of engineered timber products with glue and resins have made possible to have mechanically fastened compound sections amenable for large spans, improved element consistency, load capacity etc. Glue-lamination also presents the opportunity of creating curvatures in large timber elements by individually curving the component lamella (which are flexible) during the glue-up. The

(a) (b) (c)

**Fig. 3** Precedents for wood bending machines bending of lamella demands special systems of glue-up jigs and clamping, which limits the flexibility and speed at which different curvatures can be achieved (Fig. 3b, c). Typically, as a rule of thumb, the radius of curvature achievable is 200 times the lamella thickness [64]. Digital methods have been explored as a flexible alternative for glulam bending, suggesting how wood lamination curvature could inherently be programmed or predetermined [65–69].

Contemporary pavilions and architectural applications continue to expand the wood bending technology beyond furnishing scale [70] tending towards the design and production of elastically bent wood sheets amenable to robotic fabrication and assembly [71]. This paper describes the use of ubiquitous two axis Computer Numerical Controlled (CNC) technology to create bent wood skeletal structures (Fig. 1). For further understanding of the economic benefits of using such a technology we refer the reader to [38, 47, 59, 72].

### *2.4 Software Add-Ins and File Formats*

We implemented the toolchain detailed in Sect. 3 including the polyhedral 3DGS procedures detailed in [50, 51] using a C++ based framework—ZSPACE [73].

The collaborative design to production (DTP) toolchain described below is based on a discrete geometry-processing paradigm—graphs, meshes and volume meshes. This allows for lightweight transmission and reconstruction of information by various participating tools in DTP. The DTP toolchain is supported by a custom file format which uses JavaScript Object Notation (JSON) and half-edge and half-face data structures that are common to this paradigm, to transmit and process 3D model information [74].

The authors have previously developed add-ins to incorporate form finding methods such as Force Density Method (FDM) [75] and Thrust Network Analysis (TNA) [33] within the MME of Autodesk Maya [28, 57]. Further the authors have made previous investigations to use *dynamic relaxation* (DR) techniques on meshes to address fabrication related constraints [38, 42, 44].

## 3 Design-To-Production Toolchain

The collaborative, multi-author DTP process that we developed to physically realise the demonstrator spatial structure, is composed of the following steps:

- **Shape-design**: designer-guided shape-design exploration of a medial spatial graph and form finding using polyhedral 3DGS (Fig. 4a).
- **Architectural geometry**: Generation and thickening of geometry of the spatial graph using the structural and polyhedral information from the previous step and decomposition of it into fabricable parts per node; (Fig. 4b).

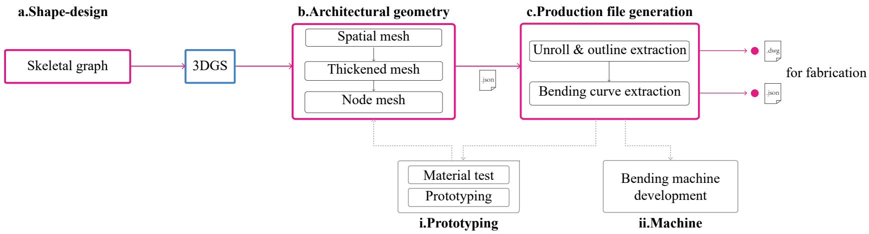



**Fig. 4** DTP Tool chain unrolled into threads. **a**, **b**, **c** serial design thread, (i) material testing and prototyping thread, and (ii) bending machine development thread

- **Production information generation**: fabrication aware optimisation of the geometry and generation of the production information per node of the spatial structure (Fig. 4c).

In addition to these, there are two other steps of material testing and design and creation of actuator-based machine for bending of the glulams. These steps informed the material thickness, size and permissible bending radius in the optimisation process of AG.

## 3.1 Shape Design

The global shape design and manipulation of the spatial structure was carried out using the framework of polyhedral 3DGS. In a typical polyhedral 3DGS application scenario, the process begins by defining the force ($\mathbf{\Gamma}^*$) and form ($\mathbf{\Gamma}$) diagrams which are made up of polyhedral cells. ($\mathbf{\Gamma}^*$) can be decomposed into a *global force polyhedron* (GFP)—representing the static equilibrium of external forces—and *nodal force polyhedrons* (NFP)—the rest of the cells inside the GFP, representing the equilibrium of forces coming together at that node in $\mathbf{\Gamma}$ [51]. In the initial step of the design a GFP was defined (Fig. 5a), which were subsequently subdivided using the schemes described in [76] to create the ($\mathbf{\Gamma}^*$) (Fig. 5b).

Next an initial $\mathbf{\Gamma}$ is constructed from ($\mathbf{\Gamma}^*$) using the reciprocation algorithm [77] (Fig. 5c, d). The equilibrium of the external forces of the *i*th node $\mathbf{v}_i$ of $\mathbf{\Gamma}$ (Fig. 5g) is represented by a closed polyhedron, $\mathbf{c}_i^*$ (Fig. 5b) of ($\mathbf{\Gamma}^*$). For each $\mathbf{c}_i^*$, the normal $\mathbf{n}_{i,j}$ and the area $\mathbf{A}_{i,j}$ represent the direction and magnitude of the axial force $\mathbf{f}_{i,j}$ in the corresponding edge $\mathbf{e}_{i,j}$ of $\mathbf{\Gamma}$ [23]. This equilibrium is achieved by updating the vertices of $\mathbf{\Gamma}$ and/or ($\mathbf{\Gamma}^*$) using a so-called perturbation procedure detailed in [77]. Figure 5e shows the equilibrium state of $\mathbf{\Gamma}$.

This sequence of defining the GFP first could be counter-intuitive for designers as the shape that they would like to exercise control on—the $\mathbf{\Gamma}$—is generated as topological dual only in the second step. The representation $\mathbf{\Gamma}$ as a collection of polyhedral cells would lack ease of manipulation in a interactive MME, as such commercially available interfaces like Autodesk Maya, generally doesn't ship with the volume

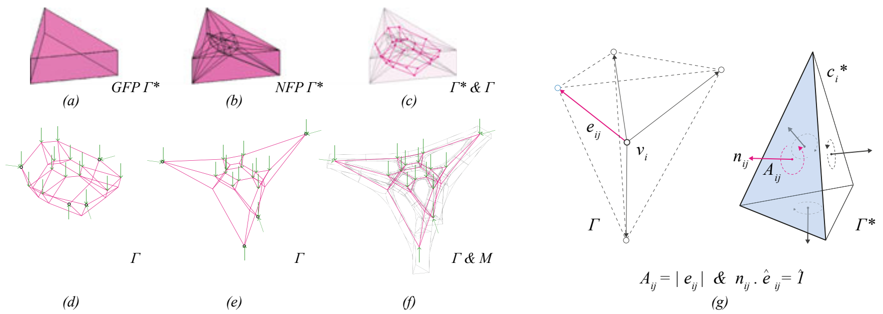



**Fig. 5** Shape design process—**a** global force polyhedron, **b** nodal force polyhedrons, **c** generation of initial form diagram from force diagram via reciprocation, **d** initial state of form diagram before equilibrium, **e** equilibrium state of form diagram, **f** correlation of form diagram and spatial mesh (see Sect. 2.2), and **g** principle of equilibrium as detailed in [77]

mesh data-structure [78] required for efficient manipulation of such geometries. An alternative procedure using *disjointed force polyhedron* [23] which represents $\mathbf{\Gamma}$ as 3D graph input is presented next.

### 3.1.1 Geometric Procedure for Polyhedral Reconstruction

In polyhedral 3DGS, as noted previously, a $\mathbf{\Gamma}^*$ is typically represented as consolidated polyhedron where all pairs of adjacent cells have co-planar and co-incidental contact faces. McRobie [79], Lee et al. [23] displayed the concept of the disjointed force polyhedron ($\mathbf{\Psi}^*$), where neighbouring cells could be made of dissimilar geometry and non-coincidental contact faces if they are equal in area and have equal but opposing face normals. The corresponding form diagram ($\mathbf{\Psi}$) can be in static equilibrium but is not a topological dual of $\mathbf{\Psi}*$ and not necessarily polyhedral in geometry. In such a representation $\mathbf{\Psi}^*$ is a collection of disjointed NFP (Fig. 3), with reciprocal dual diagrams $\mathbf{\Gamma}$ & $\mathbf{\Gamma}^*$ being a special instance of $\mathbf{\Psi}$ & $\mathbf{\Psi}^*$ respectively.

Like all graphic static scenarios, the polyhedral reconstruction of the $\mathbf{\Psi}^*$ is a crucial step. Developing on the Minkowski's theorem, the best suited method for reconstruction for 3DGS would be the reconstruction from face normals and areas [23, 80]. It displayed an iterative minimisation solver using the *extended Gaussian image* (EGI) [81] and *area pursuit algorithm* to reconstruct $\mathbf{\Psi}^*$. We present an alternative geometric procedure for EGI using the convex hull algorithm [82].

Given a set of face normal vectors $\mathbf{f}_{i,j}$ with length of the vectors representing the face area $\mathbf{A}_{i,j}$ (Fig. 6a)—either known or as target—the force polyhedron (Fig. 6f) is derived through the following sequence of geometrical operations:

1. compute a convex hull $\eta$, from the set of points $\mathbf{P}_{i,j}$ at the head of the unitised face normals (Fig. 6b);
2. compute the topological dual $\eta^*$ (Fig. 6c); By principle of reciprocity the number of faces of $\eta^*$ will be equal to number of vertices of $\eta$, which in turn would be

equal to the number of input face normal vectors. It should be noted it is not necessary to have the face normals $\mathbf{n}_{i,j}$ and area $\mathbf{a}_{i,j}$ of $\eta^*$ to have the correct orientation and required area respectively by construction (Fig. 6d);

3. An iterative projection solver is used to perturb the vertices of $\eta^*$ to meet the dual objectives (Fig. 6e).
   - $\hat{n}^*_{i,j} \cdot \hat{\mathbf{f}}_{i,j} = 1$, where $\cdot$ is the vector dot product. The projection force per vertex is computed using the procedure described in [38, 83].
   - $\mathbf{a}_{i,j} = \mathbf{A}_{i,j}$ using the area pursuit method described in [23].

In exceptional cases, such as a 2D node where all members at that node are co-planar or an open node (Fig. 7), like [23] we would be required to introduce virtual force vectors to help facilitate the construction of $\eta$ & $\eta^*$. As these are only to facilitate construction of the diagram, the corresponding virtual faces in $\eta^*$ for each input virtual force vectors would not have a target area or orientation during step 3 of the above procedure and will have no corresponding member in $\mathbf{\Psi}$.

It can be noted, the special case of adding *zero face*, as in [23], is not required as by construction the number of faces in $\eta^*$ will be equal to number of input face normal vectors $\mathbf{f}_{i,j}$ (Fig. 6).

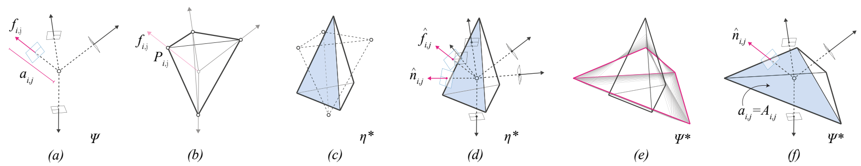



**Fig. 6** Polyhedral reconstruction—**a** force vectors extracted from input form graph, **b** normalised force vectors, **c** convex hull generated from points $P_{i,j}$, **d** topological dual of convex hull, **e** iteration steps of the equilibrium projection solver and **f** force polyhedron

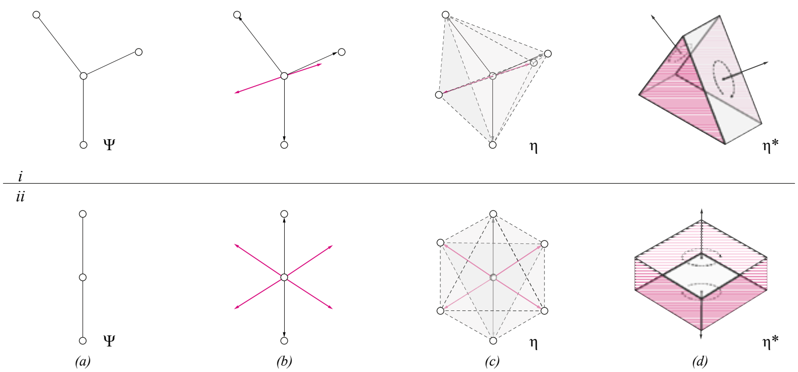



**Fig. 7** **a** Node condition, **b** added virtual vectors, **c** initial convex hull and **d** topological dual of convex hull with virtual faces highlighted for specials of (i) a 2D co-planar node and (ii) an open node

The procedure is easily adaptable to work with multi-node initial input of $\boldsymbol{\Psi}$. In this case for each node $\mathbf{v}_{\mathrm{i}}$ of $\boldsymbol{\Psi}$, the outgoing edges $\mathbf{e}_{\mathrm{i,j}}$ and target face area $\mathbf{A}_{\mathrm{i,j}}$ would be used as inputs for the geometrical construction of $\boldsymbol{\Psi}^{*}$ (Fig. 7a). It can be noted the procedure after perturbation, each unitised face normal of $\boldsymbol{\Psi}^{*}$ would meet the constraint of

$$\hat{n}^{*}_{\mathrm{i,j}} = \hat{e}_{\mathrm{i,j}}$$

The equilibrium procedure, like in [34], can furthermore be weighted by using the weighting factor $\gamma = 0, \ldots, 1$. This factor increases or decreases the influence of the $\boldsymbol{\Psi}$ or $\boldsymbol{\Psi}^{*}$, on its counterpart during the iterative process. To achieve this, a target vector $\mathbf{t}_{\mathrm{i,j}}$ for each pair of corresponding normalised vectors $\hat{n}^{*}_{\mathrm{i,j}}$ and $\hat{e}_{\mathrm{i,j}}$ is defined as follows:

$$\mathbf{t}_{\mathrm{i,j}} = \gamma \hat{e}_{\mathrm{i,j}} + (1 - \gamma)\hat{n}^{*}_{\mathrm{i,j}}$$

This weighting factor allows to define the degree each diagram stays fixed during the iterative process of finding equilibrium. If $\gamma = 1$, only the vertices of the $\boldsymbol{\Psi}^{*}$ are affected, and if $\gamma = 0$, only those of $\boldsymbol{\Psi}$ are affected. Figure 8, displays the iterative steps for both $\boldsymbol{\Psi}$ & $\boldsymbol{\Psi}^{*}$ when $\gamma = 0.5$.

In addition to the above control, the weighted iterative perturbation procedure, makes it amenable to incorporate additional design-based constraints on $\boldsymbol{\Psi}$ such as fixing certain vertices as per contextual conditions or incorporating certain minimum and maximum edge lengths along with other projection-based constraints detailed in [34, 50, 84, 85] etc. The detailed description of projection forces for each of the above constraints is out of scope of this paper. Figure 9, showcases the steps of polyhedral reconstruction on simple multi-nodal setup, while Fig. 10 displays it on the graph of the demonstrator spatial structure.

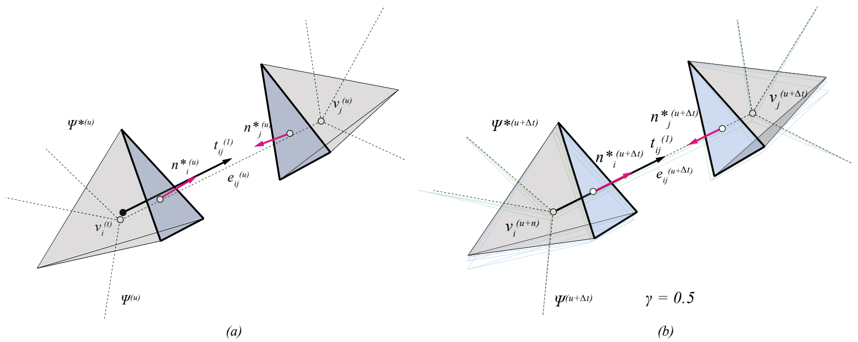



**Fig. 8** Bidirectional equilibrium in a two node situation using a weighting factor $\gamma$—**a** initial state at time u **b** converged equilibrium state at time u + Δ t along with the intermediate states

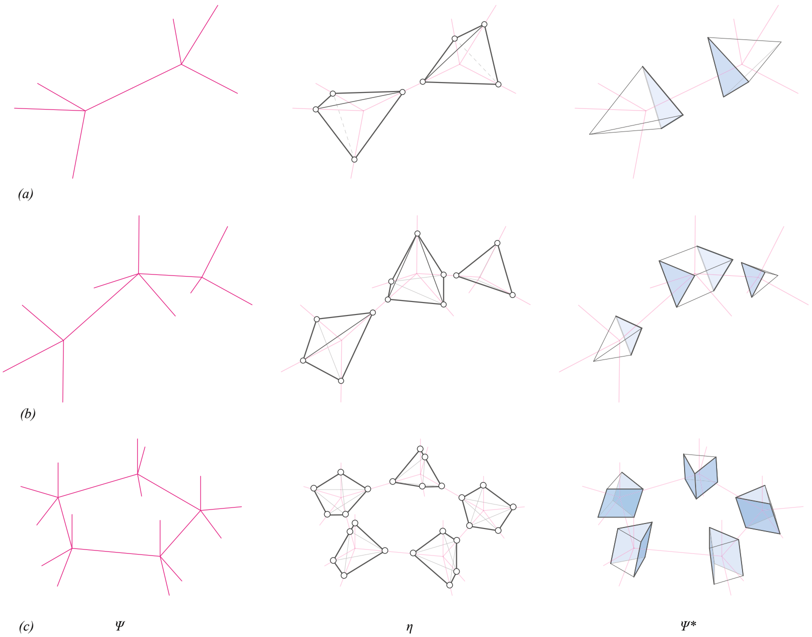



**Fig. 9** Polyhedral reconstruction of disjointed force polyhedrons from input graphs of varying nodal conditions—**a** 2 Node, **b** 3 Node and **c** 5 Node

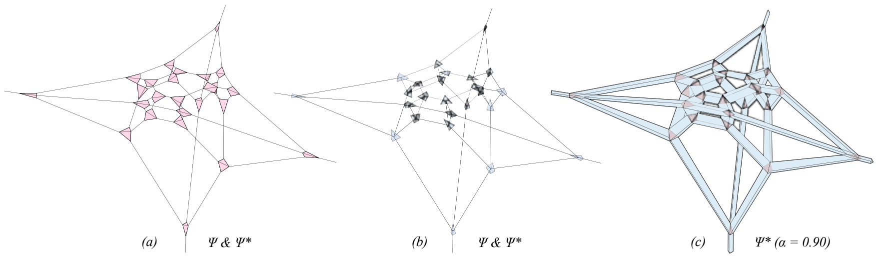



**Fig. 10** Polyhedral reconstruction of disjointed force polyhedrons from a complex input graph ($\Psi$) of the demonstrator spatial structure showcasing—**a**, **b** initial and equilibrium state of $\Psi*$ and **c** unified diagram$\Psi * (\alpha)$

## *3.2 Architectural Geometry*

First, a spatial structure mesh **M** is derived by adapting the procedure described in [59] to work with disjointed force polyhedrons.

Given $\boldsymbol{\Psi}$ & $\boldsymbol{\Psi}^*$, **M** is created by the following sequence of geometric operations (Fig. 11):

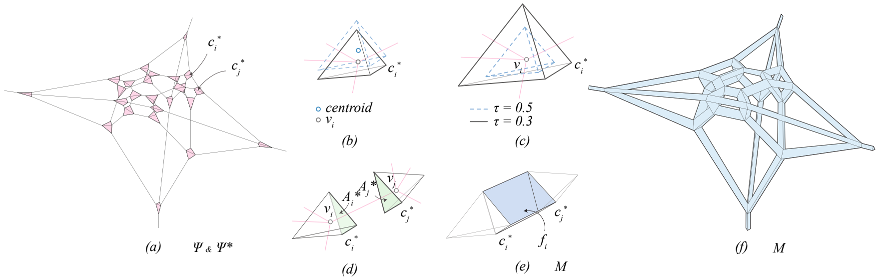



**Fig. 11** Generation of Architectural geometry—**a** Input Ψ and Ψ∗, **b** checking and aligning position of cell c∗i such that the centroid of cell matches with the corresponding node vi of Ψ, **c** scaling of cells using a factor τ, **d**, **e** bridging between face- pairs of Ψ∗ to create a faces of M and **f** resulting spatial mesh M

1. position each cell $\mathbf{c}_i^*$, such that the centroid of the cell lies on the corresponding node $\mathbf{v}_i$ of $\boldsymbol{\Psi}$;
2. scale each cell towards/away from its centroid by some factor $\tau$. This value can vary per cell and is used to control the sizing of the cross section and edge length at each node;
3. bridge between the face-pairs of $\boldsymbol{\Psi}^*$ to create faces $\mathbf{f}_i$ of **M**. For each face of **M**, the corresponding area $\mathbf{A}_i^*$ of the face-pairs of $\boldsymbol{\Psi}^*$ is stored as an attribute. This attribute would be used to compute the thickness of **M**, thereby making the thickness a function of the force acting on it.

The resulting **M** (Fig. 11f) will be a 2-manifold mesh with exclusively planar quadrilateral faces (PQ Mesh) based on generalization of Varignon's theorem [86]. For further understanding of it in the context of polyhedral cells, we point the reader to [59].

An additional geometrical bevel operator was introduced to the procedure to control the bend radius of the timber laminates on higher subdivision of **M** produced using the adapted Catmull-Clark subdivision scheme [87] as described in [57] (Figs. 12 and 13). It can be noted that even with these operators the property of PQ mesh is maintained thus ensuring that **M** is developable and can be unrolled into a plane without intersection [24].

Next, **M** is decomposed into patches of faces around each node ($\mathbf{Mv}_i$) (Figs. 1 and 17) based on the fabrication bed constraints of the laser cutter or CNC machine (see Sect. 4). Each strip of $\mathbf{Mv}_i$ is offset to create layers of timber laminates in proportion to the corresponding face areas in $\mathbf{c}_i^*$, which as noted previously is stored as a face attribute of **M**. This entails that the material thickness is proportional to the force acting on it (Fig. 14). For the demonstrator, based on the forces acting and material prototyping tests (see Sect. 4) the number of layers varied between 3 and 9 layers, which was composed of combination of 1/4 and 1/8 inch laminates. 1/4 inch laminates were used for the first 5 layers and the subsequent layers were of 1/8 inch laminates. The color variation in the laminates were used to capture and highlight this tectonic variation of material thickness based on structural performance (Fig. 1).

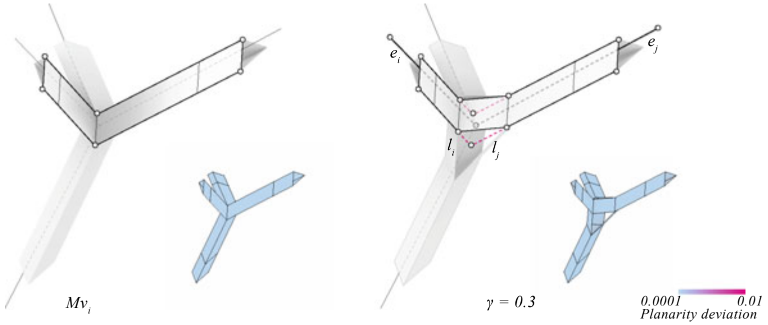



**Fig. 12** Bevel operator driven by an user specified factor $\gamma = \text{li}/\text{ei} = \text{lj}/\text{ej}$, $\gamma \in (0, 1)$. The inset colored geometry showcases the planarity deviation

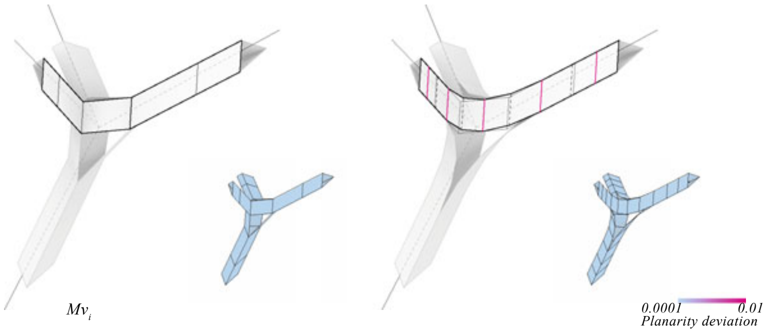



**Fig. 13** Subdivision operator using an adapted Catmull-Clark subdivision scheme [87] as described in [57]. The inset colored geometry showcases the planarity deviation

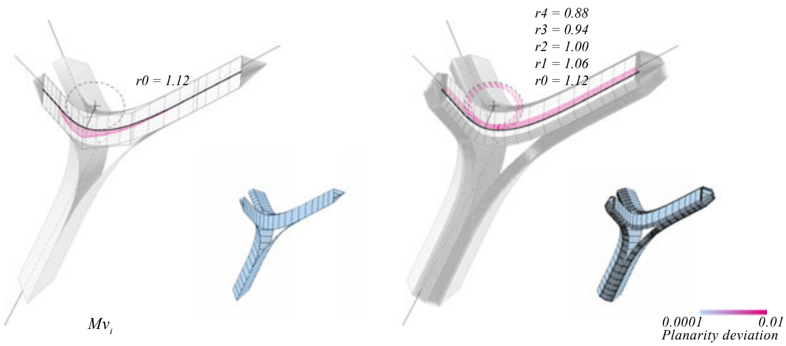



**Fig. 14** Offset operator to create layers of timber laminates in proportion to forces acting on it by generating offsets along the normal. The inset colored geometry showcases the planarity deviation

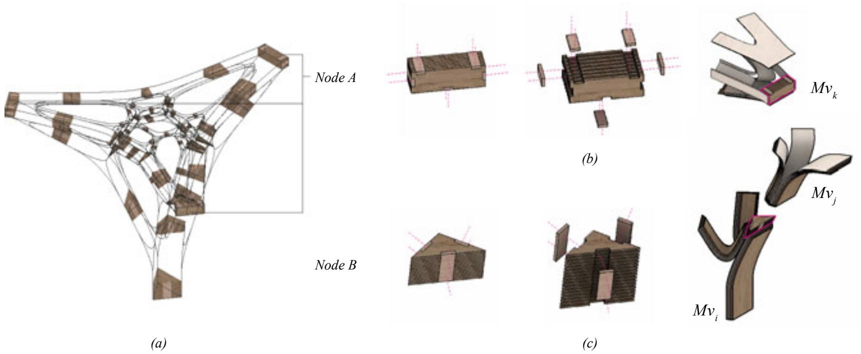



**Fig. 15** Two types of nodal connectors **a** an end connector positioned at the end of a single node, and **b** an internal connector positioned in between two nodes

The connector detail between any two adjacent node mesh $\mathbf{Mv}_i$ and $\mathbf{Mv}_j$ was made as a block which fits into the void of the spatial node mesh. The strips of the node mesh were then screwed to the connector block (Fig. 15). This connection detail, used due to the time constraint of making the demonstrator within a 10-day design to fabrication workshop, could be improved to create a more robust and interlocking detail using the timber laminates (see Sect. 6).

### 3.3 Production Information Generation

The structurally verified and thickened $\mathbf{Mv}_i$ serve as the input to create the production information for fabrication. All the layers of $\mathbf{Mv}_i$, as noted previously, are a PQ Mesh. Such PQ meshes are amenable to fabrication methodologies such as 2D cutting via CNC technology [38, 57, 59], robotic hot wire cutting [88], curve creased folding [43] etc. For the demonstrator, the 2D laser cutting was used and the outline of the unrolled strips in plane (Fig. 16) were used as the production information.

The production information for the custom bending machine were also generated using $\mathbf{Mv}_i$ (Fig. 17). The center-line graph of the top and bottom layer of each node strip is extracted and is inserted into the JSON file format and is subsequently parsed in the timber bending thread of the DTP (see Sect. 4.3).

### 3.4 Implementation

The first 2 steps of the DTP toolchain, including 3DGS routines have been implemented as a software add-in to the MME of Autodesk Maya for interactive design explorations. We use the inbuilt features in the MME to create and manipulate the

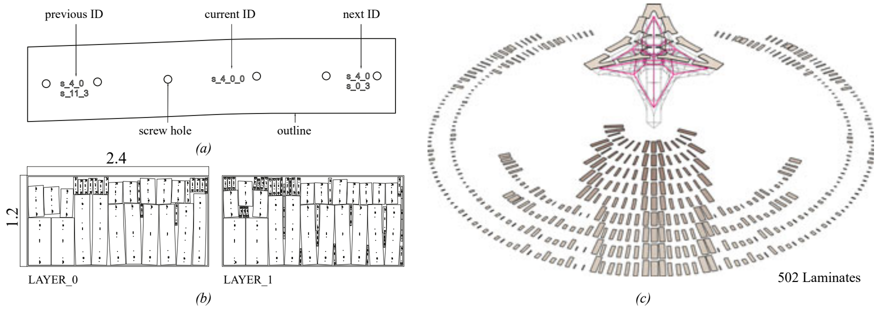



**Fig. 16** Unrolled laminates **a** programmed laminate ID and its connecting part ID, **b** compact unrolled outlines for laser cutting on a 2.4 m by 1.2 m plywood sheet, and **c** laminates in a total number of 502

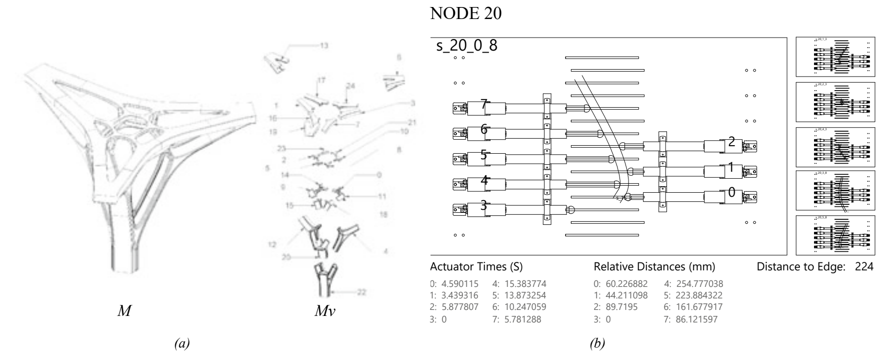



**Fig. 17** Demonstrator of the machine data in a bending process **a** node assemblies of the structure, **b** actual operation distance and time on node 20, and **c** fabrication result

spatial graph $\mathbf{\Psi}$ or polyhedral mesh $\mathbf{\Psi}^*$. The user can carry out topological changes on the diagrams using Conway operators [89], addition/deletion of cells of $\mathbf{\Psi}^*$ etc. Given an initial $\mathbf{\Psi}^*$ or $\mathbf{\Psi}$, the plugin generates counterpart and form find using the weighted perturbation method. After the equilibrium step, the user can use the GUI to generate the AG with parameter sliders to control the number of laminates, the offset layers, thickness, and the feature to export the final state of AG into the JSON file. An overview of the results using such a workflow in an MME is presented in Fig. 18. Step 3 of the DTP is carried out in the CAD environment of McNeel Rhinoceros with the usage of Grasshopper to parse the JSON, unroll the timber strips and generate the necessary production information for fabrication.

The above plugins were successfully used in teaching and design explorations in couple of 5 day computational design workshops. Participants with minimal knowledge of 3DGS, static equilibrium and design for timber were able to intuitively understand the action of forces, the weighting of the form and force diagrams and how structural and fabrication aware geometries could be generated. Apart from learning

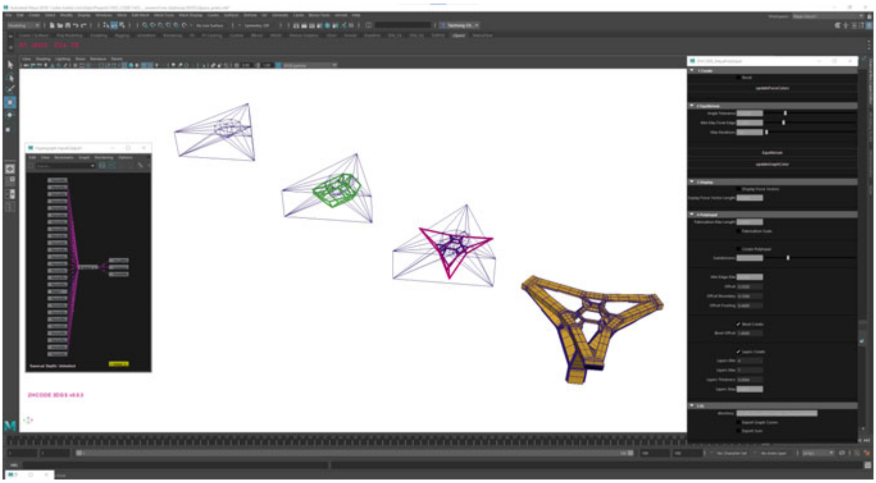
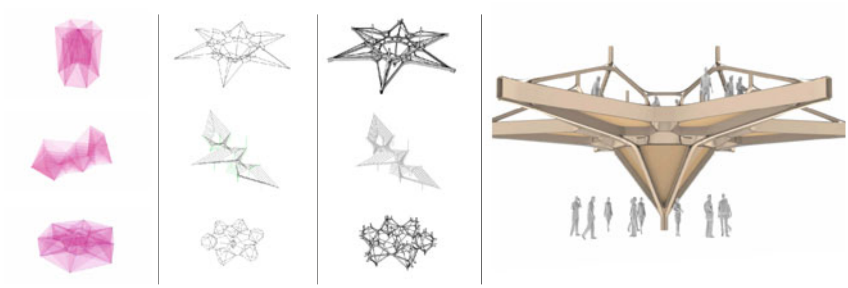


**Fig. 18** Custom add-in within the MME of Autodesk Maya highlighting the various diagrams and geometries in the DTP, custom add-in UI, incorporating add-in node in the hypergraph environment of Maya to maintain dependency graph structure

the toolchain, the participants were able to design structures such as bridges, residential units, and columns within the span of a short workshop. Some the participant result from the workshop which use the proposed DTP are displayed in Fig. 19.



*(a)* *(b)* *(c)* *(d)*

**Fig. 19** Some of the participant work from the computational design workshops using the custom add-ins showcasing **a** force polyhedrons, **b** 3D graphic statics, **c** 3D geometry, and **d** spatial combinatorics

# 4 Machine Design for Bending Timber

To achieve the design's different radii and cross-sectional condition of the laminates required the development of a customized tool based on re-configurable electric linear actuators on a table (Fig. 20). Producing bespoke, programmed wood curvature based on actuator operation that applies bending forces based on selected control points has been explored through machine prototyping [69]. Wood can be formed in unique, customized, digitally driven, programmable curvature, which is determined through the automated process of bumper placement and pneumatic actuation against them. Differently from previous work, the bending machine used on this prototype was designed using electric linear motion over pneumatic actuation. Electric actuation allows for less waste and tighter tolerances [90].

Additionally, we can know how hard the actuator is pushing and coordinate the movement with force and position through force feedback. Furthermore, bending tables using pneumatic actuators rely on using a stopper against which the pneumatic actuators press, they incorporate adjustable bending blocks which are lined up with a projected image of the desired shape. Lamella are held in place while the pneumatic actuators provide the pressure to bend the wood [69]. Through different iterations, it became clear that linear actuators allow achieving the desired positions by controlling the actuator device alone and without additional machine assemblies.

## 4.1 Bending Machine Components

The bending table, in order to use linear motion—travel distance divided by speed, is composed from the following equipment (Fig. 21).

- Seven PA-17 Heavy-Duty 14-inch linear actuators of 12 V with a 14″ stroke—and 850 lbs. of force are oriented in opposite directions to reach the maximum contact area on any given curvature. The opposing forces between the actuators -at each side of the table-aid in keeping the curve in place. Clamps are then positioned

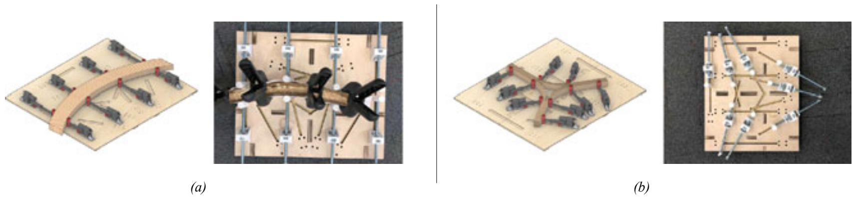



**Fig. 20** Iterations of bending machine development **a** physical prototype on multi-layered laminates (~0.125 m), **b** digital prototype on multi-directional laminates (~0.5 m), and **c** dual robotic bending (~3.0 m)

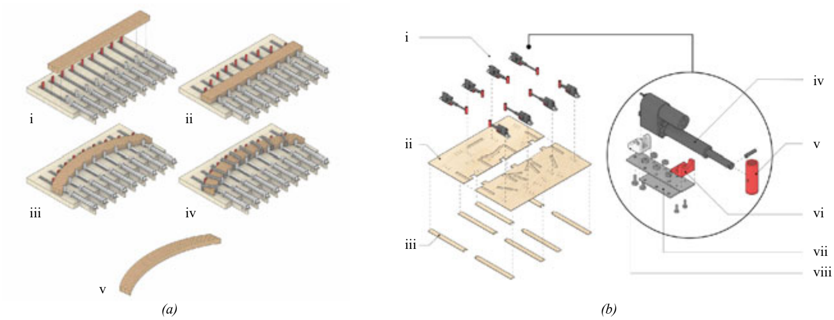



**Fig. 21** Bending process—(i) neutral table/linear lams with glue (ii) computationally adjust stoppers (iii) activate pneumatic cylinders (iv) add clamping along glulam (v) final curved glulam member; (b) Bending machine (i) linear actuators (ii) CNC-milled plywood table (iii) CNC-milled table supports (iv) heavy duty electric linear actuator (v) 3D-printed bumper (vi) 3D-printed actuator seat (vii) aluminum mounting plates (viii) heavy-duty mounting bracket

along the curved piece. Clamps—although not required- allow removing the part from the table, freeing it for the next bend.

- Seven heavy-duty mounting brackets are used to hold each actuator to the bending table
- Seven custom-designed 3D-printed bumper heads are attached to the pistons at the actuator's end. The bumpers are designed to maximize the contact area of the actuator against the laminations.

The base to hold all the above has two 12.7 mm (1/2inch) plywood sheets. Slots were milled on the plywood sheets to provide the bumper heads with and stabilize their motion during actuation. The position of the slots was based on the analysis of the curvatures. The aim was to maximize the relationship between the curves' control points and the actuators' positions. Finally, wooden pallets were used as a substructure to the plywood sheets due to their inherent robustness. Digitally, the actuators were controlled through seven high-current motor drivers, four Arduino UNO control boards (each Arduino controlling two actuators) and multiple DC power supplies.

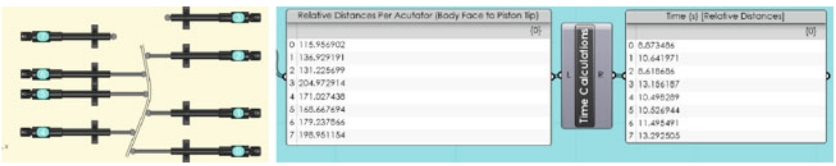
## 4.2 Material Testing

Various material tests were performed to refine the thickness of the lamellas, the stepping between them and define the curvature radii that were achievable. Initially, thin lamellas of Douglas Fir were tested. However, the lamellas required thinner sections to achieve the tight curvature on the upper part of the demonstration prototype. Veneer-core plywood, a material commonly used in furniture making, formed by two layers of plywood with a central core made of veneer was used due to its high degree of flexibility. Veneer-core plywood is traditionally not used for glulams.

Nevertheless, its behaviour was more flexible than the thinnest available lamella that could be made from other wood whilst achieving a high degree of stiffness after lamination. Tests were made using veneer-core plywood in 1/4 and 1/8 of an inch thickness. Furthermore, experiments mixing both thicknesses on the same lamination were successful. An important consideration when using this material over wood or plywood lamellas is the grain direction of the central veneer. The material is very flexible in the direction of the veneer grain, but it does not bend in the opposite direction. This characteristic defined the maximum length of each component on the final piece. It also characterized how the laminations were laid out on the sheets for 2D cutting.

### 4.3 Digital Workflow

The orientation of the curved members on the bending table is iteratively adjusted based on the pre-defined position of the bumpers and the control points of the desired curve/graph—parsed from the JSON file created in Sect. 3.4. The aim is to achieve the maximum contact area between the bumpers and the curve. Additionally, the contact should be on the strategic positions that define the shape—such as those defined by the control points. Another constraint on the definition was to ensure that all the actuator distances were achievable. Finally, the thickness, translated as the distance between the actuators at each side of the table, is considered. Once these three conditions are satisfied, the distance values of each actuator and the position of the lamellas on the bending table—measured from the edge—are extracted. The distance values extracted from the grasshopper model are then translated to the Arduino IDE interface [91] (Fig. 22). The linear actuators are driven to the correct distances by stacked Arduino UNO circuit boards, motor drivers and their corresponding Arduino proprietary programming.




(a) (b)

**Fig. 22** Computational simulation of bending process **a** digital machine sets **b** relative distance per actuator and period of holding position

## 5 Fabrication and Assembly

All constituent blocks of the demonstrator were produced using the DTP workflow described in the previous sections and the resultant output files. In total, 24 nodes consisting of 502 timber laminate strips in total were laser cut, glued to create 129 glulams of which 114 glulams were bend into shape using the custom actuator tool in 10 hours.

A digital workflow with corresponding physical tools was developed to bend the unique 114 pieces. The lamella for the different laminations are realized via a two-axis laser cutting machine and a CNC router. The 2D curvature of the glulams is registered and held in shape via a custom build actuator- tool. The bending machine uses linear motion. Linear actuators are driven by a custom-developed McNeel Rhinoceros—Grasshopper script that iteratively positions each element on the bending table, aiming to maximize the contact area given the curvature of the piece and the actuators on the table. The script then adjusts the travel distance based on the thickness—number of laminations—the part will require. It is important to note that laminations changed in number and thickness in all the parts as they were driven by structural requirement.

The assembly sequence (Fig. 23), given the small scale of the demonstrator although not a scalable solution for large scale application—was carried out upside down for ease of handling of the node blocks and minimisation of false work. The lightweight prototype was assembled in 12 h and flipped to its final orientation (Fig. 24). The expected external forces at the top corner of the spatial structure as seen in the initial GFP (Fig. 5) were resolved via the use of tension cables.

It should be noted that the use of individual laminates was a proxy material for ply/dimensional lumber elements and the use of laser cutter was a proxy fabrication for lam shape profiles to produce customised flat part profiles given the short workshop timeline.

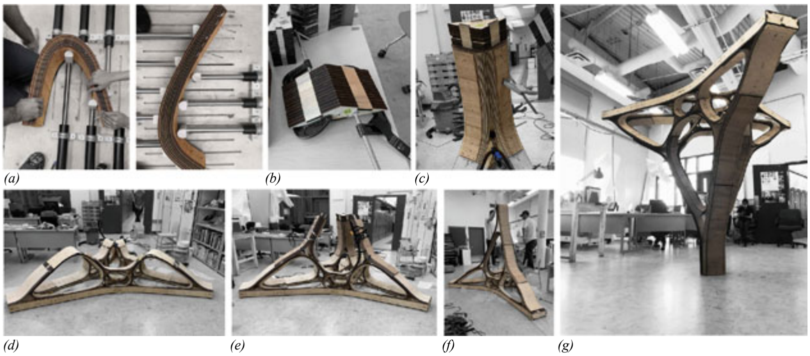



**Fig. 23** Assembly process **a** bent laminates **b** glued connectors **c** assembly a connector on a node **d** phase 1 assemblage **e** phase 2 assemblage **f** phase 3 assemblage **g** final product

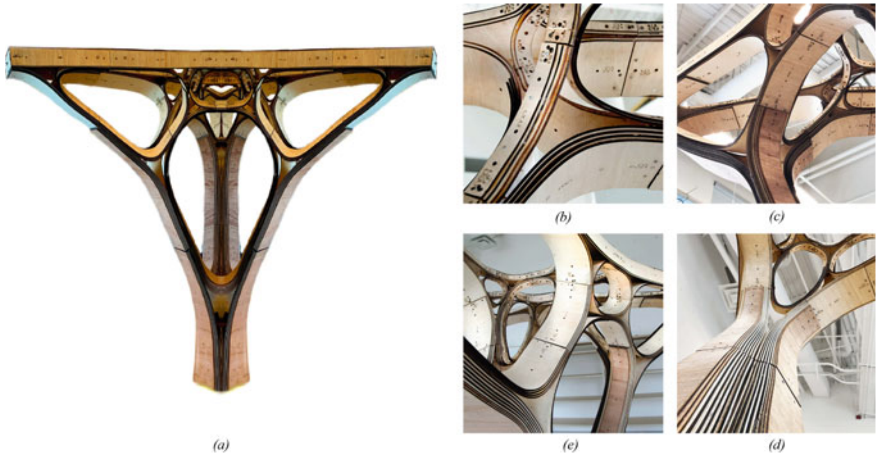



**Fig. 24** Shape profile and overall detail

## 6 Outlook and Conclusion

The proof-of-concept spatial structure and the associated DTP toolchain together demonstrate the viability for it to be developed further for large scale applications. The following areas of work could be improved to help streamline the process for full-scale application:

- **Digital design interface—**further development and improvement of the designer friendly interface in MME's for more direct and willful manipulation of spatial structures.
- **Closed node geometries—**development of geometric procedure to compute intersection for closure of node strips for application with multi layered laminated system.
- **Cross section optimisation**—development of a fast, optimisation method to optimise the cross-section size via the scaling factor (see Sect. 3.2) per node would help alleviate manual intervention / usage of global scaling factor.
- **Assembly sequencing**—development of a more robust and scalable assembly sequence with minimal false work and potentially with self-registering interlocking node block strips.
- **Interface detail**—development of male–female interface details to avoid misalignment during assembly. The design of the interface can also consider registration points that will aid the assembly process.
- **Feedback incorporation**—development of a more robust geometrical method to incorporate the constraints of the bending machine within DTP could allow averaging the control points of each curve so that the positioning of the linear actuators better corresponds to most of the curves. The position of the actuators

can be modified, and the base tables rationalized into 4 or 5 tables that could cover all the different curves.

- **Machine development**—engaging multiple actuators simultaneously is a crucial factor. Controlling multiple actuators is complex; an inter-integrated circuit (I2C) with its highly modular approach that can be used to control various Arduino boards from a single master could be tested in the next iteration of the machine. This would allow the actuators to operate simultaneously when information is relayed from the DTP thread to a master Arduino board instead of having to divide it into multiple Arduino boards. It will simplify the digital operation and make for a more friendly interface.
- **Scale Up—**adapt and develop the current DTP to work on a larger scale architectural and industrial construction scenario.

In conclusion, the proposed DTP for spatial timber structures showcased procedures in computational design and fabrication to reduce the material usage for spatial structure by aligning geometries to structural principles, timber processing technique to efficiently achieve the varying structural thickness using ubiquitous 2 axis CNC technology, reduce the complexity of node connection of spatial structure for ease of assembly and time-efficient ways to achieve bent timber using an actuator tool which reduces wastage. All the above features are in sync with some of the sustainability goals set out by the United Nations, especially in the domain of consumption and production patterns (UNSDG 12.5 & 12.8).

Further, the paper showed that embedding such a workflow in an MME would enable the designer to manipulate and explore novel spatial design tectonics and highlighted the benefits of using discrete geometry based workflows for downstream production. In addition, the paper displayed the didactic value and knowledge transfer of 3DGS, equilibrium and static aware geometry creation by using the DTP in an interactive MME (UNSDG 4.4 & 4.8). We also described the design and production of custom machine tools and the fabrication and assembly process of a demonstrator timber spatial structure and the key learning thereof, which opens several trajectories for further investigation [76].

**Acknowledgements** We would like to thank all the student participants of our free open to all online Timber Tectonics workshop at DigitalFUTURES 2021 and CAAD Futures 2021. Some of the results produced during the workshops are shown in Fig. 18.

The research paper focused on describing the integrated DTP toolchain for the demonstrator prototype. The project team for the physical demonstrator comprised many more contributors. The full project credits are listed below.

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# Unlocking Spaces for Everyone

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**Abstract** Unlocking spaces for everyone has never been more important for public and private sectors within the Architectural, Engineering and Construction (AEC) industry. Knowing how shape the invisible forces that surround us brings a new dimension to designing buildings. Clients, architects, planners, landscape designers, and engineers, not only influence the lives of the residents of their buildings but touch the lives of everyone else viewing, passing by, and sitting next to them. Buildings have the responsibility to care for and protect the context they sit within. Forward-thinking legislation and the possibilities offered by the Industry 4.0 such as advances in computational capabilities and interoperable open-source tools, unlocked micro-climate assessments as never before, in the UK and internationally. Bioclimatic design, a branch of urban climatology, is currently used to transform spaces into destinations, for people, flora, and fauna. By covering aspects of wind engineering, natural and artificial lighting, outdoor thermal comfort, and air quality, bioclimatic designers help shape inclusive, safe, resilient, and attractive spaces, buildings, and infrastructure. This creates more sustainable cities and communities, lowers disparities, heat vulnerability, lack of daylight availability, and poor air quality. This chapter describes the 'why', 'how' and 'what' of bioclimatic design at the city- and building-scale, followed by how it is now fully embedded in the pre-planning stages of medium-to-large buildings across the UK and in many other countries globally.

**Keywords** Bioclimatic design · Urban climates · Wind microclimate · Daylight · Glare pollution

**United Nations' Sustainable Development Goals** 11. Sustainable Cities and Communities

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_44

# 1 Introduction

Merging technologies of Industry 4.0 enabled revolutions in many fields, such as, architecture [1], computing-based disciplines like cloud computing [2], or even forestry [3].

Without advances in computational capabilities, interoperable workflows, and forward-thinking legislation, bioclimatic design as described in this chapter wouldn't exist.

The following paragraphs describe the 'why', 'how' and 'what' of bioclimatic design at the city- and building-scale, followed by how it is now fully embedded in the pre-planning stages of medium-to-large buildings across the UK and in many other countries globally.

## *1.1 Bioclimatic Design*

A commuter who walks to work leaves the comfort of their home and embarks on a journey that may take them through areas that are: shaded or sunlit; next to walls that are warm; across grass that is cool; under the trees that offer shelter from the rain; around a building's corner where the wind suddenly accelerates; along roads where polluted air is inhaled; and so on. As the individual encounters these differing microclimates, the body responds by becoming warmer/cooler, perhaps sweating/shivering, and reacts by changing pace, adjusting clothes, leaning into the wind, or avoiding roads that are busy and polluted [4].

Even if the different features at the street level, the surface covering, the buildings' shapes, and the choices of the landscape around the cities that the commuter may encounter, have been designed as the outcome of countless decisions, all of the different microclimates can be predicted and managed through bioclimatic design.

The term 'bioclimatic design' was pioneered by the Olgyay brothers in 1963, when they published 'Design with climate: bioclimatic approach to architectural regionalism'. This is the first textbook to support the design of 'climate-responsive and sustainable buildings' [5], which is still relevant today.

Almost six decades later, in 2017 Oke et al., published the first design textbook to support the emergent predictive science of 'Urban Climate', once urban climatology had become a recognised subfield of meteorology and climatology [4].

These textbooks pioneered two different and intertwined fields, but they both helped designers (practitioners and researchers) to shape better buildings and cities. We can name the field as 'bioclimatic design' with an additional meaning concerning urban climatology.

In the meantime, COVID-19 has led to the first rise in extreme poverty in a generation [6], but it has reminded us that healthy and livable cities require open public spaces [7], and the importance of investing in a climate-resilient future [7].

Thus, bioclimatic design has become even more complex, filled with the expectation to unlock spaces for everyone and everything, and interconnected with how cities and societies are shaped.

Cities define the urban climate, they set the scene. Buildings, however, alter the urban microclimate around them:

- They change the wind microclimate when they are taller than the average height of the surroundings, to an extent where they change how people use outdoor amenity spaces, or they become life-threatening [8]
- They affect sunlight and daylight availability to nearby buildings and public spaces; they can generate glare for drivers during the day, and light pollution to the surroundings during the night
- Through absorbing and releasing heat, buildings impact the flowering of plants to occur earlier in urban areas; they create lower space-heating costs but higher space-cooling requirements in cities; they cause increased heat stress on human residents in the summer, in less dense fogs, and an increased rate of chemical reactions leading to smog [4].

Even if this is an emergent field, bioclimatic design presents the challenge that the entire Architectural Engineering and Construction (AEC) sector is experiencing: change.

Bioclimatic design, in particular when it comes to wind microclimate and sunlight and daylight, used to rely on physical models that were tested in wind tunnels [9, 10] and heliodons [11] respectively.

With advances in computational capabilities and open-source software tools, wind microclimate and sunlight and daylight studies have been digitalised, bringing a new series of opportunities for leveraging common CAD models and data to assess and interactively present building stack effect, accelerations, outdoor thermal comfort, air quality, disability glare, and light pollution studies.

Practitioners involved during the early design stages must keep the pace of the design teams, iterating through options, and informing about mitigation measures at the first opportunity.

Making good use of the common data, CAD geometry, and computational resources is key to a successful design in the so-called 'Architecture 4.0', post-BIM. It's about computing minimally and strategically, while using experience and expertise to add value to the projects. Nevertheless, the underlying secret is communication. Complex assessments require simple and intuitive means of expression. Software developers help practitioners to seamlessly present gigabytes of information in real-time.

Researchers studying the impact of buildings and cities on their microclimates have been finding strong correlations between a citizen's wealth and their exposure to the adverse effects that urbanization causes: heat vulnerability, reduced daylight, and low air quality.

These studies [7, 12] can guide planners and practitioners to design better and more equal cities in any part of the world: access to green open fields/woods, well-lit spaces, and areas with low air and light pollution are key to make poor areas of cities more resilient to climate change, less dependent from air conditioning, and socially less deprived.

## 1.2 Case Study

AKT II's office building—the White Collar Factory (WCF), in central London—provides a perfect opportunity to show how the various aspects of bioclimatic design are linked by data.

Bioclimatic designers can harness value through the effective use of data, shared 3D CAD models and interoperability. In particular:

- Wind-induced stack effect, accelerations, and air quality rely on wind microclimate outputs
- Outdoor thermal comfort is linked to wind microclimate and sunlight/daylight assessments
- Light pollution and disability glare, as an extension to the sunlight/daylight studies, uses the same geometry of the other fields.

AKT II's offices are within the fourth and fifth floors of the WCF building (Fig. 1): a redevelopment of a prominent corner site at the Old Street 'Silicon Roundabout' in the heart of London's 'tech city'. The construction was completed in 2017. The scheme provides a new, 16-storey, 237,000-square-foot office tower, together with a low-rise campus of further office, retail and residential provisions, and a new public square [13].

**Fig. 1** White collar factory—© Halo

The building fits the ideal case study as it presents:

- Large openable windows, where the building stack effect may reduce their fruition to frail or disabled people and the air quality may compromise their use.
- A corner entrance which is exposed to downwash, funnelling and corner-separation effects.
- A running track and rooftop terraces that are used predominantly in the spring and summer but are both exposed to strong wind and sunlight.
- A large courtyard, where people spend their lunch breaks, and restaurants use as outdoor dining spaces.
- Southern/western facades that are fully exposed to the free stream from the dominant winds in London, which may cause distress at the street and roof levels, and perceived accelerations.
- A congested roundabout to the north, which makes air quality a key assessment considering the use of the outdoor and indoor spaces.
- Nearby residential buildings, with possible adverse impacts on their sunlight levels during the day together with artificial light pollution during the night.
- A busy road network in the proximity of the building, where glare, due to the glossy elements on the facades, may hinder the capability of drivers.

At the time of the building's design and construction, the most up-to-date guidelines and assessments were carried out. However, since its construction, new microclimate guidelines have been published or have become more established across the UK; these will be followed in this chapter:

- Wind Microclimate Guidelines of the City of London—published in 2019 [14]
- Outdoor Thermal Comfort Guidelines of the City of London – published in 2020 [15]
- Daylight and Sunlight Guidelines of the British Research Establishment (BRE)—published in 2011 [16]
- Light Pollution Guidance of the Institution of Lighting Professionals (ILP)—published in 2021 [17]
- Air Quality Management of the Department of Food & Rural Affairs (DEFRA)—published in 2018 [18].

The following pages present assessments of the WCF project that are now carried out in accordance with the most recent best-practice guidelines:

- Wind Microclimate:
  - Wind Comfort and Safety.
  - Wind Loading on Internal Pressure.
  - Wind-Induced Vibrations (Accelerations).
- Natural and Artificial Lighting:
  - Sunlight and Daylight.
  - Disability Glare.

  – Light Pollution.

- Outdoor Thermal Comfort.
- Air Quality.

For each assessment, when pertinent, a comparison between two scenarios is shown, to stimulate the reader to think about several aspects that may influence the final result.

## 2 Wind Microclimate

Wind is perhaps the most common yet mysterious thing in the world. Wind is everywhere, and perhaps its existence is so normal in everyday life that we won't even notice it until it becomes disturbing. Indeed, wind is usually gentle in urban areas where dense built environments around public amenities exhibit a sheltering effect.

However, the growing trend in buildings being higher and slenderer, due to urbanisation [19], has drawn much attention on the potential wind impact from the skyscrapers onto the local environment and vice versa. Wind-microclimate assessment is therefore becoming more and more in demand in today's planning applications and building designs.

The Flatiron Building was perhaps the first skyscraper not only famous for its unique triangular design but also for its northern corner being deemed as the windiest in New York in the early 1900s [20]. The number of tall buildings has since been growing exponentially, and especially in recent years. As the complaints about strong winds around high-rise buildings began to accumulate, the authorities also start to require a consideration of wind comfort when designing new developments. The tragic incident in Leeds in 2011 [8], whereby a pedestrian was killed by a lorry being knocked over by what were believed to be strong winds introduced by a tall building, shows the importance of good wind microclimate, not just for the sake of the public's comfort, but also for their safety.

Wind intensity is not just important within wind comfort; it is also a driving factor within thermal comfort (which will be discussed in detail in the forthcoming chapter). Despite the UK-wide requirement of having a suitable wind microclimate on- and off-site the proposed development for planning approval, there is a lack of official guidelines to regulate the assessment methodology. It was not until late 2019 when the first wind microclimate guidelines [14] were published by the City of London (CoL) Corporation, followed by the first thermal comfort guidelines being released one year later [15].

The next section presents how wind comfort and safety are assessed with particular reference to the state-of-the-art technology context of Industry 4.0.

## 2.1 Wind Comfort and Safety

Wind by its nature is stochastic and full of randomness, while pedestrian comfort is very subjective. Pedestrian wind comfort is therefore challenging. Fortunately, a number of pioneers, including the giants in wind engineering such as T. V. Lawson and A. G. Davenport, have laid the foundation for assessing pedestrian wind comfort and safety. The method in general relies on the statistics of historical wind data, which are usually collected from weather stations, so that comfort and safety ratings can be obtained based on the probabilities of any wind speeds that exceed the threshold wind velocities at the pedestrian height (at 1.5 m) at the location of interest. Tables 1, 2, and 4, show typical wind comfort and safety criteria using the Lawson London Docklands Development Corporation (Lawson LDDC) [21] and City of London (CoL) Lawson Criteria [21] as an example, of which the former is perhaps the mostly used criteria in the UK and especially within the Great London Authority (GLA).

**Case study**. On the WCF, both the LDDC and City of London (CoL) criteria have been used to show the difference between the differing wind comfort and distress criteria.

The fundamental input of the entire workflow is the CAD model of the building in question, i.e., the WCF and its immediate surroundings (for this case study, the effect of vegetation has been omitted). The 3D models are then passed to a pre-processing tool, which automatically generates the computational fluid dynamics (CFD) simulation case files based on a number of key parameters as determined by

**Table 1** Lawson LDDC wind comfort criteria

| Grade | Category | Wind speed with 5% exceedance (m/s) | Description |
|---|---|---|---|
| 1 | Sitting | 4 | Sitting use, outdoor dining |
| 2 | Standing | 6 | Standing use, entrances, bus stops |
| 3 | Strolling | 8 | Leisure walking, window shopping |
| 4 | Business walking | 10 | Main objective of the pedestrian is to walk |
| 5 | Uncomfortable | >10 | Unacceptable for most of the pedestrian activities |

**Table 2** Lawson LDDC wind safety criteria

| Category | Wind Speed with 0.025% exceedance (m/s) | Description |
|---|---|---|
| Frail group | 15 | Unacceptable for vulnerable user groups (kids, elders, frails, disabled) |
| Others | 20 | Unacceptable for the general public (not used in the CoL) |

**Table 3** Lawson city of London wind comfort criteria

| Grade | Category | Wind speed with 5% exceedance (m/s) | Description |
|---|---|---|---|
| 1 | Frequent sitting | 2.5 | Sitting use, outdoor dining |
| 2 | Occasional sitting | 4 | Standing use, entrances, bus stops |
| 3 | Standing | 6 | Leisure walking, window shopping |
| 4 | Walking | 8 | Main objective of the pedestrian is to walk |
| 5 | Uncomfortable | >8 | Unacceptable for most of the pedestrian activities |

**Table 4** Lawson city of London wind safety criteria

| Category | Wind speed with 0.022% (m/s) | Description |
|---|---|---|
| Unacceptable | 15 | Unacceptable for all |

the user, such as terrain condition (for wind profile), case resolution (whether it is for an initial desk study or a formal planning submission), wind directions (as per requested for each project), etc. Next, the case files can be directly executed via local or cloud computing resources. The simulation results are then post-processed and visualised back within a CAD environment.

Figure 2 illustrates the typical wind microclimate assessment results in compliance accordingly with the Lawson LDDC and the CoL Wind Microclimate Guidelines. Summer comfort is usually the focus as pedestrians are more likely to make use of the public realm in the summer. Results indicate that the wind comfort under the newly published CoL criteria is mostly rated as Standing/Walking Grade around the WCF at ground level, which is similar to the LDDC criteria.

However, the LDDC criteria also reports large areas as being suitable for sitting whereas these turn out to be mostly only suitable for 'occasional sitting' according to the CoL criteria.

Thanks to the flexibility that a CFD-based approach provides, it is possible to identify the critical wind directions and unveil the underlying wind issues by visualising the wind's streamlines. Figure 3 shows the streamlines of the wind from the critical direction around the northwestern corner of WCF.

It clearly indicates that a downdraught is formed after the freestream hitting the western façade of WCF, and is accelerated by the northwestern corner, resulting in unfavourable wind conditions at the pedestrian level. However, the majority of the uncomfortable area is along the main road, where no pedestrian activities are expected to take place. The small uncomfortable area locally along the pedestrian pavement should be mitigated by the in-place landscaping (which is excluded in the current demonstration).

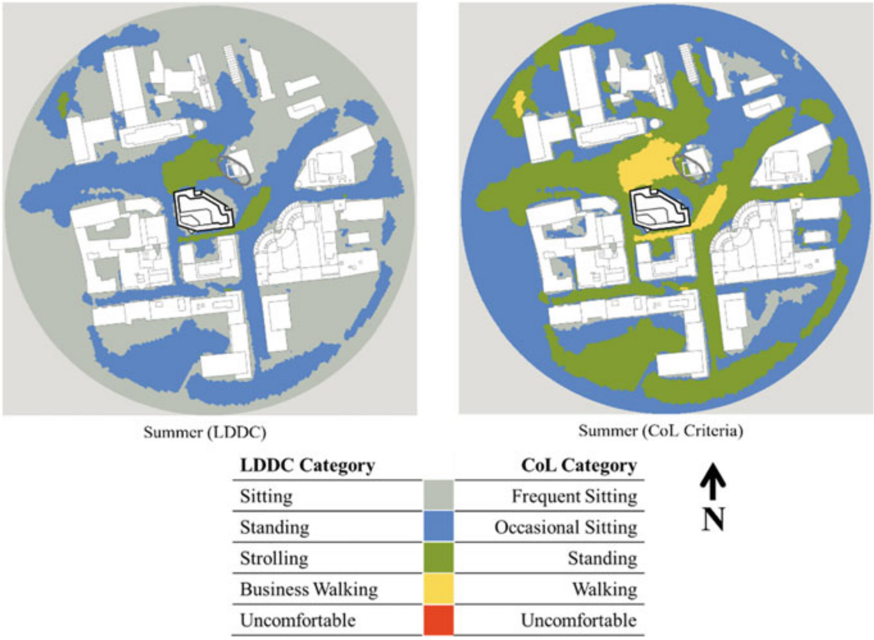


**Fig. 2** Comparison of wind comfort in summer at the street level between Lawson LDDC and the CoL criteria—© AKT II

**Conclusions**. The above demonstrates how powerful CFD is for wind microclimate assessment. It provides the full flow information of the entire simulated domain, instead of the scattered locations with limited information that are obtained through conventional wind tunnel tests. Moreover, streamlines can be plotted using the rich data obtained from CFD simulations, which gives informative indication of the underlying wind issues that cannot be gained within the wind tunnel. Of course, the current industry-standard CFD approach uses Reynolds-Averaged Navier–Stokes (RANS), which provides industry-acceptable turnaround timescales but is limited to the accuracy of the underlying turbulence model. However, in terms of the wind comfort assessment, it is generally deemed to be accurate enough [22]. With the power of Industry 4.0, more powerful computational resources will be available in the near future which may push the industry-standard approach to migrate to a Large-Eddy Simulation (LES) approach, the accuracy of which has been well established through a large number of research projects and case studies [22, 23].

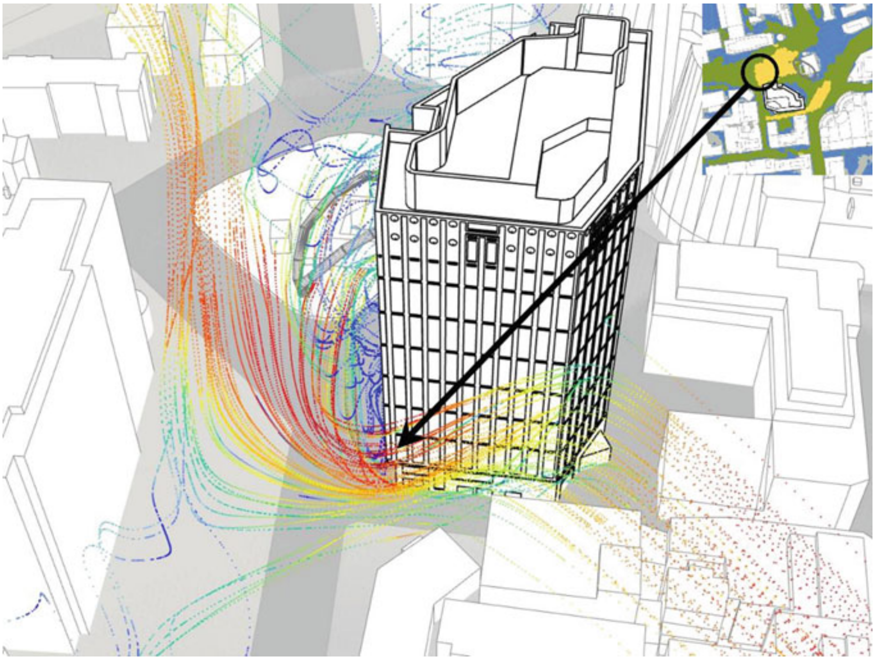

**Fig. 3** Streamlines of the wind from the critical wind direction around the northwest corner of the WCF—© AKT II

## *2.2 Wind Loading on Internal Pressure*

In addition to structural implications, the wind loading on a building also has a significant impact on the occupants. This can be due to thermal comfort and buoyancy (stack effect), air quality, or pressure that's exerted on doors and windows. To ensure consistently comfortable spaces, and within the context of sustainable development, many innovative components are often added ad-hoc within the late design stages within modern building designs. These may for example include adaptive façades with motorised building envelope vents or operable windows, however these innovative systems present challenges for the engineer, as they replace conventional cladding [24, 25] while the motorised openings are subject to any power failure [26]. It is desirable to consider this topic and incorporate (or pre-empt) measures within the early design stages instead.

**Methodologies**. For the past few decades, zonal methods have been the most popular approach when computational resources are limited. Of these, Airflow Network Modelling (ANM) treats the building and systems as a collection of nodes representing rooms, parts of rooms and system components; connections (or elements) between each node represent the distributed flow paths from windows, cracks (leaks), doors, ducts, and Heating, Ventilation and Air-Conditioning (HVAC) systems. These and external frictional forces are explicitly introduced through empirical expressions. Solutions to the internal pressure distribution are achieved very quickly, combined with local weather data, and an annual assessment (hour-by-hour) can be conducted within a reasonable timeframe. The ANM formulation by Walton [27] is used in software such as Energyplus [28] and CONTAM [29], which are widely used in Architectural Engineering & Construction (AEC) industry.

With increasing advances in computational resources, CFD has become more commonplace in industry, providing solutions to fluid-based problems which cannot be easily evaluated analytically. Nevertheless, CFD undoubtably represents the more computationally expensive end of engineering simulation. In the context of internal flow, even with today's computational resources, an annual (hour-by-hour) assessment within a suitable timeframe would be unfeasible.

**Case study**. We demonstrate these two approaches using the test case from the previous sections. The fifth floor of the building was chosen for analysis. A schematic of the floor layout with the airflow network model setup is shown in Fig. 4. The main focus of this analysis is on the four internal doors, as indicated in red in Fig. 5.

For simplicity, it is assumed that the doors and windows on this floor are fully open, the HVAC system is off (i.e., natural convection is only considered), and the floor is sealed off from the other floors. External window pressures were obtained from the pedestrian wind comfort assessment described above for the prevailing wind direction for London. The resulting pressure distribution for the two methods is shown in Figs. 6 and 7.

It can be seen in Figs. 6 and 7 that the trend of the pressure results between the two approaches is consistent with a small discrepancy of quantitate values. According to BS 8300–2:2018, to allow for access to vulnerable members of the public, the acceptable pressure-driven force on a door (at 30 to 60° open) is 22.5 Newtons, to which all doors in this example are acceptable for both methodologies.

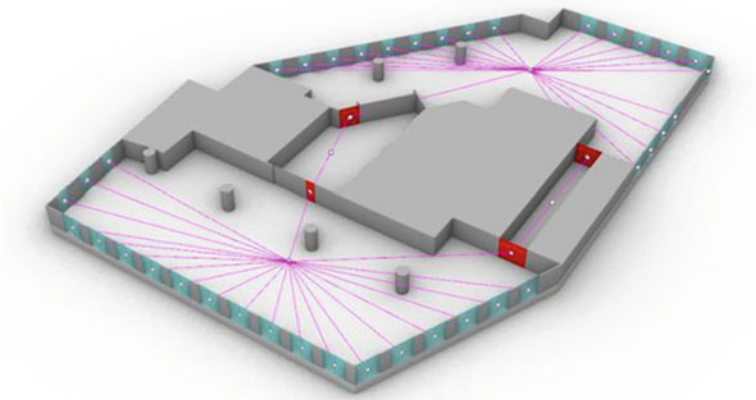

**Fig. 4** Network layout for ANM—© AKT II

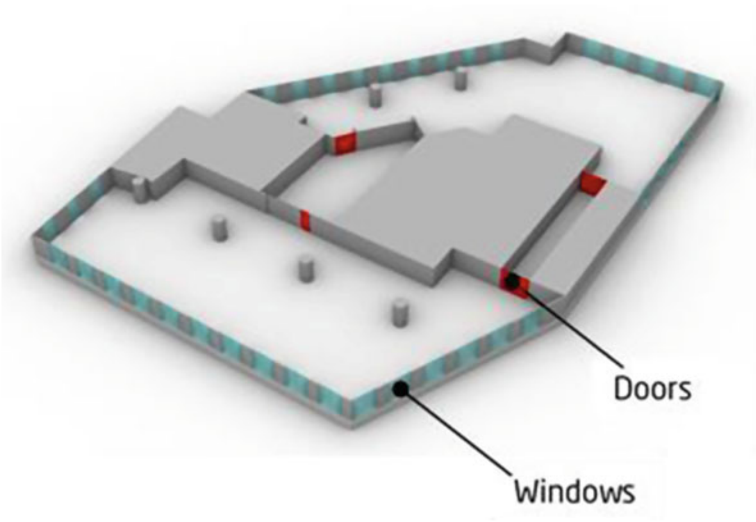


**Fig. 5** 5th floor layout for WCF and key elements of the analysis—© AKT II

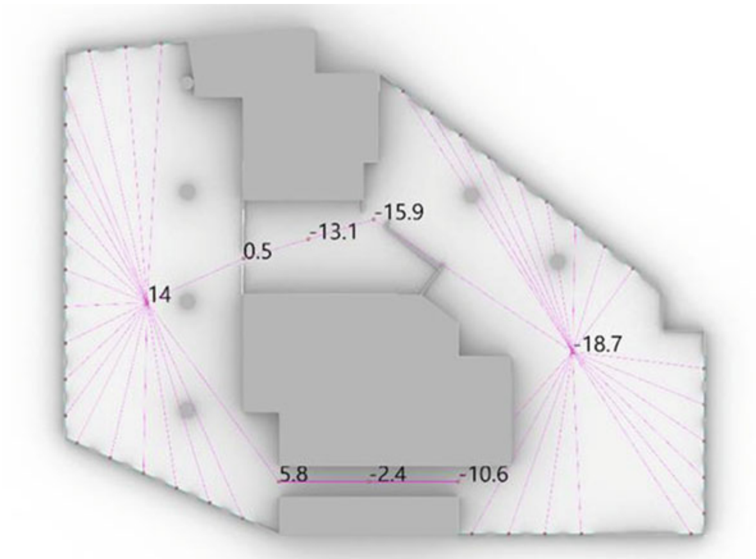


**Fig. 6** Internal Pressure calculated using ANM—© AKT II

For the pressure field, this example test case demonstrates strengths and weaknesses between ANM and CFD. On the one hand, the ANM formulation follows the assumptions that form the basis of Bernoulli's principle, notably that the flow is streamlined, i.e. the flow travels between two nodes without deviating from the path.

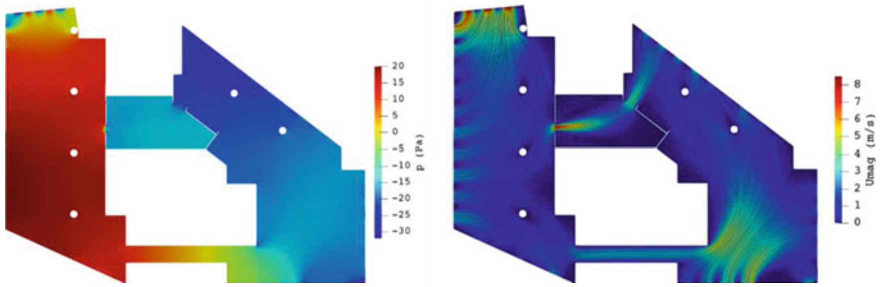


**Fig. 7** CFD assessment for the internal flowfield: (left) pressure (right) velocity—© AKT II

The potentially important effects of the room's geometry on the flowfield (incurring recirculation or stagnant regions) are therefore omitted, to which CFD elucidates. On the other hand, as seen from the streamlines in the CFD in Fig. 3, these flow characteristics are insignificant for this example test case, and so the ANM provides the pressure distribution at a fractional computational cost of the CFD. However, the CFD provides additional information for other potential occupant-comfort issues such as the wind gusts around the room. On top of this, topics such as thermal comfort, stack-effect, and air quality are better modelled by CFD, thus making it the more powerful tool for internal airflow.

**Conclusions**. Advances in CPU technology have allowed designers to consider CFD as a building design tool in industry, as demonstrated in other sections of this chapter. This section demonstrates that the more traditional method of Airflow Network Modelling (ANM) provides an adequate approximation of the pressure field for an internal flow simulation. Quick in its calculation, ANM can compute the annual (hour-by-hour) performance within a reasonable timeframe and accuracy. However, CFD can provide information of local flowfield (e.g. gusts from windows) which occupants may find uncomfortable. It may be more prudent therefore to combine these two approaches: using ANM to conduct and scope the annual performance, and CFD to perform a comprehensive assessment of a few individual cases.

## *2.3 Wind-Induced Acceleration*

In recent years, there has been an increase in demand for buildings that are fast to construct, have large uninterrupted floor areas and are flexible in their intended final use. Modern design and construction techniques enable the sector to satisfy such demands and produce buildings which are competitive in their overall cost. The architectural trend for taller structures, which embodies lightweight floor systems of longer spans, with a tendency to lower natural frequencies with reduced natural damping, has created a greater awareness of the horizontal dynamic performance of the building when subjected to environmental loading, such as wind.

An occupant's perception of wind-induced vibrations of buildings—whether this be physiological or psychological—is largely uncharted. The current industry guidelines and standards provide 'acceptable thresholds' for peak or root square mean (RMS), and accelerations of an occupied building floor (which are typically reported in milli-g, i.e. 1/1,000th of Earth's gravitational acceleration). These include the National Building Code of Canada (NBCC), International Standards Organisation (ISO 6897 (1984), which was more recently updated to ISO 10137 (2007)), and the Architectural Institute of Japan (AIJ) (1991). Academic research surrounding human perception on vibration and tolerance thresholds is very active [30]. From a survey of an office building in New Zealand, Lamb et al. [31] report that 41.7% of respondents were able to perceive the wind-induced swaying of the building, with a similar percentage finding that it was 'difficult to concentrate', with symptoms attributed to the lesser-understood 'sopite syndrome' (drowsiness), which affected their work. Occupants overcame these effects by taking multiple breaks and consuming motion-sickness tablets.

Although vibration may induce a sense of insecurity for occupants, it must be stressed that perception of horizontal vibration does not necessarily imply a lack of structural safety. To determine the wind loading on a building, during the early design stages a structural engineer would conduct a 'desk study' following the calculation procedure outlined in the Eurocode BS EN 1991–1 and NBCC. The Eurocode can be sufficient for standard buildings (e.g. prismatic massing) under 200 m tall. However, if the building geometry is more complex than those outlined in the Eurocode, the calculation becomes very conservative and more of an approximation. The Eurocode also provides limited insight when the building has a low resonant frequency, high slenderness (height-to-width ratio), and susceptibility to 'interference effects' from neighbouring buildings. Conventionally, for several decades, a wind tunnel assessment is conducted to provide this information. Wind-induced acceleration can also be derived from the results. At present however, there are no standards (on wind loading) that describe the use of CFD in this application.

Over the last couple of decades, with encouraging software and hardware advances, there have been an increasing number of publications demonstrating the feasibility (and efficacy) of LES as a design tool for wind engineering applications. In early publications, LES was largely used to provide additional insights into wind tunnel investigations [32] or to investigate the sensitivities associated with the wind tunnel setup—most notably the pressure results to the inflow profiles [33]. In more recent publications, the focus of LES is to act as a design tool, with a focus on determining peak pressure and incurring structural responses [34–37] or wind-induced accelerations [38]; this latter application is particularly promising given LES' ability to resolve large wind gusts.

**Case study**. We demonstrate the results of LES in determining the wind-induced floor acceleration for the WCF test case. For simplicity we assume that each floor consists of a concrete slab and the (usually estimated) critical structural damping of 1%.

In this example case, the building is 74 m tall with a low slenderness ratio. Therefore, a wind loading assessment would be considered cautious, and the values for

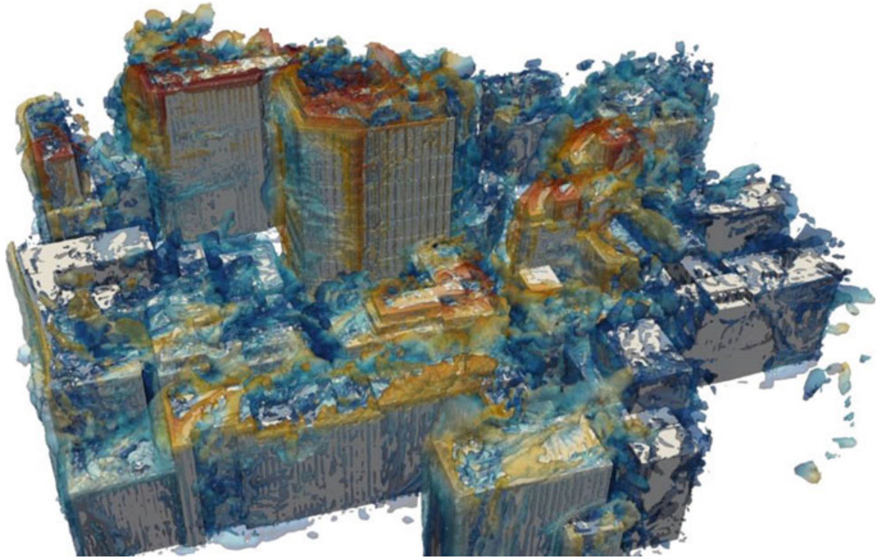

**Fig. 8** Wind structures around the WCF and context—© AKT II

the wind-induced acceleration are expected to be small and unlikely to exceed the thresholds specified by ISO 10137:2007 for an office building. Figure 8 shows the simulated wind flow structures around the target building and surrounding context buildings using LES. These structures, and the incurring fluctuating wind pressures on the target building were sampled to obtain the characteristic wind loading on the structure. The wind-induced accelerations are subsequently derived from these results.

The resulting accelerations, assessed without proximity context, for the along-wind (direction of wind), across-wind (perpendicular to wind direction), and torsional motions of the structure for a range of wind velocities are plotted in Fig. 9. We also compare these results to those provided in the NBCC guidelines. As expected, the guidelines provide a more conservative estimation than the LES assessment. An additional benefit is the turnaround time relative to the equivalent wind tunnel assessment, which allows for the engineer to finalise the design before the final assessment.

**Conclusions**. This section demonstrates the use of CFD, specifically LES, in determining the wind loads and the floor-by-floor wind-induced accelerations of a building. While the Eurocode conventionally requires that the wind loading assessment is determined through wind tunnel testing, quicker solutions provided by LES may be used in the 'desk study' stages to highlight any potential issues with the design that could then be mitigated.

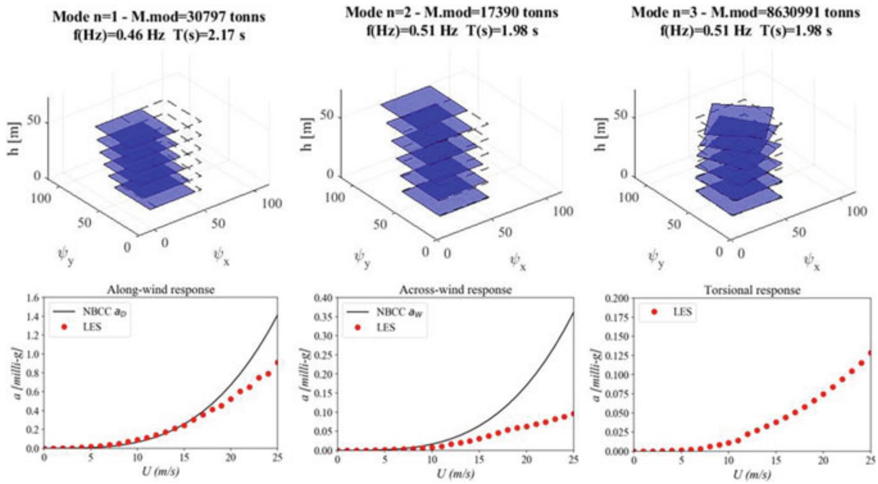


**Fig. 9** Calculated wind-induced accelerations for the WCF from LES and the NBCC guidelines—© AKT II

# 3 Natural and Artificial Lighting

## *3.1 Natural Lighting*

Digital technologies have allowed advanced solar design to become mainstream practice in recent years. Because lighting is such an integral part of how space is experienced, the convergence of these digital technologies has high potential in improving the quality of how we perceive buildings and the built environment. Because sunlight brings both heat and light, solar design has always been a balancing act between the provision of appropriate light and comfort and the avoidance of overheating. Modern workflows allow an integration of many solar indicators into holistic decisions, which allows an effective optimisation of the overall energy balance.

Open-source software such as Radiance [39] and its GPU-based implementation Accelerad [40] have provided a flexible backbone for building simulations. This has allowed designers to move away from graphical rule-of-thumb methods, and for highly accurate and computational physics-based assessments to become a standard practice.

For bioclimatic design, such workflows include energy, daylighting, light pollution, thermal comfort, and reflected glare. The computational cost of these workflows however may be high. When working on large masterplans for planning, or when developing in densely built-up urban centres with large digital models, they could potentially take hours to run on standard desktop PCs.

Cloud computing unlocks these large models, but presently still demands specialist knowledge to set up, and may incur unacceptable financial costs. Designing workflows for small workstations remains a specialist area. On the other hand, the accessibility of solar data and digital models for most parts of the world has removed a barrier in applying the technology to virtually any project.

Another exciting avenue, when it comes to solar design, is the visualisation of ‘feels like’ lighting conditions using augmented reality (AR) or virtual reality (VR) equipment. Designers are able to experience the design with its true lighting conditions, and also with physical measurements of light levels within and around the building, as it is being designed. If this modelling is achieved with an imperceptible latency (equating to real-time), on appropriately powerful hardware, it can transform the designer’s experience of the proposed space.

The following sections focus on a selection of three indicators that are used to assess comfort, safety and inclusivity within the design of daylight conditions for the built environment. These are ‘vertical sky component’, ‘sun hours’, and ‘reflected glare’.

**Vertical sky component**. New constructions affect the daylight availability within the surroundings, by overshadowing adjacent areas. Vertical sky component (VSC) is used to measure the amount of diffuse light from the sky that is available on a vertical façade. VSC is expressed as a fraction of the hemispherical light from the sky that is visible from a specific point of view. It is measured from 0 to 40% (on a vertical façade). Table 5 shows the categorisation of the ranges of VSC, and their meaning for design [16]. Digital 3D models have been used as a standard practice for determining the daylight availability through visibility checks, within the model, of the sky in all directions. Using this information, a further optimisation would be to compute the maximum height and width of a building’s massing, which could be proposed for a small site in a built-up area, while complying with the necessary right-to-light and other similar regulations for daylight access. Taking this a step further, the layout of an entire masterplan could be informed by continually assessing VSC, together with other planning targets, while iterating the design. Detailed digital models of cities furthermore allow the study of VSC to be scaled up into a quick assessment of all buildings that could be impacted by a proposed construction project.

**Sun hours**. This describes the amount of time that a location receives direct sunlight. For a location in the open field, this will amount to most of the year, whereas for a courtyard in a built-up area it could be less than a quarter of the year. Knowing

**Table 5** BRE, Vertical Sky Component (VSC) thresholds

| Grade | Category | VSC range | Description |
|---|---|---|---|
| 1 | Unobstructed | >27% | Conventional window design will usually give reasonable results |
| 2 | Slightly obstructed | 15% < VSC < 27% | Provide larger window than usual |
| 3 | Obstructed | 5% < VSC < 15% | Difficult to provide adequate daylight unless fully glazed |
| 5 | Heavily obstructed | VSC < 5% | Often impossible to provide reasonable daylight, even when fully glazed |

the daily and annual sunlight patterns for spaces that receive a lot of shadowing is essential in order to provide suitable conditions for outdoor activities. Landscape design, and the selection of appropriate plant species for the daylight conditions, is a common use for such data, which itself can be obtained at a very low cost using the 3D geometry from a project's early stages. Sun hours and radiation data are also the basis for many other analyses that are required for planning, including the outdoor thermal comfort studies.

**Disability glare**. In addition to measuring solar access using sun hours and the vertical sky component, in a dense urban setting it will also be necessary to check for any adverse impact that could be caused by the sun within the inter-building space. Sunlight reflected from highly glazed facades may cause disturbances nearby. This phenomenon is known as reflected or disability glare. Glare impact is usually visual, such as a bright reflection near a traffic signal, crosswalk or airport runway that could cause an inability to see and a high risk of accident. In rare instances, the reflection can also be so intense that it also causes significant thermal effects, such as overheating in adjacent buildings, damage to property like parked cars, or burning landscape features. High profile cases of thermal impact include the curved facades of the 'Walkie Talkie' tower at 20 Fenchurch Street in London [41], and the Walt Disney Concert Hall in Los Angeles [42].

Such impacts make glare a material concern for space users. However, as opposed to the study of VSC and sun hours, there has been a lack of standards and validated digital tools for the assessment of reflected glare within most design practices, which has resulted in these studies historically only being applied on special projects. Even then, in many cases, it has been an afterthought, and only if mitigation has been required for completed projects. Digital project models, and the emergence of robust analysis workflows in the public domain in recent years, have made it easier to create spaces where reflected glare impacts are known and are controlled within the design stage.

**Opportunities and challenges**. The goal of daylight and glare studies is to optimise the design for local conditions and to minimise any adverse impacts at sensitive locations around the site. As mentioned above, while daylight access methodologies are well developed, this is not the case for reflected glare. Due to a lack of glare standards, a range of digital approaches to the same problem have been published [43–48]. Before digital tools, the main methodology was geometry-based desk study using solar protractors [49]. This was problematic because only spot checks could be made around the site, plus the work was manual, prone to errors and time-consuming, and also it was not possible to assess reflection intensity.

Modern digital workflows model the environment in 3D and then use rendering engines to fully map the distribution, intensity, and duration of solar reflections. Particular focus has been on visibility within road and rail networks. For air traffic for example, this could be reflections from solar photovoltaic (PV) installations next to the runway which could blind pilots. The Hassall methodology is the most widely used for such cases [45]. A single HDR render of the driver's view is computed and used to calculate the precise timings and intensity of glare throughout the year. While this could also be done using a digital camera at the site, this latter technique only works where the construction already exists.

With detailed 3D models already available from the daylight analyses that are done on a project, no further specialist information is required for the glare assessment. By integrating the already available project data, and with the sensitive locations known, the study can be automated, which makes it faster, more accurate and cost-effective when compared with desk-based methods. This also allows for rapid iteration of the geometry should any significant impacts be found. Often the required adjustments to the glazing's orientation or its reflectance properties are so small that they remain invisible to the naked eye.

Some glare regulations and guidelines have been issued in recent years around the world, which helps to fill the relative gap in comparison with the well-developed daylight access regulation. This includes the City of London [50], Singapore [51] and US Federal Aviation Administration technical guidance [52]. Because glare regulation is mostly qualitative and vague, there is no standard metric or approach. Standards now need to catch up with the technology, to allow the practice to become standardised and accessible for the wider AEC industry.

Finally, one area where digital tools can help to make a large difference is in the improvement of the human connection to the experiencing and understanding of technical data. Integrating workflows with video gaming engines, such as Unity, can allow the conditions on a specific street to be experienced, either locally or remotely, using AR/VR goggles. With such goggles, the planners, designers and other stakeholders could then be able to intuitively explore how the new construction will impact the daylight access and glare for the surrounding areas. This is a matter of data integration. Making such tools accessible to a wider audience will be a step towards creating shared value in the built environment, and towards making safe and accessible places for everyone.

**Case study**. Further to the wind assessments, the 3D model of the WCF was then used to quantify the natural lighting metrics that are mentioned in this sub-chapter, which are namely VSC, Sun Hours and Reflected Glare. The VSC was investigated for key locations, and shows the adverse impact of vegetation on sunlight availability.

Figure 10 shows the current VSC on a representative location around the WCF versus Fig. 11, which shows the negative impact that vegetation may have on sunlight levels, even if it may have a beneficial impact in reducing strong downdrafts.

The public courtyard to the South of the WCF requires checks concerning its solar exposure. Modelling annual sun hours or lux levels is an efficient way of determining which courtyard areas could be fit for which activities [16]. Sun hours (and radiation) results can inform the landscaping design and the locations of seating areas or outdoor dining. The results are best visualised using contour maps for seasons or for various periods of the day (Fig. 12—Sun hours). As for other solar studies, an important benefit of digital methods here, as opposed to traditional desk study graphical techniques, is the fine granularity of the results, both temporally and spatially. These insights can be achieved cost-efficiently, in a matter of minutes. In this case, the direct sunlight is restricted in the courtyard, but outdoor space making can benefit from leveraging these patterns.

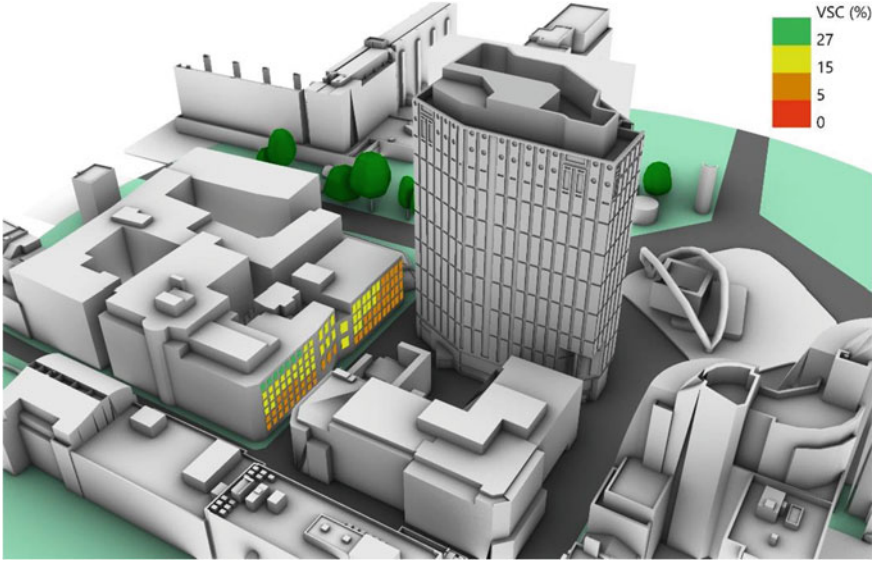


**Fig. 10** VSC on nearby buildings—© AKT II

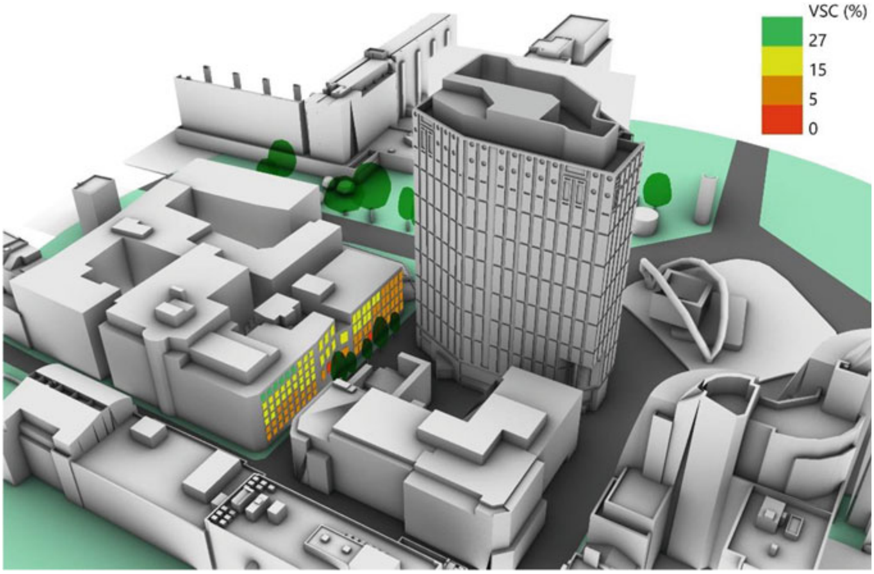


**Fig. 11** VSC on nearby buildings with evergreen trees—© AKT II

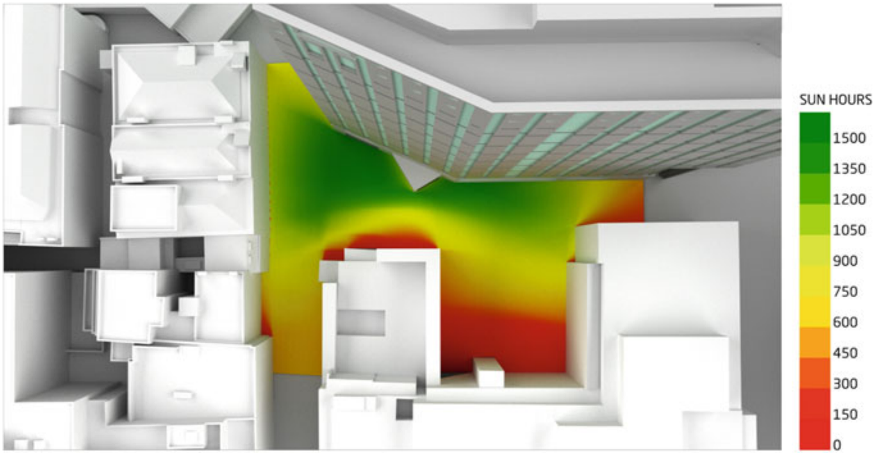


**Fig. 12** Sun hours—© AKT II

Tall buildings such as WCF have a greater likelihood of causing glare as the reflections can be seen from a larger area. Sensitive locations such as crosswalks or traffic intersections can readily be mapped digitally by integrating GIS data from sources such as Google Street View. Glare intensity and the sources of reflection were assessed at a location by creating a glare intensity render using a 3D model of the proposal and its surroundings. The render is showing the sensitive part of a driver's field of view (covering 30° around the area of focus), looking toward a traffic light. The false coloured glare intensity field in the render is calculated with Hassall methodology (Fig. 13—Reflected glare intensity caused by the White Collar Factory calculated at a nearby traffic intersection).

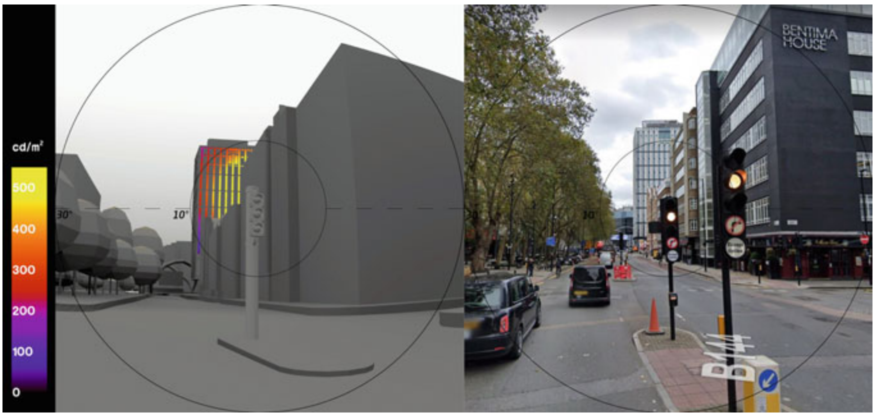


**Fig. 13** Reflected glare intensity caused by the White Collar Factory calculated at a nearby traffic intersection—© AKT II [left], © Google [right]

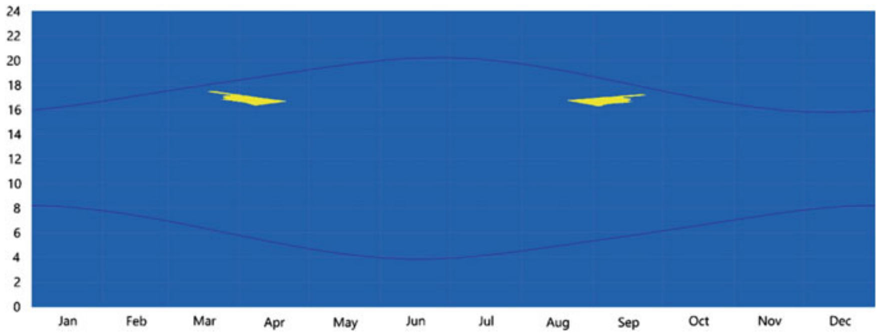


**Fig. 14** Annual times that the viewpoint at the crosswalk receives solar reflections are shown in yellow—© AKT II

Intensity is mainly a function of the distance from the centre of the field of view, the glass reflectance, and the sensitivity of the eye. In this case, there may be a glare hazard because the driver must see the traffic light or pedestrians but may be unable to do so if the glare intensity is above 500 cd/$m^2$. Thankfully, visors help mitigate the issue in this specific scenario. Times and dates when this situation might occur with clear weather can be visualised on an annual map to an accuracy of one minute or fewer (Fig. 14).

Glare becomes problematic if it is occurring for more than 50 h per year. It is time-consuming to derive this data with traditional graphical methods, and especially if the design goes through multiple iterations within its development. The digital approach moreover allows glare studies of large areas to become accurate, quick and cost-efficient, so that any adverse impact on the surrounding space can be spotted and mitigated.

**Conclusions**. Solar design for space making has in recent years benefitted from the convergence of a number of digital technologies and trends. These include freely available GIS data, open-source analysis software, affordable cloud computing power, visual programming tools to set up workflows such as Grasshopper, and the popularisation of the use of video gaming engines such as Unity within the AEC sector. By leveraging these technologies, the practice of solar design will continue to improve the quality of climate-based building design as well as the user's experience of the built environment. The mainstreaming of modern workflows has the high potential to create shared value between a building's designers and users, and to provide comfortable and safe spaces for everyone to enjoy.

### *3.2 Artificial Lighting*

Artificial lighting improves the safety of roadways and pathways, it enables outdoor and night work and evening sports activities, and it provides decorative effects to all built developments and in particular to monuments and iconic buildings.

However, artificial light can also disturb people by causing distraction if it is visible beyond the area that is supposed to be lit. The combined effects of building exterior and interior lighting, lit advertising, car park lighting, office lighting, streetlights, and the lighting from outdoor sporting venues together cause the so-called 'light pollution' that is one of the by-products of industrial civilisation.

Light pollution leads to adverse health effects (i.e. sleep deprivation), disrupts ecosystems, and interferes with starlight and astronomical observation. The most severe impacts affect highly industrialised and densely populated areas of North America, Europe and Asia. More than half of the population of the UK is unable to see the Milky Way in the night sky, and this problem is spreading into rural areas as the country's artificial lighting increases [53].

This obtrusive light can disturb people and ecosystems in three different ways:

- Sky glow (or upward light pollution), which is caused by the light propagation (or diffuse luminance) into the atmosphere from upward-directed (non-shielded) light sources and/or by reflection from the ground and other surfaces.
- Light trespass (or spill light), which is caused by unwanted light falling beyond the areas intended to be lit and into one's property.
- Glare, which is the discomfort or inability to see when the source of artificial light is much brighter than the surrounding area.

Whether obtrusive or not, the artificial increase in light can also have significant ecological effects on wildlife. Some nocturnal bird species for example may be attracted to or disoriented by bright lights, with induced hormonal, physiological or behavioural changes. Night-flying insects can either cease flying or fly in spirals when exposed to high levels of illumination. Some plants may stop flowering if the night is too short, while others may be flowering prematurely.

Light pollution must be addressed by changing the habits of society so that lighting is used more efficiently with less waste and less unwanted illumination. The Clean Neighborhoods and Environmental Act 2005 introduced artificial light into the list of statutory nuisances. Since then, planning conditions for all new developments have required that specific lighting conditions are applied according to the Institution of Lighting Professionals (ILP) guidelines [17].

The focus of current guidelines is mainly on external lighting, however unwanted spill light from interior lighting into nearby residential premises is also a concern. Because the interior lighting is often not yet finalised during the planning stage, a typical lighting installation is assumed, as the basis for calculating the surrounding illuminance levels.

Some indications of the illuminance level (which is measured in lux) may be obtained by looking at:

– The distance between the new development and the surrounding existing buildings.
– The dimensions and orientation of the new development.
– The glazing fractions of the new development's facades.
– The properties of the glazing.
– The interior lighting design (depending on the intended use).
– Light mitigation measures (such as shading devices).

Guidance for a preliminary design of interior lighting is given by 'Light and lighting—Lighting of workplaces' (BS EN 12,464-1:2021). Depending on the intended use (e.g. office space), the guidance provides this information:

– Average lux value and uniformity on the working plane.
– Height, dimensions and grid resolution of the working plane.
– Reflectance of all surfaces (ceiling, floor and walls).
– Average lux value near to hallways, elevators, stairs and entrances.

**Case study**. In the pictures below, light pollution from the WCF (in a dark sky) was assessed on the surrounding buildings Fig. 15. Office spaces were assumed on each floor, with an average lux value of 500 and a uniformity of 0.52 on the working plane. A 0.5 m band was removed from the working plane close to the wall, with a grid resolution of one metre at a height of 0.8 m from the floor. The lighting simulations were carried out by assuming a reflectance value of 0.6 for the walls, 0.8 for the ceilings and 0.3 for the floors.

The IPL guidelines [17] provide illuminance limits for pre- and post-curfew (which is typically at 11.00 PM) depending on the location. The limits refer to the surrounding 'brightness' level for four different environmental zones. For high district brightness areas, the average lux limits on the centre of a surrounding residential window should be not higher than 25 lx pre-curfew and 5 lx post-curfew (environmental zone E4).

Figure 16 shows that the average illuminance level on the windows of the residential building on the south-east side of the WCF is around 20 lx, which is below the pre-curfew limit but above the post-curfew limit, and that mitigation measures (i.e. shading devices, on/off switching sensors, dimmable lights, automatic curtains, etc.) should be integrated.

## 4 Outdoor Thermal Comfort

Forward thinking local regulations [14, 15] fuel the development of innovative workflows to capture the complexity of the urban climate at the building planning stage. It is clear from the City of London Corporation's research that the most important

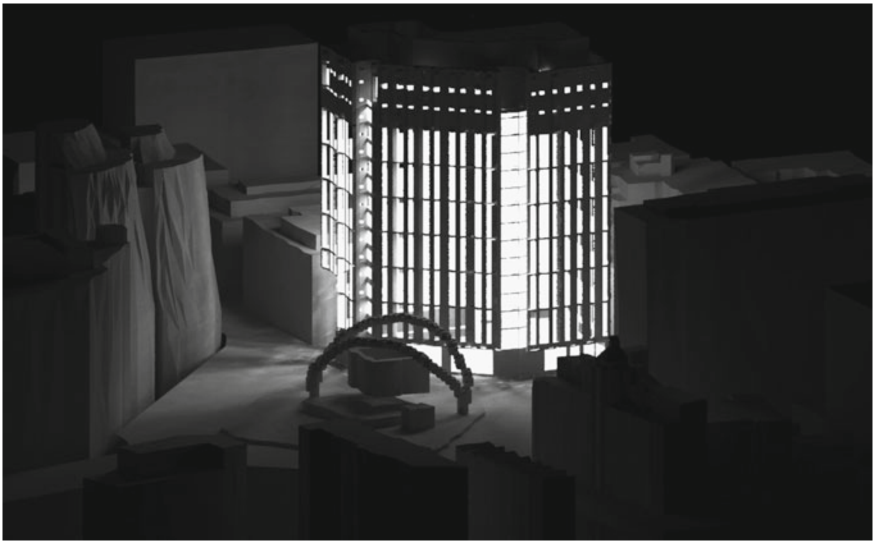

**Fig. 15** Greyscale representation of light trespass

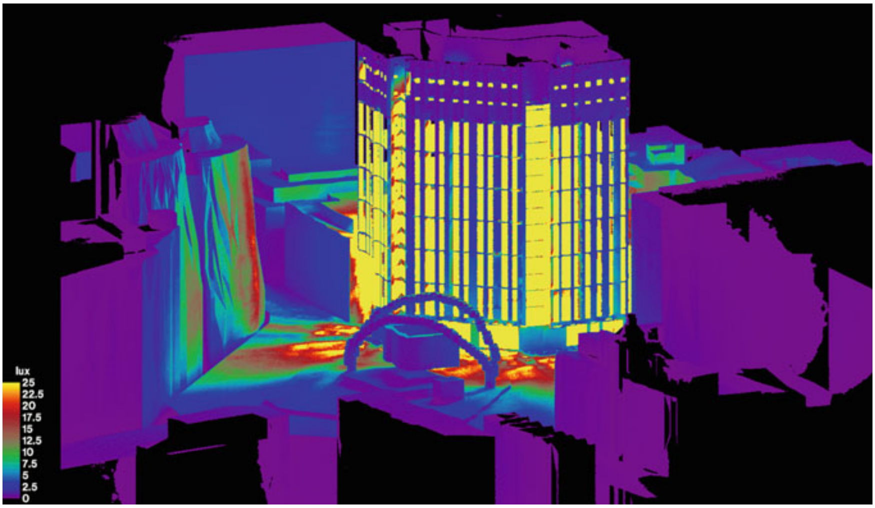


**Fig. 16** Lux level on any surface caused by light trespass

factor related to the quality of a public space is the outdoor thermal comfort, which is a combination of solar exposure, wind, air and radiant temperatures and humidity.

This is the ‘feels like’ quality of the microclimate, which the City of London Corporation terms ‘thermal comfort’. For example, a sunny open space in February might appear to be an appealing and comfortable place to dwell, but if the air temperature is low with high humidity and there is a strong northerly wind, it is likely to feel significantly colder and uncomfortable, even in the sun. This is the perception of thermal comfort as experienced by those using the space [15].

Thermal comfort is an important, recognised aspect of the urban climate. It is what we perceive.

However, because of its complexity and subjectiveness, over the years several criteria have been established to identify the thermal state of individuals outdoors. Below are some of the most adopted indices, alongside many others that are available in literature and research:

- Physiological Equivalent Temperature (PET): a rational index which is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed [54].
- Standard Effective Temperature (SET): a rational index which is defined as the dry-bulb air temperature of an environment at 50 percent relative humidity for occupants wearing clothing that would be standard for the given activity in the real environment [55].
- Predicted Thermal Sensation (PTS), which is obtained from the SET, as a modified version with an adaptive approach [56].
- Universal Thermal Comfort Index (UTCI): a rational index that is defined as the air temperature of the reference environment. It produces the same response index value as the dynamic physiological response that is predicted by the model of human thermoregulation [57].
- Thermal Sensation Vote (TSV): a questionnaire, with values ranging from −3 (cold) to +3 (hot), with a neutral value at 0. There is also Thermal Preference Vote (TPV), with values going from −3 (a lot colder) to +3 (a lot warmer), with a neutral value at 0 [58].
- Wind Chill Index (WCI): a direct index and comfort criterion for establishing the impact of wind when the dry-bulb temperature is below 10 degrees centigrade [59].
- Humidex: a direct index and comfort criterion for identifying the impact of humidity on warm temperature [60].

In the UK, UTCI is the preferred index for establishing outdoor thermal sensation. The reason behind this choice is that the Universal Thermal Comfort Index (UTCI), which was developed by the COST Action 730 [61] between 2005 and 2009, satisfies these requirements:

- Thermophysiologically significant throughout the whole range of heat exchange
- Valid in all climates, seasons, and scales
- Useful for key applications in human biometeorology (e.g. daily forecasts, warnings, regional and global bioclimatic mapping, epidemiological studies, and climate impact research)

– Independent of a person's characteristics (i.e. age, gender, activities, clothing, etc.).

Moreover, the development of an operational procedure via a polynomial regression function [57] to calculate the UTCI without solving the Fiala Model of human heat transfer and thermal comfort [62] lowered the computational cost and unlocked the opportunity to adopt this index for building design and planning purposes.

Since 2020, any new development in the City of London requires an outdoor thermal comfort assessment, based on real meteorological conditions recorded in the Square Mile, and a simplified methodology to perform an hourly assessment around the site and on any balcony/terrace for five years [15].

Outputs are similar to the wind microclimate; alongside the percentage of the time within a comfortable UTCI range (between 0 and 32°) per season (Table 6), an additional annual usage category is also represented (Table 7).

**Case study.** This methodology was applied to the WCF because of its vicinity to the City of London together with the absence of a local thermal comfort policy (Tables 6 and 7).

Figure 17 shows the seasonal percentage of time within comfortable range for spring. For planning purposes, this plot is repeated for each season at the street level and on any terraces. Results for spring show that close to the WCF the comfortable

**Table 6** UTCI—city of London seasonal comfortable range

| Range (%) | Colour schemes | Description |
|---|---|---|
| 0–25 | Blue | Typically leads to transient annual destination uses |
| 25–49 | Blue | Typically leads to transient annual destination uses |
| 50–69 | Light-Blue/Green | Typically leads to short-term seasonal annual destination uses |
| 70–89 | Yellow/Orange | Typically leads to short-term/seasonal annual destination uses |
| 90–100 | Red | Typically leads to all season annual destination uses |

**Table 7** UTCI—city of London destination use

| Grade | Category | UTCI within comfortable range | Description |
|---|---|---|---|
| 1 (Green) | All Season | $\geq$ 90% in each season | Year-round use (e.g., park) |
| 2 (Purple) | Seasonal | $\geq$ 90% spring–autumn AND $\geq$ 70% winter | Suitable for use during most of the year (e.g., outdoor dining) |
| 3 (Cyan) | Short-term | $\geq$ 50% in each season | Appropriate for short duration and infrequent use year-round |
| 4 (Orange) | Short-term seasonal | $\geq$ 50% spring–autumn AND $\geq$ 25% winter | Short duration activities during most of the year |
| 5 (Red) | Transient | $<$ 25% winter OR $<$ 50% any other season | Suitable for public spaces where people are not expected to linger for extended periods |

**Fig. 17** Seasonal % of time within comfortable UTCI range (Spring)

periods vary between 70 and 100%. For the assessment, considering that this is a commercial area, the considered hours have been trimmed from 8 am to 8 pm, as recommended in the thermal comfort guidelines [15].

Figures 18 and 19 show the summary of the seasonal results with an annual recommendation of programmatic uses. At street level, this corresponds to suitability for short-term and seasonal activities within the courtyard south of the WCF. The several internal courtyards around the site, which are less permeable, show comfort grades between seasonal and all season—which translates to a year-round use of these spaces.

At the rooftop level, conditions are mainly suitable for short-term activities year-round.

**Conclusions**. Outdoor thermal comfort is what we perceive. It is a combination of several factors and it is subjective. The recent guidelines [15] have unlocked repeatable and fast assessments of the UTCI (a complex rational index). Results show that UTCI has a strong correlation with the hourly wind speed, and therefore if we want to design spaces for year-round activities, the protected areas (even without direct radiation) will be more comfortable than those fully exposed to sun and wind intensity. This is valid for a London climate. Given the novelty of the approach,

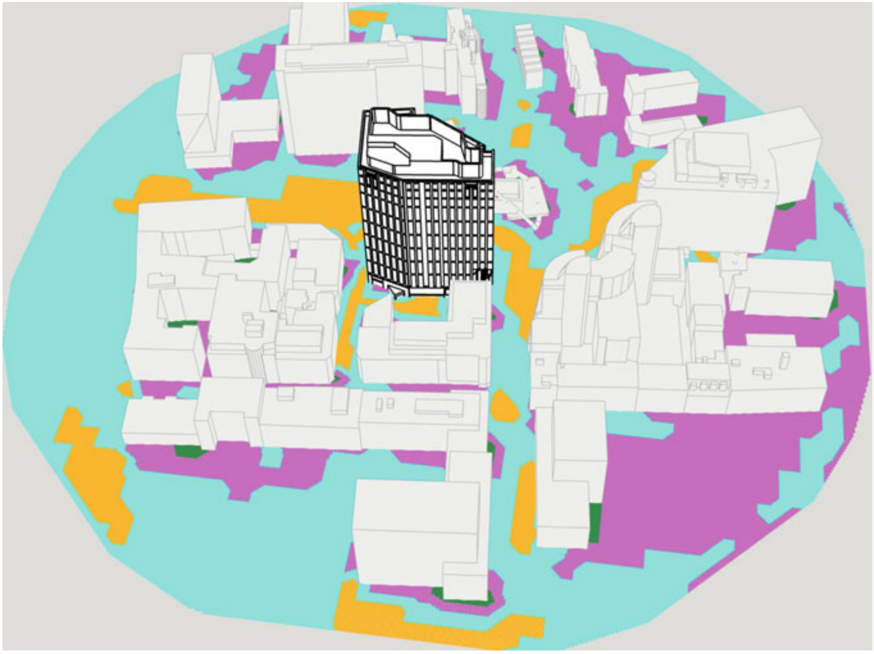

**Fig. 18** Suitable destination use according to the thermal comfort results at street level

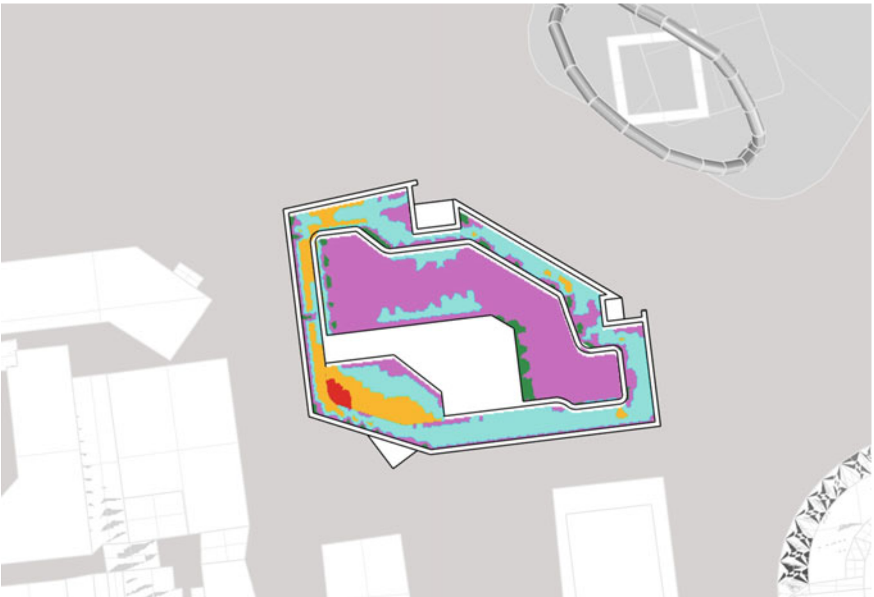

**Fig. 19** Suitable destination use according to the thermal comfort results at the accessible rooftop

further work is required to capture the various boundary conditions and building designs.

## 5 Air Quality

Air pollution is the greatest environmental danger to human health, which is exacerbated by the global population growth, increased urbanisation, and the impact of climate change on atmospheric conditions and weather variability.

Fuel combustion in motor vehicles, coal/oil/gas-fired power stations, and industrial boilers are the major emission sources of air pollutants in urban areas. Sufficient concentrations in the atmosphere are potentially harmful to humans, animals, and plants. For example, exposure to fine particles reduces lung functions in the short term and increases cardiovascular and respiratory diseases in the long term.

In 1984, a catastrophic accident caused the unintentional release of methyl isocyanate from a storage tank in India. Driven by the prevailing wind, the toxic cloud moved close to the ground and enveloped buildings. The accident caused the immediate death of around 5,000 people and more than 20,000 afterwards [63].

The understanding of atmospheric dispersion of pollutants in urban areas is essential in order to predict the potential threat of hazards and accidental events and to identify areas that are at minor or major risk.

More generally, the accurate analysis and prediction of pollution dispersion offers a broad range of beneficial implications:

– Improve air quality at the street, city, and regional scale.
– Decrease human exposure to harmful concentrations of air pollutants in high sensitivity areas (e.g. bus shelter design).
– Design of outdoor activities (e.g. play areas, dining areas).
– Design of green infrastructure as a passive control system for air pollution (e.g. vegetation barriers).
– Lessen the impacts of climate change.
– Improve biodiversity and ecological resilience.

**Air quality assessment**. Air quality is influenced by the type of development (buildings and/or infrastructure), location of the site, designated uses, and whether a suitable transport strategy is in place. Air quality issues are to be addressed at the planning stage to ensure a strategic approach through the design.

Under the Environment Act 1995, the local authorities of England, Scotland, Wales and Northern Ireland are charged with air quality duties to ensure compliance with EU/English legislation [64] of the air quality objectives (i.e., Nitrogen Dioxide NO2, Particulate Matter PM10) and to draw up an action plan of remedial measures for any areas of relevant public exposure.

To provide a statutory process for local authorities, a technical guidance [18] is also designed to support secondary users (such as transport and planning consultants, air quality experts, etc.) with guidelines on how to monitor, assess and take action to improve local air quality (air quality assessment).

A typical air quality assessment for planning applications includes:

- Determination of the baseline scenario
- Assessment of potential air quality impacts during the construction phase
- Assessment of potential air quality impacts during the operational phase
- Assessment of site suitability
- Assessment of air quality neutrality
- Identification of required mitigation measures

The outcome of an air quality assessment is mainly driven by the potential air quality impacts during the operational phase, where a 3D analysis of pollution dispersion from combustion plants, gas-fired boilers, industrial sources and road traffic is performed.

The 3D analysis is usually conducted using simulation software that is based on the Gaussian plume model [65], which is considered the simplest mathematical model for high-level predictions of pollutant concentrations. This model is frequently applied to continuous, buoyant air-pollution plumes or non-continuous air-pollution puff and is used in combination with empirical correlations to evaluate the growth of the plume dimensions with the distance from the source location.

Concentrations of pollutants are predicted at existing nearby receptors, which are classified into high, medium, and low sensitivity (i.e., hospitals, religious buildings, outdoor dining areas). Pollutants' concentrations are also reported at future receptors of the proposed building to assess the site suitability.

The modelling results of pollutant concentrations are then calibrated to the measured values from nearby monitoring stations, to check compliance with local and national regulations. Any area of non-compliance requires mitigation measures to be integrated within an action plan to improve local air quality.

**Atmospheric dispersion modelling**. In real urban scenarios, the dispersion of pollutants is a 3D-complex phenomenon that is affected by several environmental conditions (i.e., wind direction, thermal stratification, source location, type of source, buildings' configuration, building area density, etc.). However, pollution dispersion is mainly driven by wind flow with two separate mechanisms: advection and diffusion. Due to the first mechanism, the pollution plume is transported along the average wind direction at the speed of the average wind magnitude. Due to the second mechanism, the pollution plume 'grows' in three directions depending on the wind turbulence in the atmosphere. On a separate note, the wind turbulence (and so the pollutant diffusion) is affected by the atmospheric thermal stability, which can enhance or dampen vertical wind accelerations depending on the geographical location, time of day, and human activities in urban or rural environments. For example, atmospheric urban areas are frequently characterised by the so-called unstable thermal stratification, which is due to the 'injection' of heat in the atmosphere from greater human activities in comparison to those of rural environments. Furthermore, the amount of solar heat in urban areas, which is reflected in the atmosphere, is far greater than in rural areas, due to the high-built density area.

Based on the above mechanism description, interestingly, strong wind speeds, which may adversely affect pedestrian comfort and safety, contribute to the local dilution of pollution concentrations with beneficial effects on public exposure to toxic/dangerous contaminants in the air. Similarly, frequent changes in wind direction lead to beneficial dilution of pollutant concentrations.

Regarding the atmospheric thermal stability, surprisingly, the atmospheric conditions over urban areas are much more favorable to pollution dilution than in rural environments. However, pollutant emissions in urban areas (from transportation, construction, human activities, etc.) are typically higher than in rural areas, therefore, pollutant concentrations in urban areas may be always significantly higher than in the surrounding regions.

**Case study**. CFD has a long history of use in computing fluid flow around obstacles [66] and pollutant dispersion in urban environments [38, 67]. CFD has been applied to a wide range of problems, and most recently as an official tool to compute wind and thermal comfort. By using CFD, the urban geometries are reproduced in computer simulations with reasonable accuracy, including complex shapes and narrow canyons. Topography, vegetation, and mechanical features such as stacks, and air intakes, are easily included. With the increased computational power, realistic meteorological conditions such as wind direction and magnitude, temperatures, and atmospheric stabilities are simulated in CFD within a reasonable timeframe.

Traffic pollution dispersion around the WCF was simulated for several wind directions using 3D CFD. Emissions of $NO_x$ and $PM_{10}$ were calculated from the daily average number of vehicles on each segment of the surrounding road network. Background pollutant concentrations were included to predict compliance with UK regulations [69].

Figure 20 shows the normalized 3D Pollution contours around the WCF driven by southerly (left) and northerly (right) winds. 3D contours provide useful information on the dispersion mechanisms (e.g. meandering, 'chimney effects', accumulation zones, etc.). For example, the left picture shows a plume rising on the northern façade of the WCF, which is due to the strong wind recirculation in a region of low wind pressure that is induced by southerly winds.

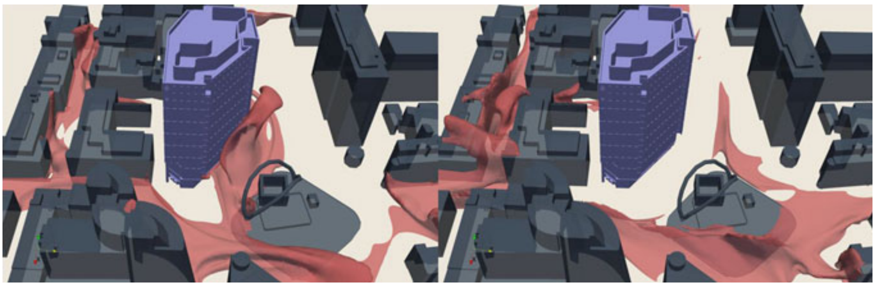

**Fig. 20** Normalized 3D Pollution contours around the WCF driven by southerly (left) and northerly (right) winds

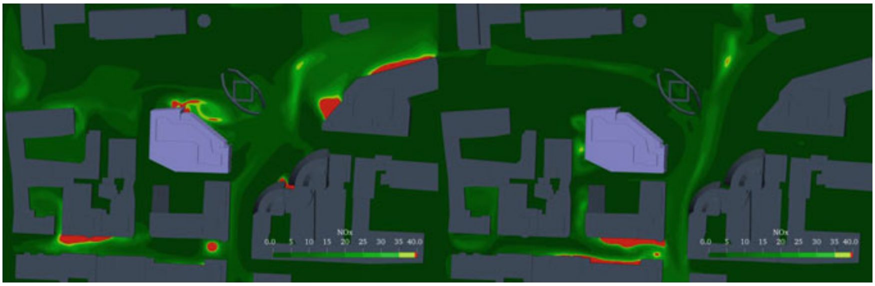

**Fig. 21** Plan view of nitrogen oxides ($NO_x$) around the WCF for southerly (left) and northerly (right) winds

Non-negligible values of pollutant concentrations may reach the second or third floor of the WCF, and will thus affect the indoor air quality at those levels.

For both scenarios (Fig. 20), the narrow street on the south side of the WCF (Old Street Yard) and the adjoined courtyard are characterised by relatively clean air, due to frequent strong winds that localised at the WCF's south-east corner.

Figure 21 shows a plan view of nitrogen oxides ($NO_x$) around the WCF for southerly (left) and northerly (right) winds.

As mentioned above, a very low concentration of $NO_x$ is predicted for both of the scenarios within the narrow street on the southern side of the WCF and within the adjoined courtyard. Differently, high concentrations are predicted on the northern side of the WCF for southerly winds, again due to the wind recirculation in the area of low wind pressure. It is worth noting that medium-to-high values of $NO_x$ are predicted within the roundabout for both scenarios, because this location is surrounded by pollution sources on each side.

## 6 Conclusions

As described in the chapter, without the rise of the Industry 4.0, including advances in computational capabilities and interoperable workflows, and forward-thinking legislation, bioclimatic design as described in this chapter wouldn't exist.

Knowing how to shape the invisible forces that surround us brings a new dimension to designing buildings. Clients, architects, planners, landscape designers, and engineers, not only influence the lives of the residents of their buildings but touch the lives of everyone else viewing, passing by, and sitting next to them.

Buildings have long been designed for themselves: striving for the best structural and energy performance, while achieving the right aesthetic. However, buildings have the responsibility to care for and protect the context they sit within.

Bioclimatic designers address all the microclimate variables that make a space into a destination. We ensure that these spaces are attractive, comfortable, safe and inclusive, as part of unlocking them for everyone. This is the recipe for a successful development with a long-lasting legacy.

At the urban level, bioclimatic designers solve a variety of issues that are ultimately different aspects of the same discipline:

– Wind microclimate (comfort and safety)
– Wind-driven rain and snow (not described in this chapter)
– Wind-induced structural loading and cladding pressure (not described in this chapter)
– Wind-induced acceleration
– Wind-induced internal pressure (or building stack effect)
– Sunlight, daylight and overshadowing
– Disability glare
– Landscape strategy (not described in this chapter)
– Light pollution
– Outdoor thermal comfort
– Walkability (not described in this chapter)
– Natural ventilation
– Air quality assessment
– Pollutant dispersion
– Heat and smoke dispersion (not described in this chapter)
– Noise and vibration (not described in this chapter).

And most of the aspects mentioned above are required for planning, which is an early design stage that, until recently, was not so demanding in its deliverables. This prior trend has now changed. There is now an awareness that making the 'right' choices early can generate real value for the design, and the pre-planning stage is no longer a simple tick-box exercise. Industry 4.0 unlocked the potential of bioclimatic design, which has now become a crucial part of the design process.

Planning authorities are aware of this. They are increasingly demanding more and more microclimate assessments during the pre-planning stage, and they want to be involved in the design to an unprecedented extent.

This is the right approach. The public interest needs to be protected, while clients want their buildings to be successful within a harmonious 'urban climate'.

As discussed so far in this chapter, the challenge that the discipline is facing is 'change':

– Change of mentality. Clients have to be convinced to invest in the early design stages (before planning), just as they invest into e.g. RIBA Stages 3 and 4.
– Change of tools. Thanks to open-source software, and readily available cloud services, the complex analyses can be performed and visualised faster than every before. Clients and public authorities however, in the same way that they accepted Radiance to replace the Heliodons, also have to accept software such as OpenFOAM to replace the wind tunnel testing for wind microclimate assessments.
– Change of skillset. As the complexity increases, the challenges of staying up-to-date with the codes of practices, guidelines, standards and tools also increases.

The challenge is to maintain a holistic approach, and to not silo the aspects of bioclimatic design, so as to maintain a truly interdisciplinary branch of building design.

– Change of national policy. There is not a prescriptive requirement at the national level in the UK. The Tall Building policy [70] is too vague when it comes to microclimate assessments, and it is related to tall and large buildings. In London, each Borough has its own policy, which most of the time refers to the city-wide London Plan and is not locally prescriptive. In 2014, the Supplement to the 2011 London Plan [71] identified the Lawson Criteria as the criteria for establishing whether the windiness of the area is suitable for a specific designated use, but this new instruction didn't include a methodology for generating the results. The London Dock Development Corporation have their own LDDC criteria [21]. The borough of Tower Hamlets does not accept CFD as part of the planning submission [72] but the City of London does [14]. There must be more statutory regulation, and more awareness that the clarity on what to deliver must come from the national government. Clients will otherwise never understand why they should invest in these assessments.

Since the publication of the first textbook regarding Urban Climate in 2017 [4], much has changed. Although they are not enough and they are not harmonised, the new regulations, which are driven by greener and more inclusive agendas, have been shaping a requirement for better buildings and cities.

The urgency of building cities that are more equal, resilient and friendly has never been stronger. It is the responsibility of clients, and the broader design teams, to make this happen.

**Acknowledgements** The authors want to thank Luke Fox, AKT II enthusiastic and highly professional Technical Writer, for his assistance in finalising and improving the manuscript.

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# Lotus Aeroad—Pushing the Scale of Tensegrity Structures

**Matthew Church and Stephen Melville**

**Abstract** The Lotus Aeroad sculpture was a focal point for the annual Goodwood Festival of Speed. Research shows it is the longest tensegrity cantilever built to date. The concept for the structure was for a scheme which echoed the philosophy of Lotus Cars, that of lightweight, pared-down design. Although the structure is simple in that it is composed of pure axially loaded struts and ties, the structural design was highly complex. Format worked exclusively within parametric environments to progress the scheme from initial form finding to the automatic production of final fabrication information. This allowed for flexibility in the design until the point when the material was ordered. We worked in conjunction with the Artists to form-find a stable tensegrity which matched the artistic intent. The global system was analysed using K2E—an parametric plug-in for Rhino-Grasshopper, developed in-house. This analysis was performed iteratively to optimise the sections used for the struts and ties to reduce the structural weight to an absolute minimum. Any unnecessary mass would require further strengthening and stiffening, adding even more material. The resulting structure was as lean as possible. The parametric workflow included a connection design script which designed the joints whilst the overall structural form was still being finalised, helping the design keep pace with the strict project deadline. Finally, this project was a test of using augmented reality at building scale. Using augmented reality software it was possible to compare the calculated positions of the elements in the 3D model to their positions on site.

**Keywords** Tensegrity · Steel structure · Lean design · Augmented reality

**United Nations' Sustainable Development Goals** 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 12. Ensure sustainable consumption and production patterns

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_45

# 1 Introduction

The Lotus Aeroad sculpture is the latest centrepiece to be developed for the annual motor sport and classic car festival, Goodwood Festival of Speed, in Chichester, United Kingdom. Unlike previous years where artist vision was paramount, the original concept for the structure was to develop a scheme which was overtly lightweight, visually logical and 'readable' but also an illustration of high technology lead design. It was to be an embodiment of the ethos of the founder of Lotus Cars, Colin Chapman. Lotus were the sponsor and ultimate client for the piece. They have a long history of efficient and lightweight engineering design, which transcends motor sport. Colin Chapman's rationale was very pertinent to the discipline of Structural Engineering and to the Aeroad in particular, namely; 'Simplify, then add lightness' [1] (Fig. 1).

The sponsors appointed production artists Unit 9 to design the piece. Format Engineers were then appointed directly to Unit 9 who then quickly arrived at the choice of a tensegrity structure as that was a very visual example of lean design made real through high technology and one which was felt to be under explored as a frame typology. The Client, Lotus Cars and the organisers of the festival were keen that the structure cantilevered from existing foundations at the centre of an elliptical lawn and over a perimeter pathway used for public circulation. They also wished to push the size of the cantilever as far as possible within a set budget, on the way exceeding the previous record for a tensegrity cantilever.

**Fig. 1** The lotus aeroad sculpture outside goodwood house. *Photo Credit* Crate47

Although the structure is, in many ways, simplistic in that it is made from an arrangement of pure struts and ties, the structural design process was on the opposite side of the complexity scale. As with many festival structures the timescale for design exploration, detailed analysis and production of fabrication information was extremely tight. In this instance engineering appointment was in late March 2021 whilst the piece was to be in-place mid June. Because of the very short time scale and their previous experience of working on this particular site, the steel fabricators Littlehampton Welding Limited were appointed early on to work alongside Format Engineers and Unit 9.

From the outset parametric design was used so that structural exploration and form exploration could remain fluid. This meant that, like sculpting in clay, the design could be moulded and tweaked into the artist's vision. Many different forms and iterations could be quickly modelled and presented to the Artist for their assent or to provoke debate on the direction of the design. Another key factor in the use of parametric design was the speed at which the design process could progress. Several different processes could be performed concurrently. For example, whilst the global geometry was still to be finalised, the scripts which designed and checked the connections could be written so the final geometry could be "plugged-in" once it was completed. Format Engineers also scripted the automatic generation of steel fabrication drawings from the final model, another task which could be undertaken in advance of the Artist 'signing off' the final form. Another benefit of the parametric workflow was that many different iterations of foundation support locations could be tested and the support reactions tested against the capacity of the existing foundations. This was important as it avoided the construction of new footings with the associated cost, time and environmental impact.

Although creating parametric scripts takes time up front compared to performing the same process manually, the geometry can then be assessed and altered and reassessed in a matter of minutes once it has been coded. As previously noted multiple variations of form and material volume can be explored and presented to the client.

The structural design of the superstructure was broken down into two distinct parts: the 'Global Structural Design', and the 'Connection Design'. The global structural design focused on determining the overall form which primarily consisted of the node locations and required strut and cable sections as outputs. The connection design consisted of accurate determination of the geometry of the joints plus the detailed finite element analysis of the mild steel plates and tubes to which they were welded. These processes are described in more detail later in this chapter.

The extreme efficiency of the Aeroad tenesgrity structure has been made possible by low cost but powerful computational design techniques. Technology is driving the refinement of low carbon design. It allows designers to explore form in a holistic way. The trade offs between competing factors of shape, material strength and stiffness no longer need to be approximated, they can be balanced accurately. The promise of the fourth industrial revolution of democratisation of machines and machine techniques has led to a rapid take up parametric design tools within the AEC industry and most importantly the ability of practitioners to develop those tools for themselves and not be reliant upon software houses or large scale technology companies. Our workflow for the Lotus Aeroad is a great example of that.

As will be seen later in this paper, the gap between a digital model and the real world was bridged with augmented reality, another example of the premise of Industry 4.0. The power of virtual reality and augmented reality tools lies in the mainstream adoption by design practices who are then able to explore the limits of form and construction of form. This democratisation can only serve to benefit further design practice.

## 2 Concept Design Aspirations

Our brief at the outset of the project was succinct:

- To design a structure which embodied the ethos of Lotus Cars, i.e. ‘Simplify, then add lightness’
- Unit 9 wanted the structure to be ‘made more from air than any other material’
- That structure should be as lean as possible with regard to material use as this is a responsible aspiration for any design but also one which would very visibly lead the way in inspiring other designers to do the same.
- To design a tensegrity cantilever.
- The cantilever should exceed the span of any previously built tensegrity.
- The structure should be elevated above the ground, both to prevent the public from climbing it and to emphasise the ‘floating’ cantilever.
- Whenever possible re-use the foundations from previous years Festival of Speed. New foundations would absorb too much of the budget, take too long to build and would add embodied energy for no discernible benefit.
- In addition to this our role was to ensure that the structure did move or deflect in an uncomfortable looking way, it was safe to build and it could withstand storm force winds.

### Materiality

Many different materials were considered during the initial design phase. Timber compression elements were considered as were stainless steel, aluminum and carbon composite tubes. Alternative tie members under consideration included nylon ropes or solid bars. The final choice of stock structural mild steel tubes and stainless steel wire with stainless steel fork ends was made for a number of reasons. The materials were easily available in the limited time available for the design and fabrication process, they had a high strength and stiffness and they could be cut, welded and paint finished by the steel fabricator, Littlehampton Welding Ltd in one location thus eliminating supply chain risks as far as possible.

Given more design research time and if building at a smaller scale we would definitely consider material options such as bamboo or roundwood timber. We would also consider re-used or reclaimed steel. Tube sections especially are becoming more widely accepted and available in the construction industry, therefore, structures of this nature are primed to take advantage of this to achieve a significantly reduced environmental impact. Re-used stock was not used at the time due to the uncertainty of material strength and the limited time in which to organise and report material strength testing. Although it was not a key factor in the design the client has intimated that the sculpture could be re-erected as a permanent feature. With the limited time available we were not able to complete research into the provenance of the right size of reclaimed tubes and hence their fatigue resistance.

New foundations were avoided hence no new concrete was needed in the ground, only high strength grout under the new steel baseplates.

## Historical Precedents

Tensegrity structures have a well-documented history with the major instigators in the field being published and quoted in some detail. Russian/Latvian artist Karlis Johanson [2] is credited with being a pioneer in this field. His 'self-tensile constructions' of the 1920s were small scale experiments in pure tension/compression frames. Johanson's work was popularised in the 1960' by Buckminster Fuller [3], who coined the phrase 'tensegrity as a amalgam of 'tensional integrity'.

Buckinster Fuller's student, the artist Kenneth Snelson, was responsible for realising a number of large scale tensegrity works and these were the reference points at the outset of the Lotus Aeroad project. Snelson's Needle [4] and Needle 2 [5] towers are 26 and 30 m high respectively and were structural span lengths that the Lotus team were determined to exceed.

The Schlaich Bergermann and Partner Tower at the Fair of Rostock [6] is 62.3 m tall but this is not a tensegrity structure in the classic sense. Compression members are joined end to end rather than suspended via tension cables and hence this structure, whilst undeniably striking, is discounted from the cannon of tensegrity forms.

## Form

The shape of the structure changed considerably from the artist's original intent of a long, linear tensegrity elevated above ground and supported by rows of columns, to the final solution of the dramatic long span cantilever. That development came about following an intensive period of design investigation and dialogue between Artist and Engineer. As previously discussed, the aim from the outset was to push a long-supported span hence the supports were moved to the rear of the structure. Several different iterations of supports were discussed before the adoption of a tensegrity 'cradle' which held the main body of the work. A small back span was included, not necessarily to balance the structure but for aesthetic purposes.

The Artists were keen that the structure was not perceived as a regular, uniform tube but had a degree of visual 'randomness' or jitter along the length. This was accomplished within the parametric script with the addition of a function which randomly pushed frame nodes away from the perimeter of the tensegrity. In addition to an element of irregularity the both Engineers and Artists were keen that the structure be perceived as tapering in cross section towards the tip. This helped further reduce material and hence mass where it was least needed.

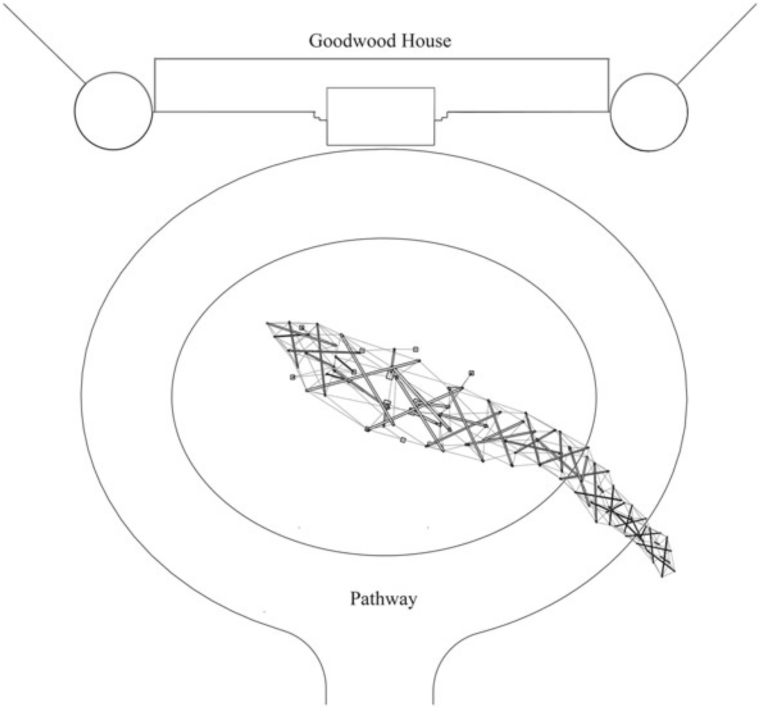


**Fig. 2** Plan view of the sculpture on the site

By entirely generating the geometry within a parametric script multiple iterations of form, size and support location could be tested for visual appearance and material volume within a very constrained timescale. With these tools the project would not have been realised.

**Size**

The structure is 21 m tall from ground to tip of cantilever and 45.5 m long from tip to tip. It is 8.2 m wide at the root of the cantilever above the support cradle and 2.6 m wide at the tip. Plans and elevations are shown below (Figs. 2 and 3).

## 3 Global Structural Design

The global structural form was generated through an iterative development with two sub-operations. In the first operation the desired form was sculpted and stabilised through form finding, then in the second operation the form and the individual members were checked to the code of practice to increase its structural performance, namely by decreasing the movements under self-weight and wind loading

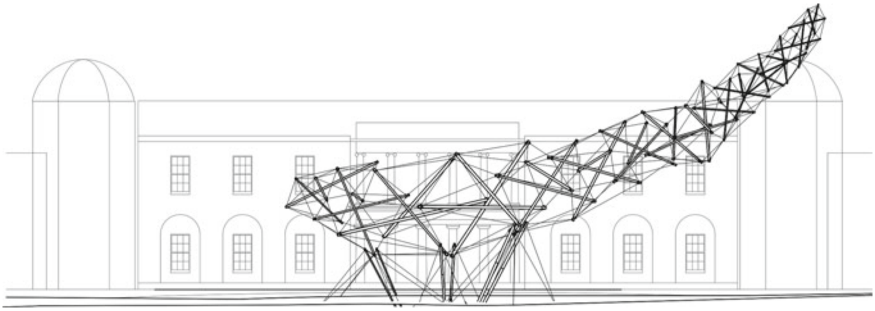

**Fig. 3** Elevation view of the sculpture in front of goodwood house

and providing sufficient strength to prevent collapse. The output of this was then exported to the next stages where the connection design and fabrication information was created.

### Form Finding

The first step in creating the 3D geometry was to use a form finding procedure which could produce a stable tensegrity form which could also be sculpted through the parametric inputs. This allowed the sketches and ideas from the design team meetings to be turned into a 3D "stick" model which could then be shown, discussed, and then modified to slowly mould the form.

This sculpture-like process was scripted into code within Rhino + Grasshopper. This script was made of several steps which gradually built up to create the final topology. The steps are outlined in the list below and in the Fig. 4:

1. Tensegrities can be created from a huge range of different topologies—Marcelo Pars has explored many different forms and topologies [7]. Early in the design process it was decided that Aeroad would be created by combining multiple "tripod" units together to create the cantilever.
2. The tripod units are stacked on top of each other to assemble a chain of prismatic cells.
3. The full length of the tensegrity was created by stacking 15 units together. To add additional stiffness, more cables are added in each cell connecting one end of each strut to another in the next cell along; this was key as it added robustness to the design. Without these the structure would collapse if a single cable was de-tensioned or removed.
4. Once the topology was set, the form was then relaxed using Kangaroo 2 [8] a physics based solving algorithm within Rhino + Grasshopper. This allowed for a stable form to be produced by adding a gravitational force to the element vertices and forcing the cable lengths to shorten—the process of this is very similar to the form finding of cable net structures but with more flexibility in the resulting geometry.

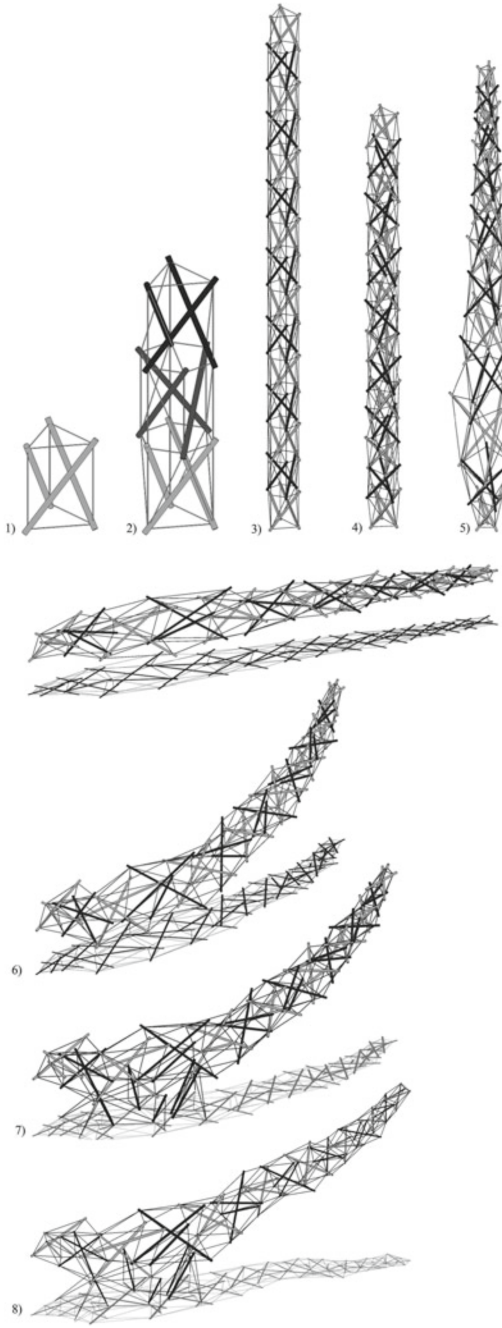


**Fig. 4** Development process of the sculptural form

5. The form was then modified to increase the spatial volume around where the structure would be supported and create a taper towards the tip as well as adding some “noise” to create a more unpredictable or ‘random’ feeling in the sculpture in line with the Artists instructions. This was achieved by using the same Kangaroo 2 algorithm as step 4 but increasing or decreasing the strut and cable lengths in specified regions.
6. The final step in creating the sculpted form was to add the desired curvature of the cantilever. The Kangaroo 2 algorithm was again utilised with additional forces to push and pull the structure into the desired shape.

### Initial Global Structural Analysis

The next stage in the development of the global form development took the stable idealised form from the previous stage and altered the cable lengths to create a stiffer structure which also had sufficient prestress to prevent the cables going slack during regular everyday wind events. The structural elements could also be sized so that they would resist the forces which would flow through them during storm events. To speed up this step, only the wind directions which caused the largest deformations were considered as the other directions resulted in an insignificant impact on the overall impression of the structure.

As previously explained the artists were keen that the structure appeared to ‘float’ off the ground and that the public were deterred from climbing it. A base structure was therefore included in the design which was also to be of a tensegrity form but one which was visibly distinct from the main body of the cantilever—see step 7 on Fig. 4. The base structure is added into the model before the analysis is performed. The base consists of another tensegrity producing a cradle around the four lowest strut ends. These struts and cables are pin supported where they touch the ground meaning that the struts and cables carry only tension and compression forces and ensuring that the entire structure is a pure tensegrity.

To achieve this the structure was analysed using K2Engineering [9, 10]—a parametric plug-in for Rhino-Grasshopper which is an additional set of tools for the Kangaroo 2 solver that accommodates an easy parametric input and output of engineering data such as section sizes and forces. This enables a smooth analysis process for structures which exhibit non-linear behaviour and structures with relatively large movements. These two aspects are essential to capture for tensegrity structures as the cables are non-linear elements because they can only resist tension and exhibit large displacements due to a relatively high flexibility.

Initially the model was analysed with an estimated section for each struct and cable so the dead load and wind load onto each member could be automatically calculated and then fed back into the analysis. The maximum force through each strut and cable could be determined. These forces were then used to calculate the smallest sections that met the strength requirements for each member. Using these new sections the analysis could then be repeated. The process was repeated three times to find the optimal cross section assignment for structural strength—the final output of this process is shown in step 8 of Fig. 4.

Using the results of this the deflected form of the structure under self-weight was then outputted and used for discussions with the design team to assess how it could be changed to better fit to the original aspiration for the form. The reason for doing this was that due to the prestress in the structure and its self-weight it had a different feel to the output from the form finding stage. The shape was then altered by changing the strut and cable lengths in the form finding analysis. This process produced a stable and structural efficient form with a minimum use of material that met the artistic vision.

**Complete Global Structural Analysis**

In the previous stage the most critical aspects of the structural analysis were performed which included the deflection and element stress under self-weight and the wind loads causing the largest lateral movements at the tip of the cantilever. In the final global design sub-process the remaining load combinations were assessed. The reason for excluding these from the second sub-process was to decrease the analysis duration as these simulations had a long running time due to their non-linearity; doing this meant that the design iterations could be performed quicker. This process only required some small increases to the strut and cable sizes due to higher stresses experienced in the new loading conditions and had only a minor impact on the overall form.

Also, in this process the structure was assessed for the high wind strategy. The purpose of the high wind strategy was to reduce the loads the structure would experience in the event of an unusually high wind by attaching two ties at a point roughly halfway along the cantilever when it was predicted that the wind speed would exceed a determined limit. This meant that the sculpture only needed to resist the peak design wind speed while it had additional supports and therefore kept the structure as lightweight as possible.

## 4 Connection Design

The purpose of the connection design script was to deal with all the complexity inherent in the form as the elemental simplicity of the structure required each connection to be bespoke. The core idea behind the connection design was to create the nodes from modular pieces which could be welded together in a repeatable process. To do this every tie type had an associated fin plate design. Therefore, the nine cable types plus the two bar types (which were needed as two elements were shorter than the minimum fabricable cable length) needed 11 fin plate geometry types. The fin plates and their associated welds were designed for the maximum tensile capacity in every feasible direction; this meant that any individual connection likely used more material than was necessary, but it led to a much easier fabrication process and reduced the risk of any confusion between connection geometries. In any case, the fin plates remained partially optimised as cables with lower forces would have a small cable diameter which would in-turn result in a smaller fin plate. The resulting fin plates are shown in Fig. 5.

Although the design of the 502 fin plates could be collected into 11 groups which needed designing, the same could not be done for the 102 strut ends. This is because every strut end had a unique combination of fin plate sizes, forces, and inclination angles of the cables. To overcome this every connection needed to be assessed individually by creating a finite element model for every node.

The connections were designed following the process below and in Fig. 6:

1. The first analysis stage was to analyse the connection with the fin plates attached to the struct section with the forces from global analysis. The cap plate which was already required for architectural and finishing reasons was also included in the model to restrain the end of the tube from warping. If the material was shown

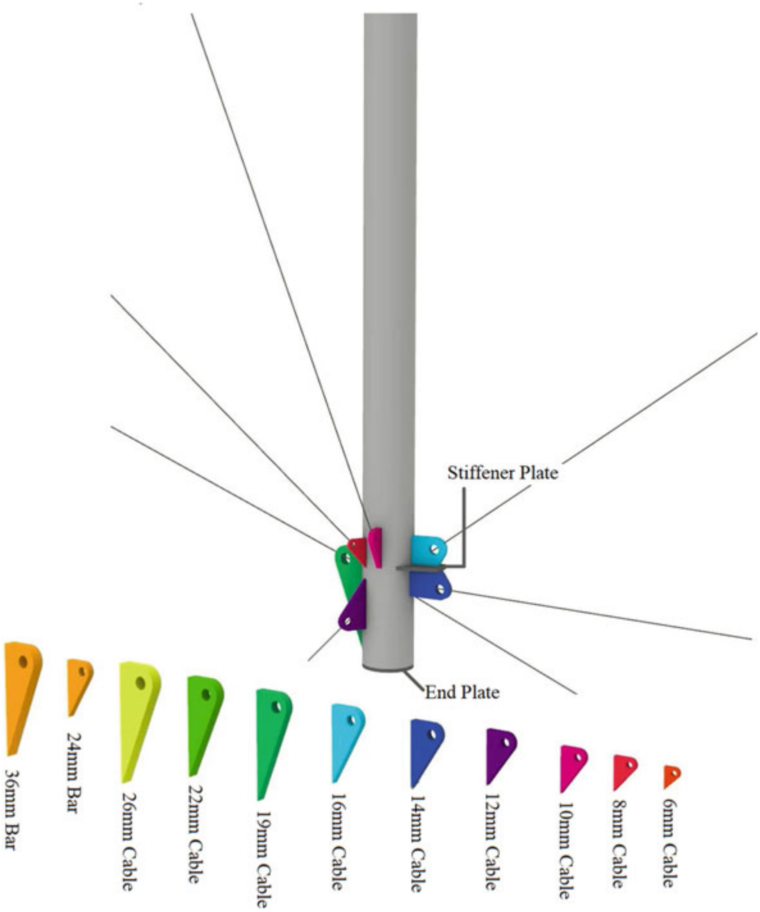


**Fig. 5** Strut end design and tie fin plate types

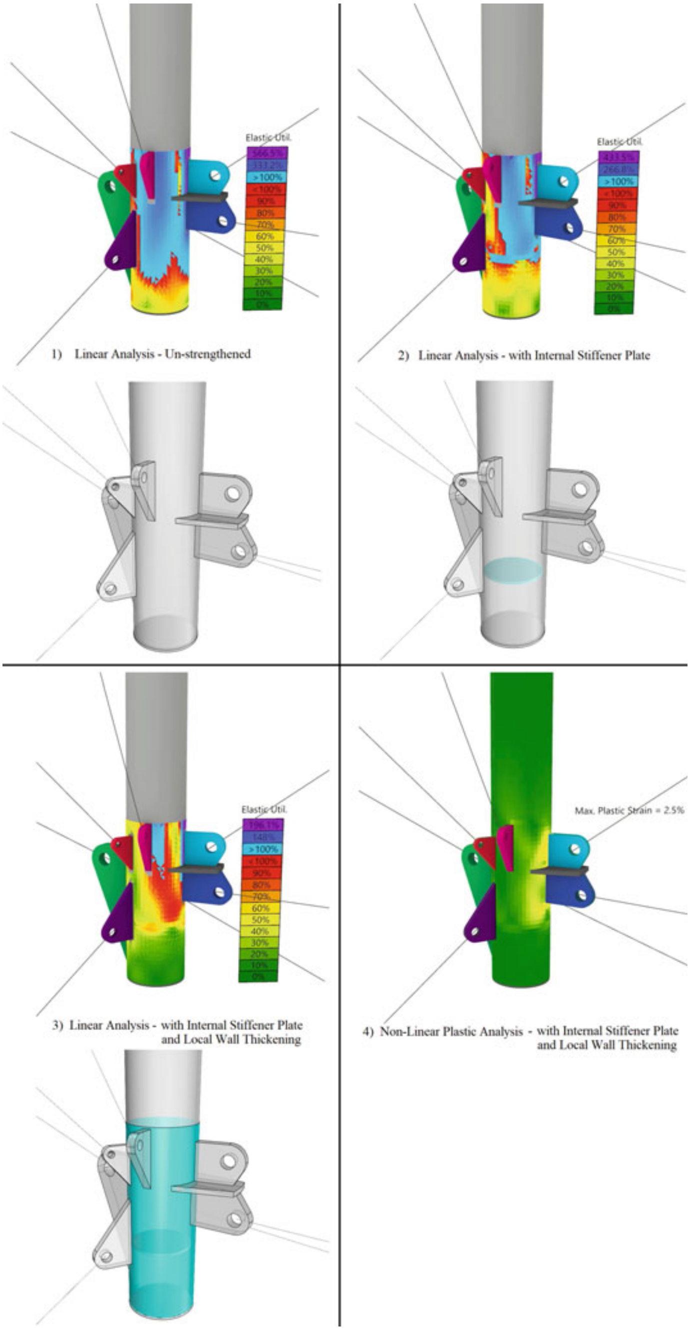


**Fig. 6** Connection design and optimisation process

to be below the yield limit, then the connection was determined to be sufficient, if this was not the case then the design went to the next stage.

2. The second stage was to perform the analysis again but including an internal stiffening disc which the contractor confirmed could be welded within the tube by a distance equal to the inner tube diameter. If the material was still yielding, then the connection went onto the third stage.
3. In this stage the same analysis was performed a third time, but the strut element was locally thickened at the end which could be fabricated by welding a thicker CHS section in the region of the connection. If the material was still yielding in this stage, it went onto the final step.
4. The final analysis used the same geometry as step 3 but analysed it using a non-linear solver which could capture the plastic yielding of the material. Therefore, the areas which saw high local stresses would instead yield distributing the force to the area nearby. To check that the connection did not fail from excessive plastic deformation, the von mises strain was checked against the steel plastic strain limit.

The process allowed for connections to be designed in a way in which the material was only added when and where it was needed. For example, if the connection only needed a small amount of stiffening then the internal disc stiffener would be added, if it needed to be a bit stronger then the tube was thickened but only in the region of the connection. This meant that the structure used as little material as was possible for the fabrication techniques employed. Although it may at first appear that optimising the connection design would have had little effect on the total steel weight in the structure, this is not the case in reality. As the sculpture is only loaded by self-weight and wind (which is highly dependent on the cable and strut diameter) any increase in the connection weight may result in higher force through one or more elements which then also increases the self-weight and wind load. This detrimental cycle occurs as the global structural analysis is heavily optimised for structural mass meaning any changes in the loading change the output results. This is a key challenge to acknowledge when optimising a structure to reach the upper limit of material utilisation, as there is no spare capacity for any increases.

## 5 Fabrication

The previous steps in the design process came together to produce a 3D fabrication model which captured every strut, cable, fin plate, and stiffening element. The final step was to translate this into information the fabricators could use with their typical fabrication techniques to produce each element.

The stainless-steel cables were fabricated by Jakob Rope Systems who produced the cables to the exact lengths required for the structure. The purpose for doing this was to avoid having to adjust the cable lengths in situ as this would have been practically impossible and had been likened to tuning a piano but where tensioning any one string affected the tension in every other string. Obtaining the correct lengths may seem like a simple task at first, however the fabrication model was based on the final geometry once it had been loaded with its self-weight. This meant that the cable lengths in the fabrication model already accounted for some elastic extension. Therefore, so that the cables were the correct length when they arrived on site, Jakob Rope Systems used the loaded cable lengths and load under self-weight to calculate the resting length of the cables.

The struts were fabricated by Littlehampton Welding who ordered the laser cut tube sections and plates and welded them together to form the completed strut elements. The specification of the tube and plate parts were directly outputted from the 3D fabrication model and sent to the cutters. The instructions for how the parts should be assembled to create each strut had to be given via 2D drawings which the fabricators could read from. To achieve this Format Engineers created an automated script which could take the final geometry of each strut and automatically populate it with 2D views that showed every dimension and component tag that made up the struts. This script was created in Grasshopper making use of the EleFront plugin [11] which could access the Rhino 2D drawing tools within grasshopper. Using automation in this way removed hours of tedious CAD drawing work and enabled the complete set of fabrication information to be issued in a much shorter time frame.

## 6 On-Site

The sculpture arrived on site as a complex assembly of 302 unique strut and cable pieces which needed to not only be connected correctly but this also had to be done while the structure was partially unstable and up in the air (Fig. 8). This is akin to an unstable 3D jigsaw puzzle that needs many of the elements to be in place before it stands under its own weight. Prior to the contractor arriving on site, we had already discussed with them an erection sequence which required least temporary support whilst the structure was unstable. That erection sequence was modelled using segments from the global 3D model and illustrated in a 2D drawing format as a series of cantilever assembly steps as well as the 3D model being issued to the Contractor.

Even with a highly detailed set of drawings and a 3D model the erection proved to be a challenge for the contractor. Because cables run in front of and behind tubes at different angles with empty 3D space the structural pattern is difficult to read from a computer screen and even more so from a flat 2D drawing. In order to help with the process, staff from Format Engineers attended site with copies of the 3D model within the augmented reality (AR) software Fologram [12]. This enabled the 3D model to be viewed on the tablet with the real world as a background (see Fig. 7). The correct setting out the elements could be easily compared with the as built arrangement and corrections made before the error had propagated too far. This was an opportunity to show a typical steel fabricator and contractor how AR could be used to streamline and smooth the process of the construction, which they were fascinated by.

**Fig. 7** Comparing the Real and Calculated Position in AR

It's important to note that even with many steps in place errors still crept in and a significant impact of this was that a number of cables remained slack when it had been fully assembled, even though the structure was designed so that every member would be under stress in its final position. Its still unclear what the exact causes of this were but some hypotheses are given below:

- There may have been some slight deviations between the designed base plate locations and the exact locations on site.
- One of the fin plate types was specified with an oversized bolt hole by mistake, but also for tolerance reasons every bolt hole was at least 2 mm larger in diameter than the bolt which was not accounted for in the structural analysis.
- Some of the cables could have been overstressed during assembly which caused them to "bed-in" more than predicted.
- The exact strut lengths, positions of the fin plates, or cable lengths may have been off due to manufacturing tolerance or error.

None the less, the structure was re-analysed including for the slack cables, and it was deemed that it still met the structural criteria as there were extra cables added for robustness. If a tensegrity of this scale and complexity is constructed again in the future special care should be taken to avoid these possible problems, or this issue should be mitigated by allowing the cables to be adjusted on site.

**Fig. 8** The final part of the sculpture being lifted into place. *Photo Credit* The Goodwood Estate Company Limited

## 7 Conclusions

The Lotus Aeroad is a prominent example of a tensegrity structure, its huge length and height belies the amount of material required to span that distance. All the parts of the structure when packed together only take up one half of a standard shipping container. Whilst the elements are simple, being only circular hollow section struts and stainless-steel cables in tension plus small amounts of steel plate at the connection all of which are simple to fabricate the lessons learnt on the Lotus Aerod project are that the structural form finding and the analysis are extremely complex and that the construction of the piece is challenging.

Parametric workflows are crucial to the form finding and the optioneering. Whilst there have many examples of small scale maquettes [7] and demonstration models [13] which have been used to finalise forms a computer based generative environment can cycle through thousands of options, allowing the designer to take the role of 'puppeteer', changing input parameters which may influence the form and getting instant feedback on the appearance. It also enables feedback on structural performance to take a prominent role in the shape making process. This is an important consideration for tensegrity structures where every kg of unwanted material has an over-amplified feedback on the performance. This process within the parametric environment is greatly enriched by the ability to include physics-based solvers within the analysis. The Kangaroo 2 physics solver and the Format Engineers in-house structural analysis toolset built on top of that were critical tools in the development of stable forms and instant feedback on structural performance. A physics based 'kernel' within the design and analysis toolkit was essential as it allowed for the accurate simulation of pre-stress and deflected shape.

Without the parametric based toolset the time scale would not have allowed for any exploration, rigorous design and detailing for practical and safe erection. The latter was particularly important as it was found very early on in the build that the sensible sequence of erection once past the base was not obvious. The 3D model could be modified to reflect different stages of build and check the stability. This and the use of the Fologram augmented reality plug-ins meant that after several false starts the erection was able to proceed at pace and meet the deadline imposed by the festival.

A comparison of different cantilevering structural typologies and their length to weight ratio compared to Lotus Aeroad is outside of the scope of this paper (but would be a useful exercise). However we believe that the tensegrity structure could be demonstrated to be the least volume of material for the span compared to all steel section trusses or other similar more 'conventional' solutions. In this respect the Aeroad was an important step in determining the viability of tensegrity forms in real world scenarios. We now appreciate that although the form can be extremely light and material efficient the analysis of the structure is extremely complex and great care and careful planning is needed in its construction. This type of construction could be suitable for tall and long structures such as communication towers, lightweight enclosures, roofs and bridges, and should be considered more often at the early optioneering stages of design.

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# Data-Driven Performance-Based Generative Design and Digital Fabrication for Industry 4.0: Precedent Work, Current Progress, and Future Prospects

**Ding Wen Bao and Xin Yan**

**Abstract** With the development of computing technology, architectural design has been impacted and changed significantly over the past decade. It led us to rethink the new design methodology and application, such as the data-driven performance-based design method and its relevant digital fabrication for Industry 4.0. The paper explores the theories and practices of "Overall Structure Performance Data-Driven Design" and "Swarm Intelligence-Based Architectural Design" by collecting, reviewing, and analyzing cutting-edge design methodologies and proposes a new algorithm framework that combines performance data with agent-based modelling for design. The paper demonstrates the original process and iterative argument affiliated with the "Multi-Agent-Based Topology Optimization" (MATO) method, as proposed by Bao and Yan in 2021, which has the potential to provide a new path for the future computational design of buildings. Finally, the paper concludes with an analytical study and future expectations for complex bionic morphology digital fabrication generated by the related methodology above.

**Keywords** Generative design · Swarm intelligence · Topological optimization · Robotic fabrication · Data-driven performance · Additive manufacturing

**United Nations' Sustainable Development Goals** 9. Industry, Innovation and Infrastructure · 11. Sustainable Cities and Communities · 12. Responsible Consumption and Production

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_46

## 1 Introduction

In modern engineering, computer-aided design techniques such as Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) have become essential tools for analyzing and evaluating architectural designs with accurate and rapid data feedback. Through quantitative analysis using simulation calculation technology, changes to each design in the architectural design process caused by structural, sound, light, heat, wind, and other performance factors can be timely and accurately assessed. Many software programs based on these computational techniques play significant roles in designing and implementing complex architectural projects. However, most of these programs are used for analyzing and correcting completed building layouts, and their performance data is primarily utilized for analyzing and processing existing models.

On the other hand, with the development of digital architecture theory, biomorphic model-based form-finding technology is gradually moving from pioneering design to practice. Swarm Intelligence algorithms are increasingly being used by architects and researchers in architectural design due to their simple logical architecture, excellent portability, and wide application prospects. Swarm Intelligence is a formal simulation logic of complexity that originates from flocks of birds, swarms of bugs, human social grids, and urban operational systems [1]. By applying the behavioural logic of organisms in nature to buildings, architects can enable intelligent buildings to exhibit biological and environmental response strategies. However, the application of swarm intelligence algorithms to architectural design is still in the experimental stage, and this dynamic design logic often fails to converge in a final design due to the lack of data feedback from the building itself and its environment.

In this context, the research of applying the performance data of the building on the multi-agents to realize the performance data-driven bionic computational architectural design will be helpful to break through the above dilemma and provide a new way of thinking for future architectural design. Bionic computational design based on performance data is becoming increasingly popular, and emerging architects are introducing multiple computer numerical control (CNC) or robotic construction tools to realize these designs and using building information modelling systems to manage and manufacture building prefabrication. Computational design methods and advanced manufacturing processes will gradually update the paradigm of architectural design and more accurately use data to enhance the performance of future buildings.

## 2 Structural Performance Data-Driven Design

### *2.1 Architectural Computational Modeling and Performance Data Feedback*

Since the 1960s, computer-aided simulation methods such as finite element methods and computational fluid dynamics have gradually been applied in many engineering fields. We can establish an interrelated path between complex building geometry models and building performance analysis to achieve quantitative feedback on building performance through computer graphics and related scientific theories. The overall logic of this workflow can be divided into three steps: model discretization, setting input parameters, and computational simulation analysis.

First, after the architect obtains a conceptual geometric model based on the design intent, computer graphics technology is used to discretize the complex form into more regular elements to obtain a computational analysis model; this computational model shares the same nodes between neighbour elements to transfer performance data. For different analysis objects, different types of elements can be selected for model discretization: one-dimensional truss elements subject to axial forces only (corresponding to a truss structural system) and beam units considering bending moments (corresponding to the beam-column structural system), while more complex 3D models, there are shell elements overlaid on the surface and solid elements filled inside the continuum. Then, only the model property coefficients (material properties) and environmental condition parameters (boundary conditions) need to be set according to the actual situation to enter the computational analysis simulation process. Through discretization, the analytical difficulties caused by the complex geometric model can be replaced by a large number of relatively simple theoretical numerical calculations, and the architect can then modify the solution through performance data feedback until the requirements are met.

This workflow, shown in Fig. 1, essentially follows the paradigm of "post-rationalized geometries" [2], which involves optimizing an existing free-form design into a reasonable alternative model. The advantage of this approach is that each profession is less dependent on the others and can work independently. However, this independence can result in a lot of repetitive cycles of revision during the architectural design process. At the same time, the linear workflow inevitably overlooks many possibilities of morphological solutions due to the lack of overall control over the performance data of all aspects of the building.

With the development of digital architecture theories and technologies, some approaches to building morphology generation aimed at "pre-rationalized geometries" [2] are gaining the attention of architects and scholars. These methods use performance data as the basis and change the above one-way linear modification mode from "geometric model-performance analysis-manual modification" to "geometric model-performance analysis-computer reconstruction" through relevant theoretical and procedural algorithms. The "geometric model-performance analysis-computer reconstruction" approach realizes efficient linkage between building form

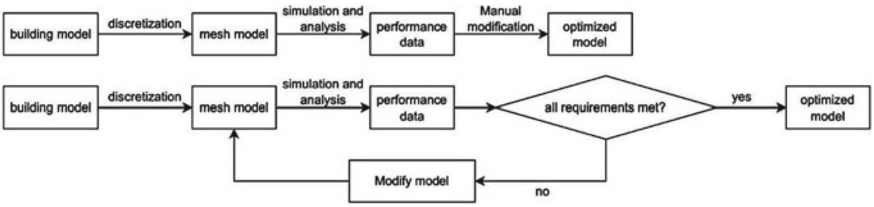



**Fig. 1** Comparison between workflows of "Post-rationalized Geometries" and "Pre-rationalized Geometries"

revision and building performance evaluation, making it easier to find the "preferred solution" of building form that can meet various needs simultaneously.

### 2.2 Performance Data-Driven Architectural Design and Form-Finding

As one of the most significant aspects of architecture that affect morphology, the method of form finding has long been of great interest to architects and structural engineers. In the past two decades, more and more researchers have started to focus on quantitative structural form-finding algorithms based on finite element analysis. Compared to the qualitative methods represented by graphical statics, these methods based on performance data can not only consider the real material resistance and damage characteristics but also facilitate the breakthrough of the existing structural system to find a new and efficient structure for a specific situation.

The Evolutionary Structural Optimization (ESO) [3] and Bi-directional Evolutionary Structural Optimization (BESO) [4], proposed and developed by Mike Xie's team at RMIT University, have been used to develop a new approach to structural optimization. ESO and BESO can determine whether structural elements should be removed or added at each iteration based on the relative magnitude of the sensitivity numbers, such as strain energy density, calculated from the structural performance data of the model elements. The BESO method can be applied to the structural analysis of completed buildings, such as the analysis of the tree structure of Gaudi's Sagrada Familia [5] and the analysis of the shell structure of Palazzetto dello Sport of Rome [6] (Fig. 2).

Through the BESO algorithm and its plug-in Ameba, architects and designers can introduce real mechanical behaviours into the scheme design to generate innovative, efficient and organic architectural forms, such as the new structural designs for traditional Chinese architecture from DigitalFUTURES 2019 workshops supervised by authors (Fig. 3). In practical projects, architects can even apply gravity and wind load on floor slabs, façade systems and central cores to create various types of leaning towers by authors (Fig. 4).

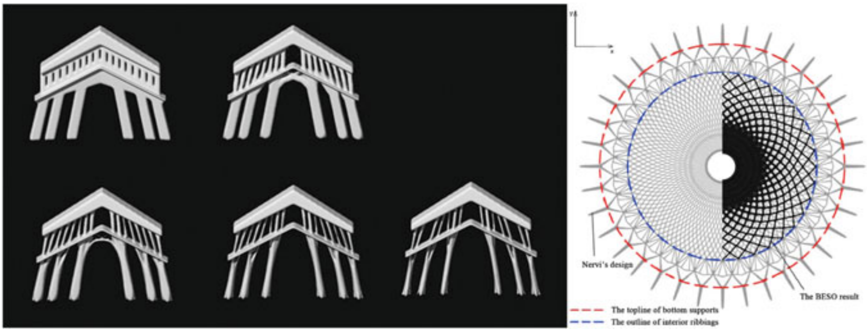
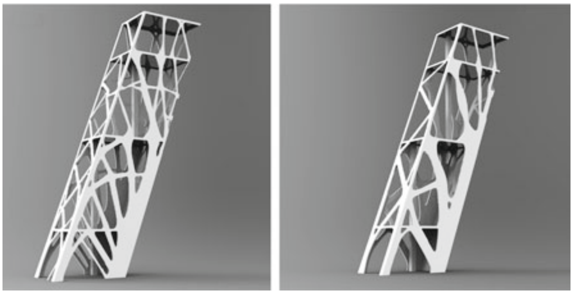



**Fig. 2** Analysis of Sagrada Familia Façade [Left] and Dome of Palazzetto dello Sport [Right]

**Fig. 3** New structural designs for traditional Chinese architecture

**Fig. 4** Diverse structural designs for leaning towers using the BESO method by Nic Bao, Xin Yan and Yulin Xiong



The topology-optimized structure, driven by performance data, meets the requirements of complex working conditions, which is incomparable to qualitative form-finding algorithms. The Akutagawa River Side project in Takatsuki City, completed in 2004, was the first practical project to apply the ESO method for structural optimization of shape finding. Moreover, a renowned Japanese engineer, Mutsuro Sasaki, has collaborated with architects such as Toyo Ito, SANAA, and Arata Isozaki to create innovative buildings using his original Sensitivity Analysis Method and Extended ESO Method. The Sensitivity Analysis Method is suitable for adjusting curved surfaces in architectural designs to meet structural rationality requirements, as seen in the Kitagata Community Centre (Fig. 5), Kakamigahara Crematorium (Fig. 6), and Rolex Learning Center (Fig. 7). The Extended ESO Method can automatically generate reasonable structures under predefined conditions, with a process similar to standard structural topology optimization, as demonstrated in the Qatar National Convention Center (Fig. 8) [7]

In addition to the large-span buildings described above, topology optimization techniques can still be used to drive high-rise building design. Unlike the large-span buildings above, which mainly deal with gravity, in high-rise building design, the main problem that the building structure has to deal with comes from the lateral loads caused by the wind flow at high altitudes. However, for the performance data-driven design approach, wind load changes in the load conditions in the computational

**Fig. 5** Kitagata community centre

**Fig. 6** Kakamigahara crematorium

**Fig. 7** Rolex learning center

**Fig. 8** Qatar national convention center

model, which certainly helps to simplify the process of designing the form and structure of high buildings. For example, in the CITIC Financial Center project in Shenzhen, the engineers obtained the optimal arrangement of diagonal intersecting grids of different orders through topology optimization and modified them based on the requirements of building lighting and construction to obtain the final results (Fig. 9) [8]. Zaha Hadid Architects has also conducted a data-based analysis to find the shape of a super-tall building structure, such as the One Thousand Museum condominium in Miami (Fig. 10).

**Fig. 9** CITIC financial center Shenzhen

**Fig. 10** One Thousand Museum condos Miami

### *2.3 Performance Data-Driven Optimization of Building Components*

Besides providing a holistic morphological concept for buildings, performance data-driven generative design methods continue to play important roles at smaller scale components. In real-world projects, local building components often need to be as material efficient or aesthetically simple as possible while meeting certain structural performance requirements. In the face of practical needs, performance analysis data can be used to meet specific functional requirements and individual choices more precisely. In recent years, beamless floor slabs have been a popular research topic in lightweight structures. Through finite element analysis, researchers can easily obtain the force distribution of the floor slab and determine the reinforcing part of the floor slab through topology optimization or stress line extraction. For example, the Block Research Group (BRG) and Digital Building Technology (DBT) at ETH Zurich used principal stress lines obtained from finite element analysis to determine the location and morphology of the reinforcing ribs of the floor slab [9, 10]. The XtreeE research group has used topology optimization to design the performance of columns [11]. The Smart Node, a collaboration between RMIT University and the Chinese University of Hong Kong, optimizes the connection nodes in the pavilion's wooden structure to meet mechanical requirements while satisfying arbitrary angular connections (Fig. 11) [12].

In addition, RMIT Centre for Innovative Structures and Materials (CISM), led by Prof Mike Xie, conducted pioneering work on the theoretical development and practical application of various structural optimization techniques. CISM also optimized floor slabs, partition walls, columns and bridges using topology optimization techniques [13–15] (Fig. 12, 13, 14 and 15).

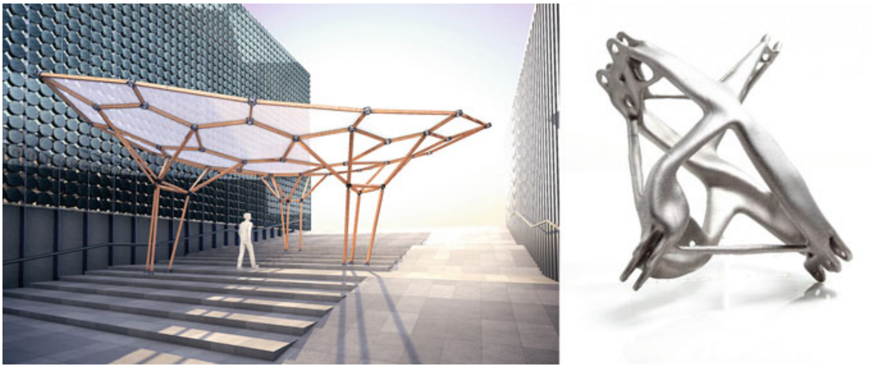


**Fig. 11** Smart node pavilion

**Fig. 12** Topologically optimized floor slab by Jiaming Ma, Mohamed Gomma, Nic Bao and Mike Xie

# 3 Swarm Intelligence-Based Architectural Design

## *3.1 Biomimetic Morphogenesis Design Based on Swarm Intelligence*

The emergence of complexity theory in the last 40 years has significantly impacted on our understanding of form generation. The conceptualization of form has shifted from the macro level to a focus on the operation of the underlying complex systems of

**Fig. 13** Topologically optimized partition wall by Nic Bao, Xin Yan and Mike Xie

**Fig. 14** Tree-like columns and pavilion by Nic Bao, Xin Yan and Mike Xie

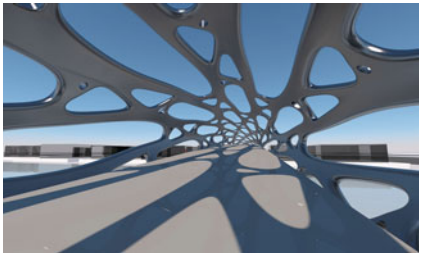


**Fig. 15** Topologically optimized FootBridge by Mike Xie and Nic Bao

form generation. Swarm Intelligence algorithms, which create multi-agent systems based on rules abstracted from the biological world, offer architects a more dynamic and comprehensive approach to studying the self-organized form generation of architectural structures.

### *3.2 Swarm Intelligence in Architectural Design*

Architecture has long been interested in natural and biomorphic simulation. Within the last decade, architectural firms such as Kokkugia and Biothing have used multi-agent algorithms to explore the morphogenetic potential of swarm logic to generate new architectural forms. Swarm-based design research has emerged at various academic institutions, including Columbia University (GSAPP), the Architectural Association School (AA), University College London (UCL Bartlett), the Southern California Institute of Architecture (Sci-Arc), the University of Pennsylvania (UPenn), and the Royal Melbourne Institute of Technology (RMIT). Pioneering architects such as Alisa Andrasek, Roland Snooks, Robert Stuart-Smith, and Marc Fornes have advanced the computational morphology of swarm intelligence and multi-agent algorithms through their laboratory design practices. Roland Snooks, in particular, has focused on formal research on behavioural design and the use of algorithmic computing through multi-agent algorithms, which closely links algorithmic design, machine learning, robotic fabrication and advanced materials to generate intricate architectural forms (Fig. 16). He has also proposed using finite element structural analysis to extend the structural agent system and establishing a global evaluation system for the whole structure by assigning structural behaviours to multi-agents and getting real-time feedback. These ideas have inspired the author's exploration of swarm intelligent computational design methods driven by structural performance data [16].

**Fig. 16** Kazakhstan Symbol using the multi-agent algorithm by Roland Snooks

# 4 Bioinspired Generative Design Approach Based on Structural Performance

## 4.1 Framework of New Design Methodology

As an emerging digital architectural design method, performance data-driven design derives from the scientific and rational analysis of architectural design concerns such as structure, sound, light, heat, and wind, giving buildings material rationality with their objective and precise characteristics. Meanwhile, swarm intelligent design simulates the social behaviour of biological groups in nature to produce complex formal functions, adding a perceptual biological perception to architectural design. By combining the advantages of both approaches, we propose a new performance data-driven bionic swarm computational design approach [17]. This approach consists of two abstract data layers: the Finite Elemental Analysis Layer (FEA layer) and the Multi-agent System Layer (MAS layer). As shown in Fig. 17, this algorithmic architecture involves a typical building morphology model located in the FEA layer, presented as a mesh model. Due to its natural discrete cell structure, it can be easily imported into various engineering analysis systems to obtain performance data. Meanwhile, multi-agents are introduced into the MAS layer to generate new forms through interactions based on vector-based behaviour rules. The multi-agent system can be linked to the architectural mesh model using the Material Interpolation Scheme [18] and the Marching cube algorithm [19], and the behaviour vectors of the multi-agents are computed based on performance data from the mesh model and various constraints from multidisciplinary sources. Thus, the closed-loop evolutionary logic of "computing performance data from the mesh model, influencing the behaviour of the agents from the performance data, and mapping the agents to new building forms" is achieved.

By applying the above algorithmic framework, architects can use performance data to drive swarm intelligence to generate and optimize building forms. The benefits are twofold: first, the simple vectorized behaviour rules of the swarm intelligence facilitate different users to develop behaviour rules for the agent based on various functional requirements and constraints in order to avoid other conflicts and defects such as poor ventilation, difficult evacuation, and pipe collisions when optimizing the building form performance; second, the complex role of the swarm intelligence allows the building form to evolve in a variety of directions, thus generating various optimized building forms, and avoiding the problem of forming monotonous unique solutions under the traditional engineering optimization form-finding method.

## 4.2 Data-Driven Performance-Based Generative Design

Applying the above algorithmic framework, we have developed a multi-agent-based topology optimization (MATO) method that applies the algorithmic framework

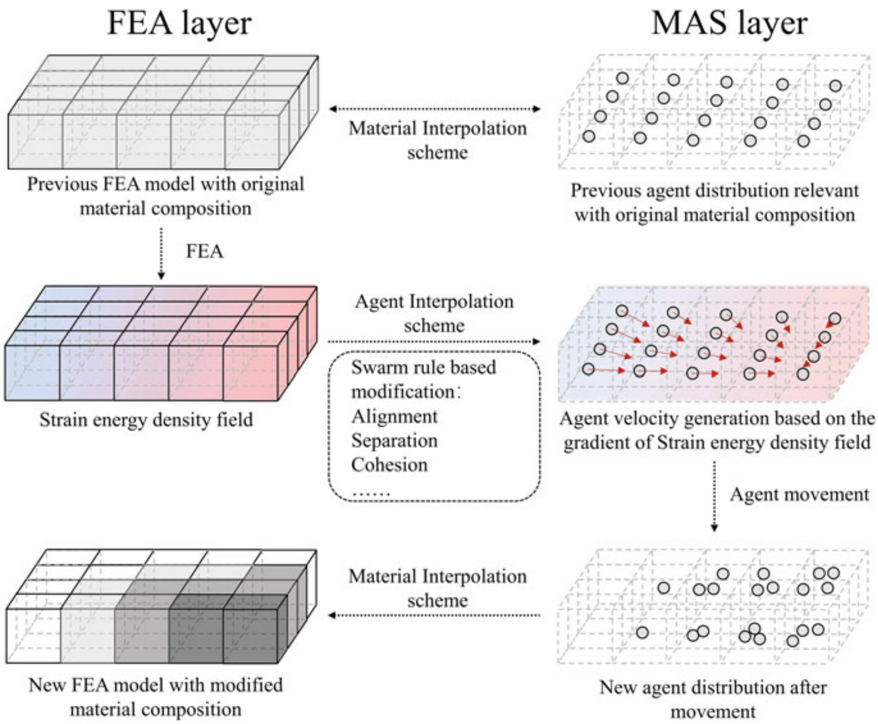



**Fig. 17** The diagram of the performance data-driven bionic cluster swarm computational design

described above to exploit the respective advantages of performance data-driven design and swarm intelligence algorithms. With this approach, swarm intelligence is structure-aware and can simultaneously generate diverse topology-optimized forms with high structural performance. We attempt to combine the local self-organizational generation methods of swarm computing with recursive global structure analysis, providing an open framework for architects to program multi-agents based on their intent and behaviour. This enables collaboration between multiple disciplines, integrating local and global awareness in the design process.

The MATO method establishes a correspondence between the mesh model and the agent model through a material interpolation model, allowing the mesh model to change easily with the movement of multi-agents in evolutionary iterations, providing a model basis for the next structural performance calculation. Within this context, an increase in the number of agents within the range of a mesh element enhances the material properties of that element and vice versa. The structural performance data obtained based on the finite element technique is applied to each agent through an interpolation function, generating their gradient vector in the strain energy density field as the initial velocity of the agent. These initial velocities move the multi-agents toward high-strain energy density, enabling material convergence and structural optimization.

Meanwhile, the three most basic behavioural rules of swarm intelligence species, namely separation, alignment, and cohesion, are used to modify the velocity of the agents, as shown in Fig. 18. The Alignment Rule is a local smoothing method that can adjust the movement direction of an agent according to the average movement direction of its neighbours to achieve local coordination. The Cohesion Rule can guide the agent to consider the global optimal position movement in the global scope, avoiding the problem of material dispersion, which often occurs in structural optimization problems. After experiments, the MATO method has been shown to have significant advantages over traditional topological optimization methods in generating diverse optimized structures, as 2D results shown in Fig. 19 and 3D results are shown in Fig. 20.

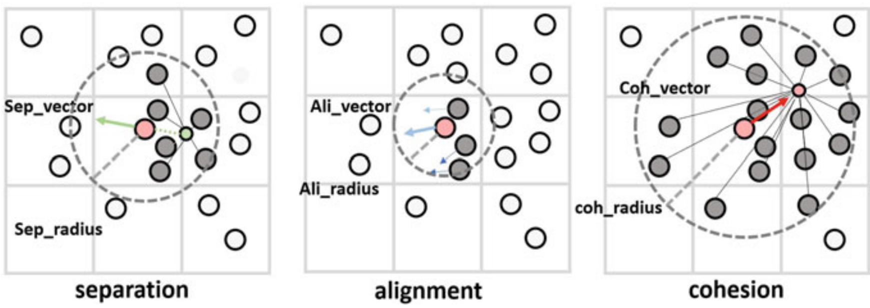



**Fig. 18** Three behavioural rules of swarm agents

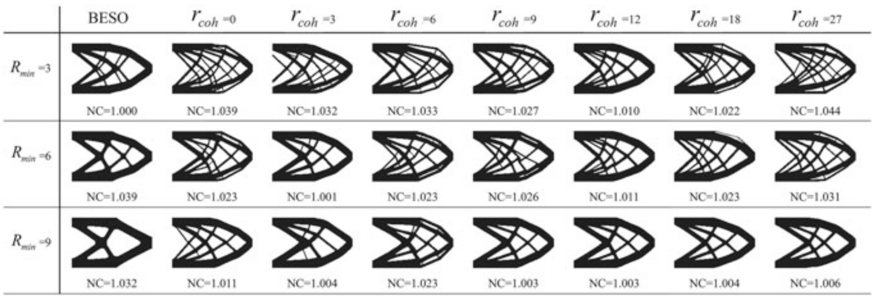



**Fig. 19** Diverse optimized layouts by MATO method

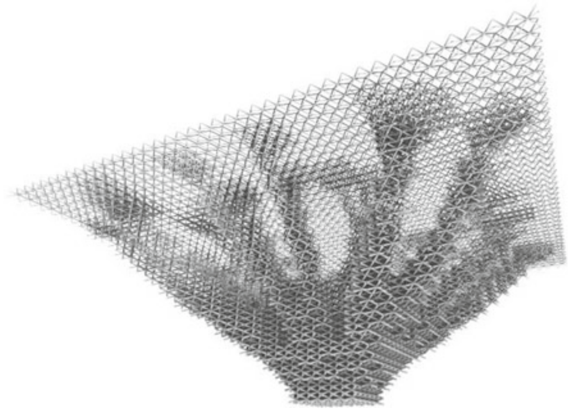


**Fig. 20** Space grid structure based on data by MATO

# 5 Advanced Digital Fabrication

## *5.1 Large-Scale Robotic 3D Printing Technology*

With the arrival of Industry 4.0, robotic construction has become increasingly important in the development of today's construction industry. Factories can manufacture non-monolithic prefabricated building components cost-effectively in mass production, thanks to digital processing simulations based on industrial robots and customized tool designs for different construction materials [20]. Internationally renowned architecture schools and pioneering academic architects, such as the Institute for Computational Design (ICD) led by Achim Menges at the University of Stuttgart, the Gramazio Kohler Research and Robotic Fabrication Lab chaired by Fabio Gramazio and Matthias Kohler at ETH Zurich, Autonomous Manufacturing Lab directed by Robert Stuart-Smith at the Weitzman School of Design, University of Pennsylvania, and the Tectonic Formation Lab founded by Roland Snooks at the School of Architecture and Urban Design at RMIT University in Australia, are all pioneers in this field.

To realize the bionic swarm intelligence designed forms, Roland Snooks has equipped the Tectonic Formation Lab with a variety of robotic fabrication technologies and is currently focusing on 3D printing research in polymers, ceramics, and metals for the additive manufacturing of large-scale custom architectural components (Fig. 21). The lab is dedicated to exploring cutting-edge pilot projects and large-scale prototype development to establish the potential of its research architecture and extend the meaning of its architectural practice. Some examples of their work include the designing and fabricating of an interior partition wall for Monash University's SensiLab and the "Floe" art installation for the NGV Triennial, which were both created using their innovative methods (Fig. 22).

**Fig. 21** Robotic fabrications by RMIT Architecture | Tectonic Formation Lab

**Fig. 22** "Floe" art installation at National Gallery of Victoria (NGV) by Roland Snooks

## 5.2 *Augmented Reality Holographic Digital Construction Technology*

Fologram, a technology company founded by Gwyllim Jahn and Cameron Newnham, faculty members from RMIT School of Architecture and Urban Design, has taken the world by storm in the last two years with its augmented reality holographic digital construction technology. This program overlays digital guidance in the workspace to assist in the construction of complex projects requiring a series of measurements, verification, and targeted management, providing step-by-step guidance for masonry work during construction (Fig. 23). Architects and builders have already used Fologram to realize complex structures and art installations, such as the "Steampunk" pavilion at the 5th Tallinn Architecture Biennial in Estonia (Fig. 24), which was also designed with swarm intelligence algorithms, and the live construction of the "Floe" art installation at the National Gallery of Victoria.

**Fig. 23** AR-assisted construction using Fologram

**Fig. 24** Steampunk Pavilion by Gwyllim Jahn, Cameron Newnham, Soomeen Hahm Design, and Igor Pantic

# 6 Conclusion

In summary, both performance data-driven design and bionic swarm optimization morphogenesis are digital technologies that have gradually improved with the development of computing technology. Over the past decade, these cutting-edge theories have evolved into project practices. Based on the review and development of these two emerging generative design methodologies, this paper also proposes a performance data-driven computational design method based on bionic swarm optimization, which provides a new path for the future computational design of buildings by deeply combining the two. In this approach, rational performance simulation data is applied to the behaviour of swarm intelligence in the form of vectors. Together with other perceptual human control factors, this data can be derived into various "preferred solutions" of building forms. This process realizes a two-way cycle of "geometric model-performance analysis-computer reconstruction," which is an efficient, open computational design framework that integrates rational analysis and perceptual generation.

At the same time, the complex and variable building forms generated by this method can be easily realized by introducing advanced manufacturing in construction. The rich and comprehensive data information about building performance obtained during the generation process will play a crucial role in the subsequent management of the building information system and the manufacturing process of building prefabricated parts. This data will ensure that robotic construction and augmented reality holographic digital technologies can be successfully implemented in the subsequent construction industry. The complete data chain from computational design to the advanced manufacturing process will gradually update the paradigm of architectural design, thus empowering future buildings to be more precise and rational.

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# Parameterization and Mechanical Behavior of Multi-block Columns

**D. Foti, M. Diaferio, V. Vacca, M. F. Sabbà, and A. La Scala**

**Abstract** The research aims at studying the mechanical behavior of a monumental structure to preserve the historical-architectural heritage as recommended by the Sustainable Development Goal 11.4 to "strengthen efforts to protect and safeguard the world's cultural and natural heritage". This research focuses on multi-drums classical columns, a very common typology in the architecture of ancient Mediterranean civilizations. These columns are made of stone drums of considerable size compared to its entirety, thus, their resistance to vertical and horizontal loads is entrusted to simple support and friction between the drums. So, the present paper proposes a parametric study of the geometrical characteristics, mechanical properties and interactions of the blocks with the aim of describing their influence on the dynamical response of columns, highlighting fundamental aspects concerning their vulnerability. The analysis is performed by means of the Distinct Elements Method (DEM). Many numerical analyses have been conducted to investigate the effects of parameters that influence the dynamic behavior of the examined structural elements and identifying their stability domains.

**Keywords** Parametric structural analysis · Cultural heritage conservation · Multi-drum column · D.E.M. · Rocking

**United Nations' Sustainable Development Goals** Goal 11 Make cities and human settlements inclusive, safe, resilient and sustainable

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M. Barberio et al. (eds.), *Architecture and Design for Industry 4.0*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-3-031-36922-3_47

# 1 Introduction

## *1.1 The State of Art*

Reality and what surrounds us is often presented to our eyes as something extremely complicated and sometimes difficult to understand; this is especially true in the field of scientific research, but it also undoubtedly extends to the professional field of engineering and architecture.

One of the key objectives to achieve is therefore to provide a simplified, yet accurate, representation of reality, to define a mathematical model which allows us to fully estimate the behavior of the object under study. To do this, the current state of the art envisages the use of the so-called discontinuous element modelling, which consists, after simplifying the geometry as much as possible, in subdividing the object to be investigated into elementary parts (i.e. mesh).

This chapter is intended to provide a general overview of the state of the art on the numerical modelling approaches in the structural field and, in particular, to refer to the Discrete Element modelling Method (DEM). The main aim is to discuss the applicability of such approach to structures with a cultural, historical, and architectural value, and that for cultural, social, and economic reasons must be preserved. The present study wants to highlight some peculiarities of their response to loads, which must be considered by the decision makers. The application of this methodology to a series of real case studies will also be shown, having as object of investigation the stability analysis of some stone columns.

There are two different approaches to numerically model a 3D structure: the Finite Element Method (FEM) and DEM. Both methods aim to provide approximate solutions to problems described by systems of partial differential equations, reducing the latter to simpler systems of algebraic equations that can be solved by means of well-known algorithms.

The FE method can be easy applied to materials that are homogeneous and isotropic or that can be approximated to these behaviors (like concrete), while it encounters some difficulties when representing and solving problems involving more complex media with varying characteristics.

Therefore, if modelling of heterogeneous solids with purely orthotropic behavior is required, such as masonry, the FE method requires the use of appropriate interface elements, i.e. it is necessary to model the mortar joints, so that the masonry blocks can be considered as a continuous and homogeneous medium, surrounded by these joints.

From a design point of view, the FE method is the most spread and used in modern calculation software for the design of structures, as it enables these software to solve the problem of estimating stress and deformation states induced by several load conditions and that, due to the complexity of the problem and the number of unknowns, cannot be solved by means of closed form analytical solutions.

Thanks to its versatility, this approach has been widely used since the early' 70 s in various engineering problems, from fluid dynamics to electromagnetism, as well as structural and geotechnical calculations, and it is still the most widely used method for numerical simulation and problem solving in such fields.

DEM, on the other hand, is a numerical modelling method that can represent systems composed by several distinct bodies maintaining their geometric boundaries, in such a way as to leave the separation between the elements clearly defined and, thus, by modelling their interaction.

In the case of masonry, for example, the DE method allows the masonry texture to be represented as a set of distinct blocks, thus enabling the researcher or designer to precisely analyze the behavior of the individual blocks, modelling the mortar joints as contact surfaces.

The evident geometric and constitutive non-linearity of a medium such as masonry requires a precise description of the possible responses in structural terms, including those related to local mechanisms, such as sliding phenomena along the joints or effective separation of the blocks themselves. To investigate these problems, the DE approach appears particularly reliable, as it operates by considering all the local mechanisms and adapts the analysis to the consequent variation in the initial geometric configuration.

From an application point of view, this method is usually favored in the analysis of structural collapses, by means of pseudo-static or dynamic processes. An example is the use of DEM software in the analysis of historical load-bearing masonry buildings for the compilation of the so-called "Seismic Vulnerability Sheets".

Historically, the DE method developed in parallel with FEM, initially for geotechnical applications; it was used for the analysis of slidings in hard, compact rock beds, where the failure mechanisms are defined by the discontinuities in the rock.

The representation of the object in question as a set of blocks, therefore, represents the fundamental characteristic of the DE method, contrary to what happens in FE models, where the starting point is the representation of a continuous body.

The first to propose the possibility of a numerical approach to the resolution of this problem was Cundall in 1971 [1, 2]; the need to update consequently to the sliding positions of the blocks, led Cundall to develop the method starting from the integration of the equations of motion of the blocks themselves, thus obtaining the possibility of considering large displacements. The further innovation was that this method was able to consider viscous damping coefficients even in static analysis, just as in approximate dynamic methods.

As far as masonry structures are concerned, the DE method is an extension, to complex systems, of the analytical techniques used since the early XIX century for the analysis at the collapse of such constructions [3].

In conclusion, the advantage given by DE method for the analysis of historical buildings in natural stone or masonry blocks, is mainly due to the best approximation of non-linearities and geometric material; secondly, it allows for the modelling and analysis of structures of considerable size, without suffering too much from an increase in computation times, contrary to what happens in the classic FE models.

### 1.2 DE Method

Many different DE methods can be found in the technical literature [4, 5]; it is, however, possible to identify some common features:

- DE models start basically from the hypothesis that the blocks are rigid, and that the deformability depends on the mortar joints; it should be noted, however, that recent developments in technology have led to deformable block models.
- The blocks interact by means of edge-to-edge contact points or groups, but not through a uniform contact surface; this prevents uniform redistribution of the stresses over the entire block surface.
- Thanks to the possibility of considering a complete separation of the blocks, DEM analysis can be utilized in the field of large displacements.
- "Time-stepping" algorithms are used in DE models to solve quasi-static problems.

Given the importance of the boundary conditions in solving the static and/or dynamic problems for DE modelling methods, it is obvious that a correct representation of the contact surfaces between the individual blocks is of fundamental importance for an accurate calculus.

In many DE models, the representation of the contact surfaces is done by synthetizing the surface into a cloud of points, called 'contact' points, in which the contact forces are applied, the latter ones depend on the displacements of the blocks at the corresponding point.

Although idealized as a series of points, the need to still apply the classical constitutive laws to each joint (i.e. in terms of relative stresses and displacements) has led to the need of defining the area of the contact surface represented by the contact point. Thus, the properties associated to each contact point depend on the area to which it is related.

Regarding the numerical analysis, it is assumed that velocities and accelerations are constant during each time step. DE methodology is based on the concept that this time step is sufficiently small, so that no variation can propagate between the discrete elements during the calculation step. For this purpose, very small-time intervals of about $10^{-6}$ s are considered, so that in the simulated system, collisions and contacts between bodies can be satisfactorily captured.

In the present paper, DEM was applied by adopting the software 3DEC [6]. 3DEC is a three-dimensional numerical software based on the discrete element method for discontinuous modelling.

The basis of this software is the numerical formulation widely tested and used in the two-dimensional version, UDEC [6].

3DEC is based on a Lagrangian calculus scheme that is particularly suitable for modelling large displacements and deformations in a system consisting of blocks.

The features of 3DEC can be summarized as follows:

- The analyzed structure can be modelled as a 3D assembly of rigid or deformable blocks;

- The discontinuities due to mortar joints are modelled through the contact points located between the boundaries of distinct blocks;
- The continuous or discontinuous behavior of the joints is generated on a statistical basis;
- 3DEC employs a time-explicit solution algorithm that accommodates both large displacements and rotations, and allows calculations in the time domain;
- 3DEC is programmable using the FISH language (short for FLACish, FISH was originally developed for two-dimensional continuous finite difference software, FLAC [6]). With the FISH programming language, it is possible to write your own functions to expand the possibilities provided to the user by the program to meet specific needs.

## 2 Dynamic Impulsive Analysis of Stone Columns

The monumental patrimony of Italy and other Countries in the South of Europe has a deep-rooted constructive tradition which adopted the stone as its characteristic element of construction; it is in fact since ancient times that it is possible to find the presence of constructions and monuments made of local stone, which differ deeply according to the construction materials available in each area, for example, in the South of Italy the “Trani” marble, the “Lecce carparo”, etc. are well known.

The abundance of quarries has therefore allowed the spread of stone structures that have come to the present day, but it should be noted that the characteristics of such structures are quite different from each other and a unique general approach to their study is still a challenge. In fact, masonry buildings (including those made of bricks) are characterized by a greater variety of structural elements differently from the modern structural schemes that adopts three structural elements: beams, pillars and plates.

It is evident that the urge to create majestic works using materials that do not provide any tensile strength, has brought the ingenuity of the master builders of the time to extreme levels, and this is the reason why today we can find in this type of constructions the presence of many structural elements: vaults (at least dozen different types are recognized), arches (characterized by several different geometrical configurations) and columns.

In particular, the present chapter deals with the study of the structural behavior of the latter.

The Countries which stand in the Mediterranean area are, as previously said, traditionally linked to the use of stone as a fundamental material for buildings; already in prehistoric times to which belong religious monuments such as the dolmen.

Moreover, in the subsequent periods, the inclusion of several Countries in the region of Magna Graecia and the consequent Greek and Roman dominations, led to the spread of Hellenistic culture and consequently to constructions that go from the classical characters of ancient Greece to the post-Alexandrian eclecticism and the overlapping of the already consolidated Ionic, Doric and Corinthian orders.

Subsequently, after the fall of the Roman Empire, due to the continuous state of war, there was the stripping and the "recycling" of the built, also favored by the depopulation of the cities; this phenomenon continued until the threshold of the year 1000, when there was a gradual resumption of city activities.

An example of reuse of existing buildings is the crypt of Basilica of San Nicola in Bari (Italy), where the columns belong to completely different eras and styles.

The end of the High Middle Ages saw a flourishing of building activities in the cities of the South of Italy, which led to the construction of monuments that have come down to the present days, and that have given an incredible architectural variety to the territory.

Recurring elements are precisely the columns, which represent the key elements and supports in all structures made before the advent of concrete. In fact, in literature there are many studies regarding the behavior of single and multiple columns structures [7–11]. In the present chapter the results of the analyses carried out by applying the DE method to the case of stone columns are reported and discussed.

The columns were subjected to harmonic pulses of varying amplitude and frequency values with the aim of describing the activation of local/global instabilities induced by seismic events. The objective is acquired by plotting the column rocking curves [12, 13], also known as stability domains, which describe the mechanical behavior of these structures.

The curves were drawn by varying some fundamental parameters that influence the dynamic response of the system: slenderness of the column (which is defined by the ratio between the total height H and the diameter of the base B), number of drums, contact properties and damping.

The range of slenderness has been varied in the range $4 \leq H/B \leq 13$ to cover all the types of columns belonging to the Doric and Ionic orders characteristic of the architectures of ancient Mediterranean civilizations.

## *2.1 The Geometric Model*

The investigated columns, which stand in the Mediterranean area, are characterized by several geometrical parameters depending on the dimensions of the overall structure. Thus, a parametric analysis is requested to consider the high variability of such geometric parameters. This led to the need of preparing a routine that would allow automating the construction of the geometry for several cases, starting from few significant parameters.

The cross-section of the column, identified as an icosagon, has been assigned and the following parameters have been considered:

- Column slenderness (H/B) defined as the ratio between the height and the diameter of the section at the *imoscape* (the lower base section of the column);
- Column diameter at the *imoscape* of the column;
- Number of drums in the column shaft (maximum number allowed 48);

- *Entasis*, the ratio between the diameter of the column at the top and that at the *imoscape*;
- The ratio between the length of the column shaft with a constant cross-section and the overall height of the column;
- Four quantities linked to the geometry of the capital, in detail the height and the width of the echinus and abacus;
- Three different “scaling coefficients” along the three directions x, y and z that allow the column shape to be scaled homogeneously or differently.

This approach allowed defining a great number of possible geometrical configurations which can be considered representative of the existent patrimony of such structures.

## 2.2 The Mechanical Characteristics

In the mechanical modelling, the blocks were considered infinitely rigid, to obtain greater overall reliability of the results, and because of the need to reduce the time required by the computer for the solution of the equation of motion.

The drums have been considered made in limestone, which is widely used in the construction of these structures because it is easy to find and work. A density of 2,200 kg/m$^3$ has been assumed for limestone.

The behavior along the joints between the drums is defined by Coulomb’s law which, in turn, depends on the cohesion $c$ and internal friction angle $\Phi$.

The stiffness coefficients of the joints in the normal and tangential direction are assumed to be 100.0 MN/m, as for the 3DEC software [6] they are equal to the ratio of the relative elastic modulus divided by the dimension of the drum in the direction of the force.

The interaction between drums is governed by complex phenomena concerning impacts and the consequent energy dissipation. The amount of energy that is lost during the motion is difficult to quantify except through in-depth studies of the materials as shown in [14]. It was therefore considered appropriate to assign an average damping coefficient of 0.5 for the tests carried out, and, to examine how the variation of this parameter could affect the global response of the structure, different values of the damping coefficient have been considered.

## 2.3 The Load Conditions

Impulsive loads, specifically, harmonic pulses defined by a co-sinusoidal and sinusoidal acceleration laws were applied to the base of the columns (Fig. 1) [4, 5].

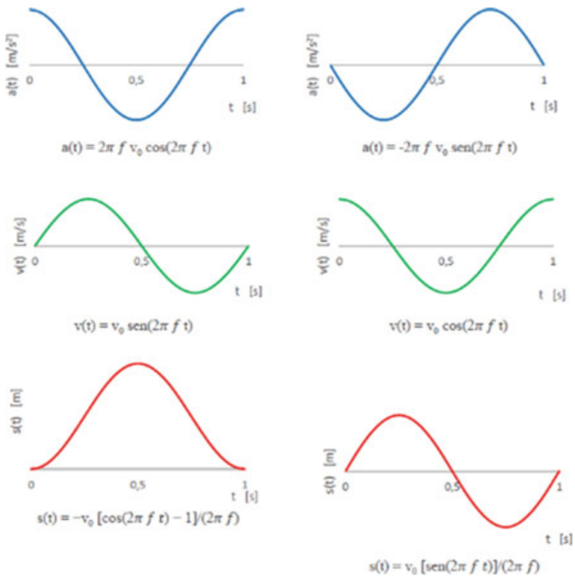


**Fig. 1** Harmonic pulses considered in the analysis of columns expressed in terms of acceleration, velocity and displacement: **a** co-sinusoidal pulse; **b** sinusoidal pulse

The results obtained were then plotted in the plane which presents along the axes the frequency and the peak acceleration of the harmonic pulse according to [17].

## 2.4 Results

A dynamic analysis of the modelled columns subjected to the harmonic pulses has been conducted and the following four behaviors were observed:

1. the column remains intact despite more or less evident displacements and rotations of the drums (Safe Area);
2. the column collapses entirely after it oscillates at least once around the base, i.e. the collapse occurs after the base of the column exhibited one or more impacts with the supporting surface (mode I);
3. the column collapses entirely without oscillating around the base, i.e. without the base impacting the ground before integral collapse (mode II);
4. the column undergoes a partial collapse (mode III).

By plotting the observed results in a frequency-peak acceleration graph of the harmonic pulse (Fig. 2), the regions of stability/instability of a column can be identified.

The points in red identify the line of overturing without impact (mode II); all points above this line represent regions of total collapse; the points in yellow identify regions of overturing with impact (mode I), while the points in fuchsia identify the region

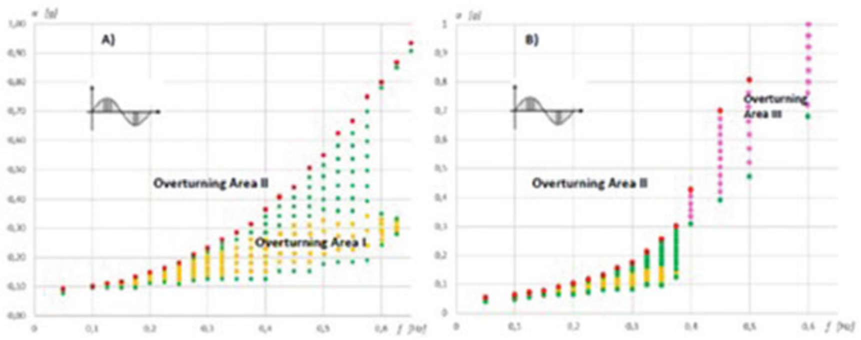


**Fig. 2** Frequency peak acceleration of the harmonic pulse diagram of a column, with a slenderness equal to 4, subjected to a sinusoidal impulse in acceleration at the base; in red mode II, in yellow mode I, in green stability, in fuchsia partial collapse: **a** monolithic column, **b** column composed by 4 drums

of partial collapses which is clearly only present in multi-drum columns; all other points are part of the region of stability for the column.

The region of safety in the frequency-peak acceleration plane clearly depends on different parameters that influence the dynamic response, in particular: (a) the dimensions; (b) the column slenderness H/B ratio; (c) the number of drums that compose the column; (d) the damping coefficient; (e) the contact properties between the drums. Thus, to acquire a detailed knowledge of the muti-drums columns, a parametric analysis was performed by varying the aforementioned parameters in wide ranges of values. In the following, the results of such parametric analysis are presented and discussed with a detailed attention to the influence of each parameter for multi-drums columns.

### 2.4.1 Effects of Column Slenderness on the Stability Domains

As previously mentioned, columns of the classical Doric and Ionic orders have been analyzed, characterized by a slenderness ranging from 4 to 13 [15, 16] composed by a fixed number of drums (in the case here discussed such number is set equal to 8), with a base diameter B equal to 1.0 m. However, to conduct a parametric analysis, the column height was varied from 4 to 13 m. In Fig. 3 a sketch of the cases considered in the parametric analysis is shown.

According to Dimitrakoppoulos and DeJong 2012 [14] the results will be plotted in a dimensionless plane whose axes are defined according to the following relationships:

$$a[adm] = \frac{a_g}{g} \cdot \frac{H}{B} \tag{1}$$

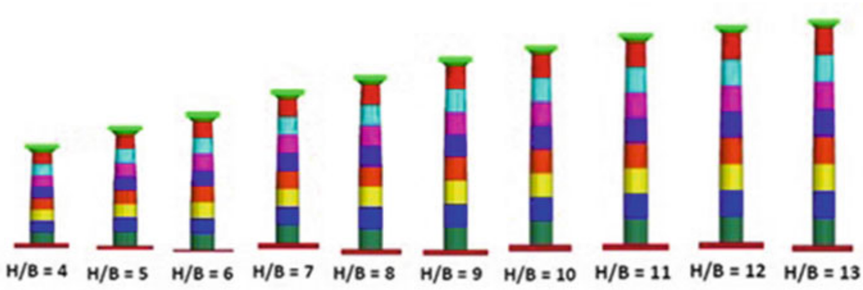


**Fig. 3** Cases considered in the parametric analysis with a slenderness varying in the range from 4 to 13

$$f[adm] = \frac{2\pi f}{\sqrt{\frac{3g}{2\sqrt{H^2+B^2}}}} \tag{2}$$

where $g$ is the acceleration of gravity, $a_g$ and $f$ are the amplitude and the frequency of the applied harmonic pulse, respectively.

The left column of Fig. 4 shows the graphs in the frequency-peak acceleration plane; the right column shows the graphs in the same plane but with dimensionless axes according to the relations (1) and (2).

Figure 5 shows the overall results obtained for the 10 columns analyzed, that means the ten cases of slenderness.

The diagrams obtained in the dimensional plane show that the stability region of the multi-drums columns decreases as the H/B ratio increases, especially for low frequency values: for the column with slenderness H/B = 4 at the frequency f = 0.05 Hz the acceleration that induces the collapse is equal to 0.102 g, while for the column with slenderness H/B = 13 the acceleration corresponding to the collapse is equal to 0.037 g (almost three times lower than that for H/B = 4). For increasing frequency values, the green curves tend to get closer to each other, but globally they always confirm the same order: the highest one is related to the stockiest column and the curve appears lower than the first one as the slenderness of the column increases.

The analysis of the yellow curves highlights that the area enclosed by them decreases significantly as the slenderness of column increases and therefore, contrary to what might be expected, a squat column will be more susceptible to global collapse after oscillation than a slimmer column. The red curves occur at lower frequency and acceleration values for increasing slenderness; in detail, for slenderness H/B = 4 the bifurcation occurs at f = 0.298 Hz while for H/B = 13 it occurs at f = 0.150 Hz. Therefore, there is a region in which partial collapses occur and whose area increases as the slenderness of the column increases.

Similar analyses were carried out by stressing the columns with sinusoidal pulses.

Differently from the case with a co-sinusoidal pulse, the columns subject to sinusoidal pulses show the following behavior, as it can be observed in Fig. 6: the areas

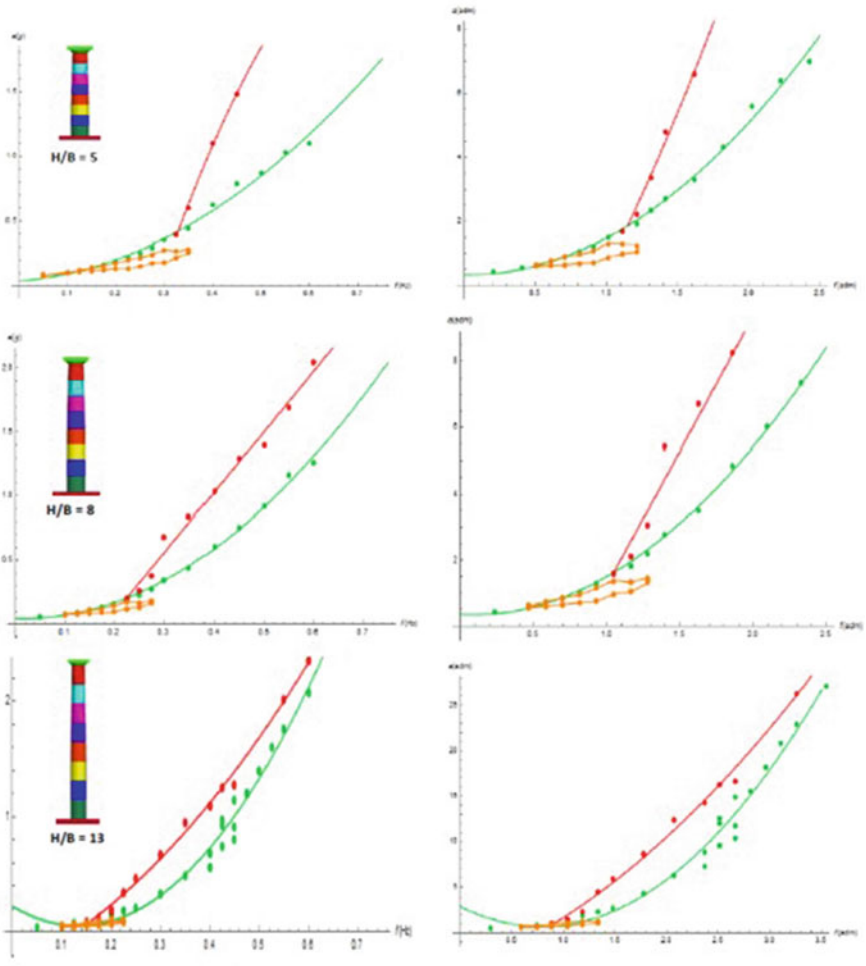


**Fig. 4** Frequency-Peak acceleration diagram for a column with H /B ratio variable from 4 to 13 subjected to a co-sinusoidal pulse acceleration at the base: the left column presents the graphs with dimensions of the axes respectively in Hz and in g, the right column shows the dimensionless axes

surrounded by the yellow curves are much smaller than that obtained by the sinusoidal pulses, so that they do not occur in the case of the squat column with H/B = 4. Furthermore, the red curves break away from the green ones at a frequency between 0.10 and 0.15 Hz, while in the previous case this behavior began at frequency values lower than those now considered for higher slenderness ratios and in a wider frequency range (0.15–0.35 Hz).

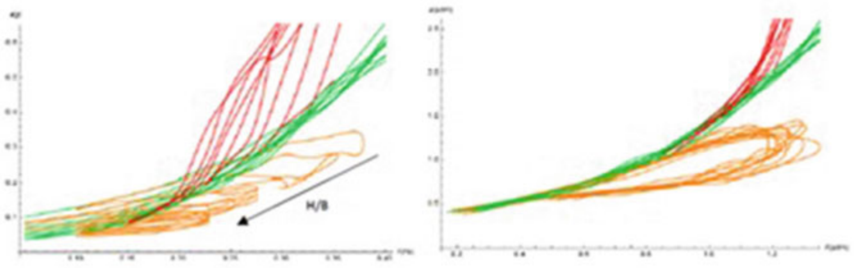


**Fig. 5** Frequency-Peak acceleration diagram for the 10 columns with H/B ratio variable: the left column presents the graphs with dimensions of the axes respectively in Hz and in g, the right column shows the dimensionless axes

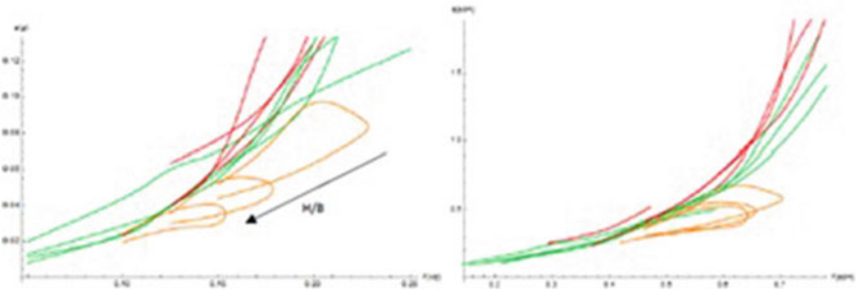


**Fig. 6** Frequency-Peak acceleration diagram for columns with H/B ratio ranging between 4 and 13 subjected to sine pulse acceleration at the base, on the right dimensionless graph

### 2.4.2 Effects of Global Column Dimensions on Stability Domains

It is known that the global dimensions of structures, even if characterized by the same geometrical ratios, significantly influence the dynamic behavior. The study of the variation of the basic dimensions is intended to observe the scale effect on the behavior of the multi-drums columns. Therefore, the slenderness of the columns will be fixed and their base dimension, and consequently their height, will be varied to respect the established H/B ratio.

The analyses were carried out by subjecting many columns to an acceleration that varies in accordance with a co-sinusoidal harmonic pulse. The following values of the parameters have been set:

- column slenderness H/B = 12;
- diameter at the column base B ranging between 0.25 m and 2 m;
- number of drums equal to 8;
- internal friction angle equal to $\Phi = 30°$;
- damping coefficient 0.5.

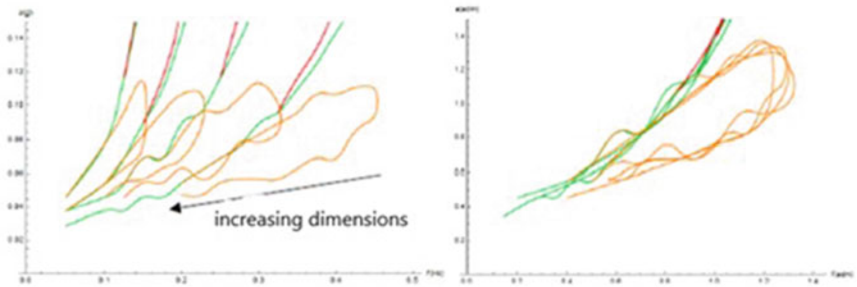


**Fig. 7** Frequency-Peak acceleration diagram for columns with H/B = 12 subject to co-sinusoidal pulse acceleration at the base, diameter at the column base B ranging between 0.25 m and 2.00 m, number of drums 8; internal friction angle Φ = 30°; damping coefficient 0.5; on the right dimensionless graph

The results are plotted in Fig. 7.

The results confirm that the larger columns are less vulnerable to collapse as the area of safety increases with the scale of the column. It is possible to notice that the trend of the green curves grows faster as the column scale increases; the yellow curves have the same extension along the ordinate axis (they cover a range of extremes 0.04–0.115 g), while they present a reduction along the frequency axis as the scale increases. The red curves follow the same pattern as the green curves, growing faster and appearing at lower frequencies as the scale increases.

### 2.4.3 Effects of the Damping Coefficient on the Stability Domains

During the motion, the interaction between the drums, which compose the column, generates energy dissipation phenomena. These latter are considered in the numerical simulation through 3DEC by introducing in the model a damping factor.

In the following analyses, the value of the damping factor has been varied to establish its influence on the overall behavior.

The analyses were carried out by subjecting the columns to accelerations, which are co-sinusoidal harmonic pulse, and setting their characteristic parameters as follows:

- column slenderness H/B = 12;
- diameter at the column base B = 0.50 m;
- number of drums 8;
- internal friction angle Φ = 30°;
- damping coefficient varying in the range 0.3 ÷ 0.7.

The results are plotted in Fig. 8.

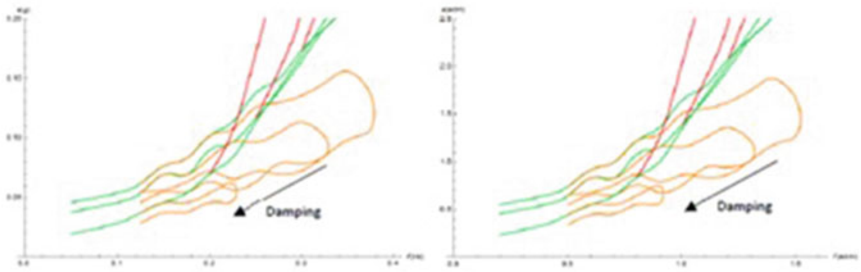


**Fig. 8** Frequency-Peak acceleration diagram for columns with H/B = 12 subject to co-sinusoidal pulse acceleration at the base, diameter at the column base B = 0.50 m, number of drums 8; internal friction angle $\Phi = 30°$; damping coefficient ranging between 0.3 ÷ 0.7; on the right dimensionless graph

The diagrams plotted in Fig. 8 show the typical monotonous increasing trend for the green curves, obviously, there is a reduction in the value of the intercept as the damping coefficient increases.

It also turns out that, by increasing the damping factor, the curves grow much faster, increasing the stability zone at high frequencies. In fact, at the same frequency f = 0.6 Hz, for a damping factor of 0.3, acceleration a = 0.633 g is recorded, while a factor of 0.7 results for a = 1.033 g.

The yellow curves have the same frequency of origin at f = 0.125 Hz, and corresponding peak accelerations that decrease as the damping increases.

The area enclosed by the curve decreases as the damping coefficient increases.

As the damping factor increases also the red curves increases, and in detail, they become detached from the green curves at lower frequencies, and the area enclosed by them, which indicates partial collapse, decreases progressively due to the growth of the green ones as explained above.

## 3 Conclusions

The aim of the present work was to study the dynamic behavior of multi-drums stone columns using the method of discrete elements and performing a parametric analysis to highlight the aspects that influence the response.

The analysis has been carried out by starting from the following considerations:

- multi-drums columns do not have a vibration mode (except when it comes to very small shifts), as the adoption of a continuum model is quite far from the effective behavior;
- stability is highly influenced by the variation of the parameters of the structural system;

- the vulnerability of such structures is influenced by the dominant frequency of the earthquake.

Analyzing the obtained results, it is possible to state that a slimmer column at low frequency values is less stable due to the progressive decreasing of the area of the stability zone.

This phenomenon, however, corresponds to a reduction in the collapse zone after oscillation of the base wheel. This evidence allows us to assert that the columns become less and less sensitive to this type of collapse as the H/B ratio increases.

Finally, at high frequency values, as the slenderness increases, there is a widening of the zone in which the structure can be defined as stable.

Through the study of the variation of dimensions in scale, it was possible to conclude that columns with larger dimensions are generally more stable than those of smaller dimensions; the zone of stability appears to increase as the scale increases. This phenomenon is associated with the reduction of the zone in which the collapse is preceded by oscillations, which contributes to the increase of the stability zone in larger columns.

Finally, the influence of the damping coefficient on the overall dynamic response was evaluated. At low frequencies, by increasing this coefficient, the interface of the stable zone tends to be lower, while at high frequencies this tendency is reversed, causing the increase of this zone: a higher damping coefficient makes the structure less stable at low frequencies, while at high frequencies it increases its stability.

Conversely, assigning a lower damping coefficient will make the behavior at low frequencies more stable, and vice versa. The variation of this coefficient also influences the area in which the collapse occurs through oscillations: the area, which represents it, decreases as the damping increases, thus making the column less subjected to this type of instability.

A series of diagrams with zones of stability and collapse have been obtained from the described analyses. The construction of these diagrams allows the prediction of the stable or unstable behavior of the structure, based on the characteristics of the column and the frequency and peak acceleration of the acceleration impulse.

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