Digital Innovations in Architecture, Engineering and Construction

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Formal Methods in Architecture

Proceedings of the 6th International Symposium on Formal Methods in Architecture (6FMA), A Coruña 2022

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Digital Innovations in Architecture, Engineering and Construction

The Architecture, Engineering and Construction (AEC) industry is experiencing an unprecedented transformation from conventional labor-intensive activities to automation using innovative digital technologies and processes. This new paradigm also requires systemic changes focused on social, economic and sustainability aspects. Within the scope of Industry 4.0, digital technologies are a key factor in interconnecting information between the physical built environment and the digital virtual ecosystem. The most advanced virtual ecosystems allow to simulate the built to enable a real-time data-driven decision-making. This Book Series promotes and expedites the dissemination of recent research, advances, and applications in the field of digital innovations in the AEC industry. Topics of interest include but are not limited to:

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- Material innovations: bio-inspired, nano and recycled materials.
- Reality capture: computer vision, photogrammetry, laser scanning, drones.
- Extended reality: augmented, virtual and mixed reality.
- Sustainability and circular building economy.
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- Smart transactions, cybersecurity, gamification, blockchain.
- Quality and project management, business models, legal prospective.
- Risk and disaster management.

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Preface

Background

The ‘Formal Methods in Architecture’ Symposia are a set of events for the debate and dissemination of developments in the application of Formal Methods (*ipsum est* those that use the explicit and rigorous languages from the Mathematical Sciences) to Architecture and Urban Studies.

The Symposia series began in 2011 and has a biennial period. Circa twelve years ago, a group of professors of the architectural program of ESAP (Higher School of Arts of Porto) decided to organize a Symposium dedicated to Formal Methods. This designation, which we are trying to generalize within the global academy has its origin in the Computer Science, where it is widely used. What about Architecture? The level of formalization was so low, that the first scientific scope of the Symposia was any applied mathematics to architectural problems, with its derivative, digital Architecture.

Portuguese schools of Architecture were born from the faculties of fine arts, and not from engineering faculties. Architecture programs, when they didn’t explicitly oppose to mathematics and the ‘digital’, remained unaware of them. For example, the use of CAD by students was not only ignored, but prohibited in most schools, at least in the first two years of the course.

In this context, the first two Symposia (2011/13) tried to achieve two goals: (a) aggregate in a meeting most of the few Portuguese researchers on this area, so they could exchange their experiences; and (b) exercise a very frontal debate between those few ‘formalists’ and the majority of ‘anti-formalists’.

Times are changing. Since 2015 the Symposia internationalized and tightened the scope. These events have become much more a presentation and debate of research done inside the specifics of formalization.

The 6th edition of the Symposia (6FMA) was held in May 2022 in A Coruña, Galicia, in joint organization with ETSAC (Faculty of Architecture) of the UDC (University of A Coruña).

Scientific Fields

Areas that were represented in the Symposia are those related to:

- Collection of information (tracking and mapping (video, GPS, Wi-Fi, ISP, IoT, GSM, 5G), biometric sensing, surveying, photogrammetry, 3D scan—drones, photo, laser, computer vision)
- Semantic organization of information (GIS, BIM/IFC, ontologies for the built environment)
- Representation, visualization, and interaction (CAD, renderings and animated motion, mixed realities, human-computer interaction)
- Formal theories and analysis methodologies (space syntax and visibility graph analysis, SCAVA—space configuration, accessibility and visibility analysis, agent-based analysis, rule checkers)
- Architectural design automation (parametricism, generative design, shape grammars, processing, advanced reasoning with artificial intelligence tools)
- Automated manufacturing and construction (CAM, scale models, 3–4–5D BIM, automated fabrication)
- Active management of the built environment (participatory urban planning and Architecture, smart buildings, smart cities, life cycle management, 6–7D BIM, facilities management, flow and crowd management)
- Formal Methods in teaching Architecture (teaching methodologies, learning experiences and digital training, spatial reasoning through visual programming and coding)

Character

The Chairs aim to maintain a unique character to the series of Symposia:

First, the interconnection between the various Formal Methods, with their fruitful results, is privileged over mono-thematic meetings, which already exist for some of the methodologies; second, the Symposia seek to preserve the discussion about the deep meaning of Formal Methods within the discipline of Architecture, and not as a ghetto, alien to Architecture as a whole; third, there has been a gradual attempt to focus on the core business of Architecture, the design process; and fourth, the events don't follow the idea of making Symposia merely as support for a 'production chain' of papers. The Symposia maintain a relaxed style of sessions with enough time to present research and debate intensively without schedule pressure.

Organization of the Volume

This volume brings together a set of papers presented to the 6FMA that focus on the main topics at stake on the global agenda and for which Formal Methods in Architecture have a relevant role by responding with innovative, creative, and efficient approaches.

The papers in this volume are organized in five parts.

1. Statements by the keynote speakers and the Chairs of the 6FMA
2. Developments in space configuration, accessibility, and visibility analysis, mainly applied to urban studies
3. Developments in architectural design automation
4. Experiences in dissemination of Formal Methods in the architectural domain, with special focus in teaching
5. Other themes not covered in the previous parts.

Statements by the Keynote Speakers and the Chairs of the 6FMA

Statements by the Keynote Speakers and the Chairs of the 6FMA is an introduction to the problematic involved in the 6FMA and includes statements by the keynotes and the Chairs of the 6FMA.

Josep Muntañola presents us with a reflection on the new paths of research, namely artificial intelligence and the general dialogic interaction between brains and computers, participating in all the competences of Architecture and planning. This reflection is very well anchored in an extensive analysis of positions of several classical authors, from Kant to Ricoeur, through Langer, Giedion, Bakhtin, and many others, and addresses topics such as knowledge and freedom, structures of space and time and their psychogenetic development, and the dialog between art and science.

Sophia Psarra brings us a study on the relationship between two human ways of capturing the real, very particularly applied to space: sensory perception and intellectual construction. An important topic of her statement is the description of her undertaking of searching for this relationship in meaningful and operative formal representations of the experience of displacement through three-dimensional spaces, which raises different types of problems. Solutions pass through dynamic isovists and synthetic representations of the variability of some of their properties.

Research, diffusion, and transfer are of crucial interest for the development of new technologies in Architecture, allowing the fulfillment of their promises in the competitiveness of the sector, as well as in the accomplishment of societal challenges with sustainable development. Pilar Chias is the right person to bring us the principles of the Horizon Europe Program, which will be the general framework for the European Union's investments in R&D. That's what her paper (Chapter "Research, Diffusion and Transfer in Architecture—The European Context") brings us, very particularized in the opportunities that arise for Architecture in this agenda.

Finally, the Chairs and co-Chairs of the 6FMA present a text, developed from the opening speech, which traces some ideas about abstract thinking throughout the history of Architecture and proposes some controversial topics about the uses of formalizations: formal versus digital; the concrete and the abstract, the sensible and the intellectual in architectonic design; rationality, the golden ratio; autonomous and specific (to Architecture) developments in Formal Methods or global tools for all the stakeholders in the construction sector.

Developments in Space Configuration, Accessibility and Visibility Analysis

Developments in Space Configuration, Accessibility and Visibility Analysis deals with a set of methodologies aggregated in what we call SCAVA (space configuration, accessibility, and visibility analysis).

The first two papers have their focus on the technical development of the languages.

The next five are applications of space syntax and correlated methods to urban problems.

The last two, still dedicated to urban scale, also use more traditional techniques within urban planning.

Further and recent evolutions in SCAVA methodologies were brought to the 6FMA by keynote speaker Tasos Varoudis[1] (not in this volume) with 'topo-geometric encodings encapsulating … [classical fundamental ideas] about spatial morphology by Hillier], using 'weighted graph spectra, multi-dimensional datascapes, complex data structures and deep learning models'.

Chapter "A Spatial Analysis Proposal for Activity Affordance in Exhibition Halls", although focused on the analysis of two exhibition halls in Mexico, brings us a new development of the space syntax methodologies, proposing the use of a hexagonal lattice to represent relations of permeability among contiguous portions of peri-personal space portraying the human scale and evaluating its advantages.

Chapter "VISSOP: A Tool for Visibility-Based Analysis" presents VISSOP, a new digital tool proposal for the SCAVA area, covering isovists, space syntax, and visibility graph analysis. This new software application brings new functionalities and some operational advantages that facilitate the use of these methodologies and may bring new types of users into their use.

Chapter "Restructuring Urban Form Through Restructuring Accessibility: An Integrated Urban Network Approach" experiments with the well-established space syntax methods by seeking to develop a model for integrating the metro system with the street network for an accessibility analysis. The chapter is clear in that it does not have all the answers and seeks to raise questions that contribute not only to

[1] Tasos Varoudis; "The Art of Creating 'Data Structures' through Aggregation and decomposition—the Inner Dynamics of Computational Geometry and Spatial Morphology".

furthering well-known methods, but also to understanding their limits and possible applications.

Chapter "Urban Design, Architecture and Space Syntax in the Conception of Public Spaces—A Look at Luanda'S Revitalization" presents a space syntax framework for the analysis of the city of Luanda with its specific characteristics. It also provides the clues for the development of a conception and management of the public space that makes predictable the consequences of the actions developed, and in all aspects of the various societal problems of the development of the city—tourism, social interaction, inclusion, micro economy, and so on.

Chapter "Integrating Formal Methodologies in a Multi-Layered Analysis for Management Policies for the Pedestrian Use of Public Space" uses a complete set of formal methodologies to deal with the problem of public space management for pedestrian traffic uses: from gathering of empirical information about the uses of spaces (manual and automatic counts, queries, video images) and about the physical, geometric and functional characteristics of spaces (surveys) and to statistical and AI treatment of that information to provide empirical parameters to theoretical tools (multimodal mobility analysis, space syntax, agent-based/cellular automata), to finally define management policies and rules.

Similar issues are addressed in Chapter "Space Syntax as a Distributed Artificial Intelligence System: A Framework for a Multi-Agent System Development". The work focuses on the development of two aspects of an agent-based analysis for pedestrian traffic: on the one hand, the establishment of decision rules for agents; on the other hand, the ways of implementing these multi-agent analyses in digital tools, which is a non-trivial problem. Decision rules are established considering several criteria, with some incidence on space syntax measures. Regarding implementations, several frameworks are critically studied and more viable working guidelines are proposed.

Chapter "Examination of the Diffusion of COVID-19 Cases in Viçosa, Minas Gerais (Brazil): A Configurational Approach" develops an analysis of city configurations and spread of Covid-19, based on choice and integration measures in addition to Kernel Density Estimator to estimate the density and concentration of confirmed COVID-19 cases.

Chapter "Applying a Morphological Approach into Istanbul's Urban Landscape" proposes a methodology for spatial planning of cities to produce a protection framework in order to preserve the structural elements of the city. The main concept is the morphological region, based on the town-plan, building fabric and land use. The case study is the historic core of Istanbul.

Finally, Chapter "Evaluating Urbanity by Measuring Urban Morphology Attributes" proposes a methodology for assessing urbanity, in its most humanistic aspects of 'promoting social interaction, security, economic activities, and pleasant spaces for walking'. This evaluation is formally performed through a set of parameters, mainly of morphological and configurational nature, although more diverse than the usual ones in space syntax methodologies.

Developments in Architectural Design Automation

Developments in Architectural Design Automation deals with a set of methodologies that trie to provide automation to the architectural design process, some even reaching the manufacturing process.

The first four papers, although applied to concrete problems, appeal to tools that can easily be used in problems with a high degree of generality.

The next two deal with the design of some element or building material.

Chapter "Plausible Layout Generation Using Machine Learning, Evolutionary Optimisation and Parametric Methods" describes a complete work of automatic generation of building layouts (particularly for schools), including the creation of models by machine learning processes from a set of samples of existing buildings; creation of a set of production rules for new buildings; consideration of the size and geometry constraints of the implantation plot, automatic validation by optimization criteria (adjacencies, distances, daylight).

Chapter "Experimental Form-Finding Method. Case Study: 'Weather Pavilion'" is also an article that describes the use of a broad set of methodologies applied to a concrete case. It is also about the automatic production of the project, which considers the climatic conditions in which it operates. In the current phase of the work, the project is a static pavilion, but whose design automatically responds to the climate of the region in which it will be built. Subsequently, it will produce dynamic structures responding in real time to the weather of each moment.

Chapter "Modelling the Relationships Between Ground and Buildings Using 3D Architectural Topological Models Utilising Graph Machine Learning" describes research dedicated to the creation of a dataset of models of relationships between ground and buildings. The information in this dataset is not purely geometric, but of the type of semantic topological graphics, using the *Topologic* language. This dataset was built from hundreds of real cases, using Machine Learning methodologies, including the training, validation, and testing phases. The results point to the validity of this dataset in classifying the relationships between ground and building. Future works will see the use of this dataset as a fitness function in a formal method of generation and evaluation in project automation, through evolutionary algorithms.

Chapter "Associative Synthesis with Deep Neural Networks for Architectural Design" introduces us to a design automation process, based on analyzing existing models by deep machine learning methods and creating plausible models by deep generative processes. The article does not make the maximalist claim that these models are finished projects. It proposes their integration into a program of co-creation with humans, as creative proposals to be evaluated in interaction.

Chapter "Behind Algorithmic Geometric Patterns: A Framework for Facade Design Exploration" proposes a comprehensive and complete framework for the automatic production of facades, meeting aesthetic, economic, constructive, and environmental criteria. The proposed production algorithms can generate volumetric elements (and not just planes). The global framework extends to CAM technologies for integration into automated manufacturing.

Chapter "Formal Studies on the Parts and Wholes of Historical Bricklay Designs" proposes a parametric way for the automated reproduction of historic brick lay designs from certain heritage cultures in Turkey. The authors deepen into patterns and rules for cultural identity parameters ranging from the aesthetic design to the generative system that considers and resolves the physical construction process.

Experiences in Dissemination AND Teaching of Formal Methods in the Architectural Domain

The problem of dissemination of Formal Methods in the current practice of the architect's profession is extremely current, at a time when there are already proven formal techniques and there is an enormous pressure to digitize all professions. **Experiences in Dissemination AND Teaching of Formal Methods in the Architectural Domain** brings us a series of experiences in the field of the teaching of Architecture, which is one of the preferred ways of dissemination. But it also shows us audits of paths of approximation between research and office, and an experience of implementing Formal Methods in sectors of public administration.

In Chapter "Proposal and Application of a Graphic Method for the Definition of New Qualitative Indicators of Architectural Education", the results of a large research carried out on the teaching and profession of the architect were published, which pointed out some inadequacies between teaching and professional practice and served as a basis for the discussion on the potential of the methods formalities to address these deficiencies.

Chapter "A Data Workflow Approach for Pedagogical Sensitization to the BIM Concept" deals with BIM training for architects. And it is particularly interesting because it demonstrates that university education is not exclusively operational. It is not simply a matter of teaching how to operate with digital tools, but, on the contrary, of apprehending a global conceptual framework of the new methodology, in all its potential for use for the specific purposes of Architecture, together with a pedagogy.

Chapter "Massing and Skin: A Pedagogical Experiment with Physical and Digital Design Media" brings us a pedagogical experience that introduces Boolean operations in a first-year design studio course through analog and digital tools. The proposal addresses the development of abstraction as a skill from subtraction and addition operations through 3D sculpting to generate the mass and image editing software to define the skin using non-destructive techniques, along with a wide range of skills and tools.

The 6FMA presented another pedagogical experiment[2] (not in this volume) on the introduction of Formal Methods in the teaching of urban planning, through games.

Chapter "An Experience Around the Rationalization of Architectural Analysis" describes a set of curricular units on a graphic subject of architectural analysis. This didactic proposal seeks to understand design by formalizing graphic analysis. The

[2] Rui Florentino; "Teaching Urbanism with Sudoku".

approach incorporates spatial, functional, contextual, and technological areas and sheds light from a case study in the subject Architectonic Analysis. Analog and digital resources allow students to explore and develop their own research process to understand architecture under the premise of developing critical and algorithmic thinking.

The research and its dissemination were also a matter of interest.

Chapter "Changing Methods in Teaching for Strengthening the Relation Between Research and Practice" brought us a set of experiences of initiatives carried out and organizational forms instituted, based on EU programs, to integrate and disseminate the teaching, research, and professional practice of architects, especially the new Formal Methods. These experiences go far beyond current models of dissemination, such as traditional scientific Symposia.

In Chapter "Proposal and Application of a Graphic Method for the Definition of New Qualitative Indicators of Architectural Education", keynote speaker Pilar Chias also listed R&D possibilities in the field of Formal Methods in Architecture, within the framework of EU research policy strategies, especially in Horizon Europe Agenda.

Other communications at 6FMA showed technology transfer strategies for public administration.

An intervention[3] (not in this volume) presented the work carried out by the technical services of the municipal administration of a Portuguese city (Matosinhos) in the sense of introducing formal methodologies in urban planning and management.

Chapter "Integrating Formal Methodologies in a Multi-Layered Analysis for Management Policies for the Pedestrian Use of Public Space" refers to the need and the efforts made to transfer the technology of the study described therein to the technicians of the municipality. The implementation of urban pedestrian traffic management policies requires the endogenization of Formal Methods in the administrative body that carries out this management.

There are multiple ways to enforce dissemination. For example, Chapter "Actors: A Hybrid Formal Model for Cognitive Buildings" tries to bring smart buildings, a technological area to which Architecture has shown itself to be quite alien, into the field of architects' interests. The strategy used is to insert the definition of the behavior logics of the buildings' intelligent automatic systems into a language that architects are more used to—BIM, so that they can also participate in the modeling of these behaviors.

Other Formal Methods

Some papers dealt with different topics, such as BIM, smart buildings and CAD/CAM, and were grouped in **Other Formal Methods.**

[3] David Viana, João Quintão and Luís Berrance; "Formalizing Municipal Urban Planning".

Large housing project assessment issues are addressed in Chapter "Encoding Social Values of Local Communities in Algorithmic-Driven Design Methods" with a generative model of volumetric housing configuration, in typical urban configurations, using a multi-objective optimization strategy, implemented through Non-dominated Sorting Genetic Algorithm II (NSGA-II) to optimize a combination of factors that encode data from housing regulations, social aspiration, and successful elements for resilient communities, and to be used by designers and other stakeholders for planning or evaluation, aligned with the targets for net-zero communities, housing and sustainable living.

BIM (building information model) is a well-established methodology and was a topic addressed in several interventions. For example, one intervention[4] (not in this volume) featured a large BIM database with information on heritage and historic buildings. The training of architects in BIM was discussed in the article Chapter "A Data Workflow Approach for Pedagogical Sensitization to the BIM Concept".

Chapter "Encoding Social Values of Local Communities in Algorithmic-Driven Design Methods" brought us BIM in an innovative way. The primary use of BIM is a very passive organization of information about the building, later used in queries for some active use. BIM is being used in increasingly complex uses, for example, rule checkers. Chapter "Actors: A Hybrid Formal Model for Cognitive Buildings" introduces active agents within BIM to be able to model the behavior of **intelligent (or cognitive) building** automatisms. It is no longer about passive storage of information, but about active models of behavior.

Also important for **smart buildings** management, Chapter "Generation of a Large Synthetic Database of Office Tower's Energy Demand Using Simulation and Machine Learning " creates a large synthetic database of the energy behavior of office towers, especially related to intelligent management of adaptive facades.

Chapter "Experimental Form-Finding Method. Case Study: 'Weather Pavilion'" also covers the design of intelligent dynamic structures that respond in real time to the climatic conditions of each moment.

The problem of intelligent dynamic buildings was also addressed by keynote speaker José P. Duarte[5] (not in this volume).

The proposal of Chapter "Strategies of Learning and Control of Robotic Manufacturing Methods in Architecture" deals with the digital paradigm in Architecture learning, focused on automation through robotic arms. The authors focus on the creation of software and hardware that are used in machine learning and control strategies to broaden access to practical applications by non-experts in teaching and research contexts.

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[4] Patrick Loureiro and Rui Seabra; "BIM Methodology Integration in the Maintenance and Rehabilitation of Heritage and Historical Buildings".

[5] José P. Duarte; "Static and Dynamic Optimization: from Concrete printing to Responsive Facades".

Alternative Organization of the Volume by Topics

Readers may notice that the main criterion for organizing the papers was methodological differentiation, according to the types of methods that are preferentially used in each of the papers. This division encountered two main difficulties. Firstly, many works use more than one methodology, following the preferential character of FMA Symposia. And second, although there are papers whose main objective is the specific development of the methods and languages, many others deal with fruitful applications of Formal Methods to concrete problems that Architecture and urbanism have to face. As they gain consistency, Formal Methods change. They are not mere syntactic languages, but are transformed into discourses, filled with meanings relevant to human activity in the natural and social environment.

In order to facilitate the reading of the volume, some topics are here developed.

History, Theory, Critique

Formal Methods in Architecture do not mean a completely new paradigm. While participating in its permanent innovation and being more than doing the same in another way, Formal Methods are part of a long road.

Encouraging debate with the traditional disciplines of Architecture—history, theory, and critique—is a clear purpose of the series of Symposia. And many of the presentations fed this aim explicitly.

Invited keynote speakers Josep Muntañola,[6] Sophia Psarra[7] and Carlos Seoane[8] did just that. Their speeches are not present in this volume. But professors Muntañola and Psarra have provided some summary statements (Chapter "The Formalization of Architecture as a Social Dialogical Tool: An Introduction to Innovative Theoretical Frames in Architectural Design" and "The Architectonics of Form: Intelligibility of Space and Form in Space–Time") and they are well known and prolific writers, so we invite you to read their work. Carlos Seoane is one of the most distinguished Galician architects and we extend our invitation to the study of his material work.

Chapter "An Experience Around the Rationalization of Architectural Analysis" describes a set of curricular units of the Architecture program at the University of A Coruña, which fall precisely in this field. This program provides the conceptual framework based on a broad concept of rationality, within which Formal Methods (which at this historical moment are much more restricted and partial) can be framed.

Chapter "Associative Synthesis with Deep Neural Networks for Architectural Design" is clearly oriented toward the potential of AI (artificial intelligence) to interact with human creative processes. Tackling broad creative areas such as

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6 Josep Muntañola, "The Formalization of Architecture: to Design is to Produce Signs as Social Interaction Tool".

7 Sophia Psarra, "Modelling Embodied Space and Movement in 3D".

8 Carlos Seoane; "the Red Carpet".

animated film, sculpture, and landscaping, along with Architecture, goes to the heart of the problem of creation in the design process. It analyzes the differences and proximities between human cognitive processes and AI machines, comparing, for example, human learning with historical examples with machine learning from a set of learning samples. It proposes co-creation processes between human and artificial processes.

Chapter "Experimental Form-Finding Method. Case Study: 'Weather Pavilion'" also targets this broad discussion. Formal Methods are presented only as a mean (maybe privileged) to achieve intemporal goals, for example, the relation between Architecture and Nature.

Methods Interconnection

Another of the objectives of the Symposium—the interconnection between methodologies—was present in several presentations.

One of the most accomplished integrations in recent years concerns the direct link between **automated design production** processes (such as parametricism, shape grammars, and others) with CAD technologies **and automated CAM** manufacturing systems. Chapter "Behind Algorithmic Geometric Patterns: A Framework for Facade Design Exploration" makes this integration into a proposed structure for the design and production of facades. Chapter "Formal Studies on the Parts and Wholes of Historical Bricklay Designs" has a similar but more concrete proposal for Turkish heritage brick lay designs.

Chapter "Actors: A Hybrid Formal Model for Cognitive Buildings" attempts to present the behavior modeling of **smart buildings** using **BIM** technologies, relating the two technologies.

The usual form of synthesis processes (i.e., the automatic creation of projects) is that the generative grammars of projects generate a large multiplicity of proposals that will be analyzed by the **analysis tools**. Chapter "Plausible Layout Generation Using Machine Learning, Evolutionary Optimisation and Parametric Methods" also adopts this conceptual view, but automatically integrates analysis methods (for example space syntax) into the global synthesis process, either by considering them internal production rules or by automating the evaluation of criteria.

Some papers integrate a **large set of Formal Methods** to deal with a very concrete problem. Chapter "Integrating Formal Methodologies in a Multi-Layered Analysis for Management Policies for the Pedestrian Use of Public Space" deals with pedestrian traffic. Especially relevant is the relationship between computer video processing of video camera images and the analysis made by agent-based/cellular automata processes. Chapter "Experimental Form-Finding Method. Case Study: 'Weather Pavilion'" applies a great set of methods for the automatic production of a project, considering the climatic conditions in which it operates. Those methods are applied since conception to the material production of the construction.

Societal Problems

Societal problems are also addressed using formal methodologies.

Keynote speaker José P Duarte[9] brought a reflection on a central historical problem: in the next 50 years more buildings will be built than in the entire previous history of humanity, so we have a great effort ahead of us to devise the necessary changes to the production processes.

Most papers, although they may value methodologies, are related to social and human problems. For example, Chapter "Urban Design, Architecture and Space Syntax in the Conception of Public Spaces—A Look at Luanda'S Revitalization" develops global policies for the development of the city of Luanda.

Housing quality assessment issues are addressed in Chapter "Encoding Social Values of Local Communities in Algorithmic-Driven Design Methods".

Sustainability issues are taken up in many articles. Chapter "Behind Algorithmic Geometric Patterns: A Framework for Facade Design Exploration" proposes a comprehensive and complete framework for the automatic production of facades, also meeting environmental criteria, arguing that automated design production processes make it possible not to forget these problems and to meet the increasingly complex technical intricacies. Chapter "Generation of a Large Synthetic Database of Office Tower's Energy Demand Using Simulation and Machine Learning " deals with power management for office towers. Chapter "Experimental Form-Finding Method. Case Study: 'Weather Pavilion'" intends the automatic production of the project considering the climatic conditions. Chapter "Integrating Formal Methodologies in a Multi--Layered Analysis for Management Policies for the Pedestrian Use of Public Space" is concerned with foot traffic, with its implications for the sustainability of cities and the health of citizens.

Health is also a concern of Chapter "Space Syntax as a Distributed Artificial Intelligence System: A Framework for a Multi-Agent System Development", which develops an analysis of the relationships between city settings and the spread of Covid-19.

Heritage was approached in different ways. Chapter "Examination of the Diffusion of COVID-19 Cases in Viçosa, Minas Gerais (Brazil): A Configurational Approach" deals with the morphological study of the historical city of Istanbul. Chapter "Formal Studies on the Parts and Wholes of Historical Bricklay Designs" brings us automated production processes of historic Turkish masonry projects, arguing for its ability to keep cultural heritage alive while keeping it up to date.

[9] José P. Duarte; "Static and Dynamic Optimization: from Concrete printing to Responsive Facades".

Availability

Most of the research work developed and described in the Symposium papers relied on the development of digital tools and knowledge bases. Unfortunately, most of these tools remain within the research teams that produced them.

We hold some proposals.

Chapter "VISSOP: A Tool for Visibility-Based Analysis" presents VISSOP, a new proposal for a digital tool for the SCAVA area, covering isovists, spatial syntax, and VGA (visibility graph analysis). This new application brings new features and some operational advantages that facilitate the use of these methodologies and can bring new types of users.

Chapter "Actors: A Hybrid Formal Model for Cognitive Buildings" announces a software library to model a BIM model for Bigraph representation

Chapter "Integrating Formal Methodologies in a Multi-Layered Analysis for Management Policies for the Pedestrian Use of Public Space" promises the release of an agent-based evolution to the available DepthSpace3D digital tool.

Chapter "Generation of a Large Synthetic Database of Office Tower's Energy Demand Using Simulation and Machine Learning" proposes office tower energy demand databases.

Presentation by Patrick Loureiro[10] (not in this volume) announces a large BIM database with lots of historic and heritage building data.

AI—Artificial Intelligence

Artificial intelligence (AI) reveals itself invading all fields of knowledge and technology. Many of the interventions refer to uses of AI.

Chapter "Associative Synthesis with Deep Neural Networks for Architectural Design" makes intensive use of AI learning and generative processes for automatic design production. Chapter "Generation of a Large Synthetic Database of Office Tower's Energy Demand Using Simulation and Machine Learning" uses AI to process information about the energy behavior of office towers. Chapter "Integrating Formal Methodologies in a Multi-Layered Analysis for Management Policies for the Pedestrian Use of Public Space" uses AI to define pedestrian types based on big data from images collected by city video cameras. Chapter "Plausible Layout Generation Using Machine Learning, Evolutionary Optimisation and Parametric Methods" uses AI to synthesize knowledge about school layouts from an extended study sample. Chapter "Modelling the Relationships Between Ground and Buildings Using 3D Architectural Topological Models Utilising Graph Machine Learning" does an identical process, but to typify the topological relationships between building and ground.

[10] Patrick Loureiro and Rui Seabra; "BIM Methodology Integration in the Maintenance and Rehabilitation of Heritage and Historical Buildings".

Note that new uses of AI are not limited to classifying or typing big data. It also generates production rules for active procedures based on this typing, which is essential for project automation. It is no longer just about identifying or recognizing patterns in new existing cases, but about creating new cases (projects) from the knowledge acquired by machine learning.

Special Mentions

Finally, we highlight three of the works that, in a personal evaluation of the Chairs, seem to have the greatest impact on architectural thinking. It's not just about raising problems. It is also because there is a great quality in the proposals, which seem to arrive at credible results, but which, however, seem to have been produced by very odd methods, which seem incomprehensible, even to less lay minds in these matters.

Chapter "Associative Synthesis with Deep Neural Networks for Architectural Design" guides us through some of the central issues of using AI in Architecture. Not so much for what it proposes, which is quite sensible and free from extremism, but more for what can be foreseen. First, it clearly targets the creative processes (rather than the technical aspects of construction[11]), which many opinions attribute exclusively to humans. Secondly, the depth (comes to concrete proposals) and diversity (animation cinema, sculpture, landscaping, Architecture) of the examples allows great questions about the real capacity of non-heuristic AI processes to generate automatic architectural design solutions. Third, co-production processes are composed of proposals generated in AI black-boxes that are then evaluated by humans also in what appears to be an intuitive human process (which is also a black-box, albeit a human one). The important issue here is where (and if ever) human cognitive processes are integrated, laid out in explanatory, meaningful, and interpretable (as opposed to black-box) theories.

The article in Chapter "Plausible Layout Generation Using Machine Learning, Evolutionary Optimisation and Parametric Methods" describes a complete job of automatic generation of building layouts, including the creation of models by machine learning processes from a set of samples of existing buildings; creation of a set of production rules for new buildings; consideration of the size constraint and geometries of the implantation lot, automatic validation by optimization criteria (adjacencies, distances, natural light).

The usual form of synthesis processes (i.e., the automatic creation of projects) is that the generative grammars of projects generate a large multiplicity of proposals that will be analyzed by the analysis tools. Chapter "Plausible Layout Generation Using Machine Learning, Evolutionary Optimisation and Parametric Methods" also adopts this conceptual view, but automatically integrates analysis methods (for

[11] Please excuse the informal vagueness of this creative/technical dichotomy. The intention here is not to solve these types of problems, but rather to bring attention to them.

example space syntax) into the global synthesis process, either by considering them in production rules or by automating the evaluation of criteria.

The same problem related to the previous chapter prevails. Although the heuristic is introduced here, there are processes where it appears to be absent. For example, creating models for future project automation, from a set of samples, using machine learning alone, does not seem to ensure the quality of the model to be followed. What if the samples of the learning set are bad examples? There also appears to be a loss of control on the part of human architects, as machine learning processes can be black-boxes that are totally incomprehensible to humans. The question that arises is how, and at what stages of the process, to combine human heuristic processes and artificial learning processes.

We would also like to highlight also Chapter "VISSOP: A Tool for Visibility-Based Analysis" that presents VISSOP, a new proposal for a high-quality digital tool for the SCAVA area, covering isovists, spatial syntax, and VGA. This new application brings new features and some operational advantages that facilitate the use of these methodologies and can bring new types of users.

A Coruña, Spain — Plácido Lizancos Mora
Porto, Portugal — David Leite Viana
Porto, Portugal — Franklim Morais
Porto, Portugal — Jorge Vieira Vaz

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Finally, the Chairs of the 6FMA have the deep obligation to thank the University of A Coruña for hosting this 6th edition. This acknowledgment is extended to all those in ETSAC who participated with their hard work in organizing the event.

And finally, we thank all the keynote speakers, Scientific Committee members, session moderators, and authors who made 6FMA possible.

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Statements by the Keynote Speakers and the Chairs of the 6FMA

The Formalization of Architecture as a Social Dialogical Tool: An Introduction to Innovative Theoretical Frames in Architectural Design

Josep Muntañola Thornberg and Regina Garcia

1 Introduction

The formalization of architectural design today is confronted with the tragic dilemma that confronted the philosopher E. Kant in the last days of his life when his mind was already failing. The dilemma was provoked by the starting point of his immense philosophical work when he defined the existence of pure knowledge in men and, some years later, he defined the practical knowledge related to politics and morality. Finally, in the incredible book on the aesthetic dimensions of the human mind, he wrote a first attempt to bridge the pure knowledge with the practical knowledge. That was a fundamental move, but he insisted upon a definitive and last book on the matter that, I have said, he could not develop.

This dilemma, knowledge or freedom, has been analyzed after E. Kant by a lot of philosophers starting with Hegel and after for a long list where we will underline the works by Simmel, Husserl and Ricoeur but there are a lot more. This gap between critical thinking and freedom and the last book by S. Dehaene (2022) it is an extraordinary example when he insisted in organize education in our digital world of today, as an equilibrium between the freedom and the critical thinking in children's life, on the one hand, with the fundamental social interactions with teachers as conveyors of cultural values that sadly cannot be verify scientifically, on the other hand. A very difficult equilibrium, in fact, needs a lot of clarification too.

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2 Chapter One: The Dialogical Hope

Diagram I and II show the recent work by Paul Ricoeur to include the interlocative power or architecture and planning in general education, challenging in this way the total control by the interlocutive power of verbal language. This proposal changes totally the old Heideggerian point of view used by the theoreticians of architecture in the last 100 years. (Nesbitt 1996) and opens new ways of research on the architectural design practices and theories.

Also, the following text by Jonas Langer in his personal web that defines the three epistemological origins of the human knowledge is a fundamental theoretical move.

> **THE THREE-PRONGED HUMAN COGNITIVE DEVELOPMENT BY JONAS LANGER.**
>
> My research on the evolution and development of cognition in human and nonhuman primates is currently expanding from two- to three-pronged. The first is on the origins and development of physical (e.g., causal), logical (e.g., classificatory), arithmetic (e.g., numerical) cognition in humans from early infancy on. The second is on the comparative development of these cognitions in humans, chimpanzees, and monkeys. The third, which is entirely new and just beginning, comprises computer simulation experiments to investigate and model aspects of the evolution, origins and development of cognition that cannot be studied in real time with real subjects.

The Langer's tree places the computer topogenetic branch in the right situation between ontogenesis and phylogenesis and underlines its new power without eliminating the other two branches, on the contrary, designing the meaning of the whole tree growing in a good living environmental concordance.

PHENOMENOLOGICAL STRUCTURE OF HUMAN SPACE ANT TIME
(Husserl Historical Origin of Geometry as a Linguistic Process) (Paul Ricoeur)
INTERLOCATION AND INTERLOCUTION

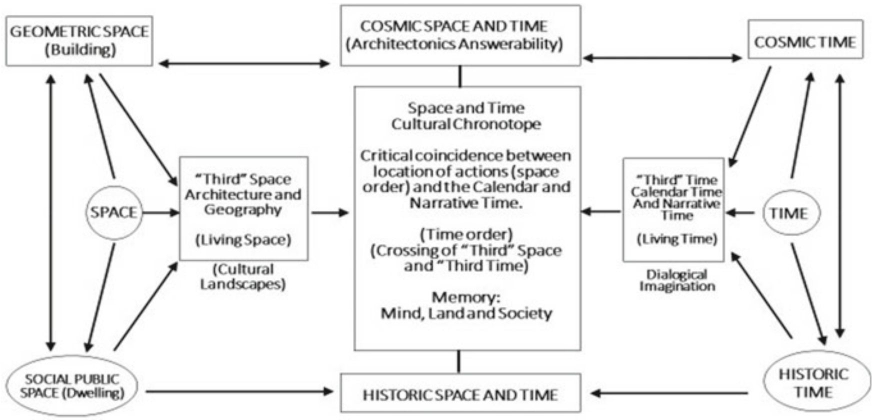


Diagram I Interlocation and interlocution intersubjectivity according to Paul Ricoeur

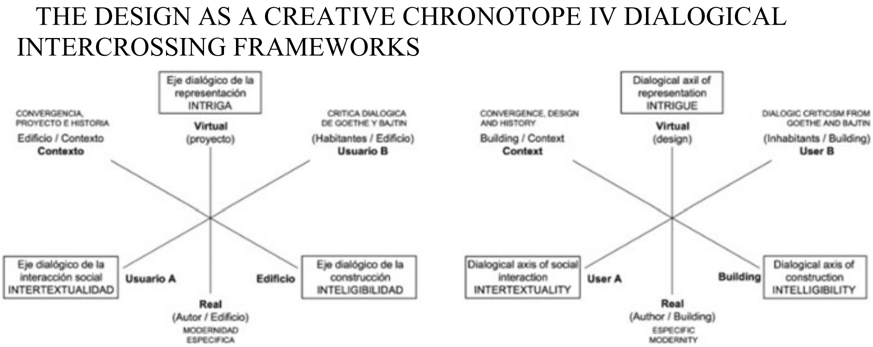


Diagram II The Fundamental hermeneutic structure of architecture (According to Paul Ricoeur) Introduce the hermeneutic structure of architecture according to Ricoeur (1969, 1984, 2000, 2001, 2002, 2004) pointing to the physical dimension of architecture as an "intelligible" dimension, analyzed as a "topogenetic" dimension in a lot of previous works where the computer is the new power today, in the third branch of the Langer's tree (Muntañola, 1975, 2006, 2016, 2021, 2022)

In a very brief form, the Diagram IIIa–c summarize the ontogenetic development of architectural cognition in children (Muntañola, 1973) where the key new points can be argued as follows:

First, the development of architectural cognition is the best example of socio-physical interlocation, that is, of the ability of children of interlocate bodies and physical places, a central ability of traditional architecture and a challenge for the artificial intelligence today. However, as can be observed in the diagrams, this cognitive ontogenetic development is far to be unilinear, it is complex and open to innovations in both the physical forms and the social interactions, to support the freedom of men as we have pointed out at the beginning of this text.

Diagram IIIa–c show that there are two fundamental epistemological transitions in the ontogenetic development at 3 years of age and at 7 years of age, when the conceptualization of time changes (Muntañola, 1980). At the same time, space changes from solid not hollow architecture to empty buildings, at 3 years of age, and from these empty spaces to double void level, as a common social space, at 7 years of age. These changes are not only physical but also social-physical and concord with the anthropological studies on the field. However, as Paul Ricoeur insisted upon, this epistemological interlocative knowledge has been forgotten in the western culture, and the interlocutive verbal intersubjectivity has taken the total protagonism, along with mathematics, in modern education. The link between architecture and the monological or dialogical dimensions of children behavior is very clear on these diagrams and a lot of research should be done in the field.

Going back to the origin of modernity in architecture, we can uncover the difficulties in relation to the use of this "interlocative" power of cities and buildings. One of the leaders of the CIAM meetings, Siegfried Giedion gave the following argument in the foreword of his well-known book "Space, Time and Architecture", in the 13th edition in 1963.

PSYCHOGENETIC DEVELOPMENT OF CHILDREN CONCEPTIONS OF PLACES TO LIVE IN

(a)

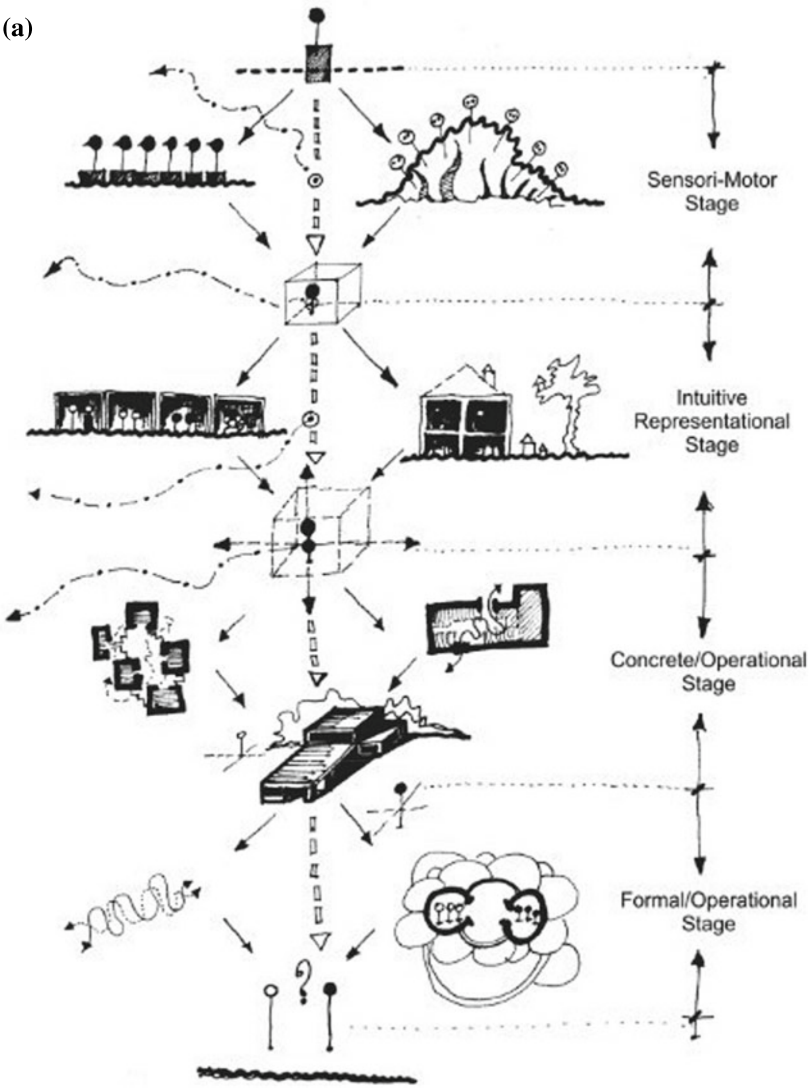


Diagram III **a** The general epistemological development of architecture in children. **b** The fundamental change around 2 years of age between the massive places, buildings with legs etc., and the empty places. **c** Monologic and dialogic cities and their socio-physical differences

(b)

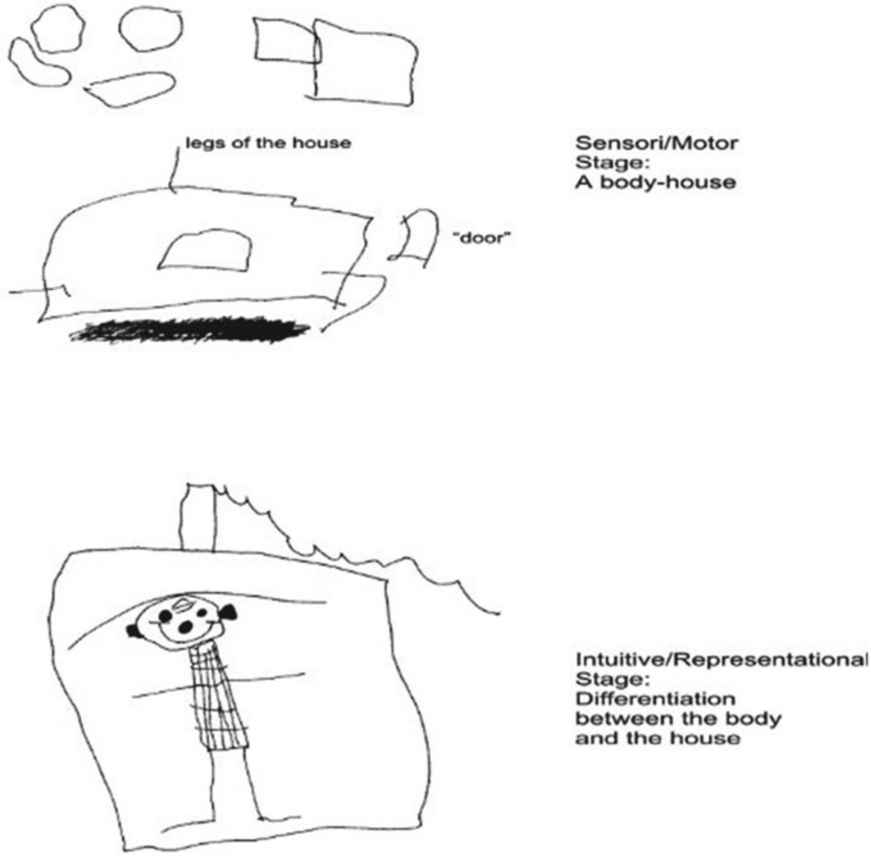


Diagram III (continued)

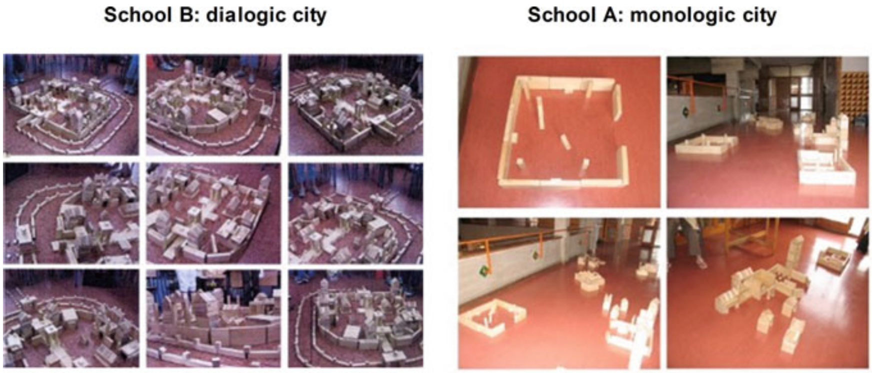
> In Mechanization Takes Command I intended to show how the gap between feeling and thinking emerges and how each generation needs to find its own solution to the problem, always the same, of how to build this opening between the inside and the outside dimensions of our real world by restoring the dynamic building able to support their new affinities (Giedion, 1963).

These ideas were expanded in his last book on "Architectural transitions", published in Spanish in 1975, where Giedion, in contradiction with previous books pointed to an intersubjective interlocation as the kernel of architectural history, not a technological development as the only origin of innovation, as he himself argued before (Muntañola, 1975).

In relation to the anthropologic and cultural branch of the Langer's three besides the basic works by Langer's itself (Langer et at. 2003), it is necessary to follow the anthropological works by D. Kirsh and others in the University of California in San

(c)

CHILDREN MODEL OF CITIES: MONOLOGIC AND DIALOGIC STRUCTURES



CHILDREN MODEL OF CITIES: MONOLOGIC AND DIALOGIC STRUCTURES AND THE SOCIO-PHYSICAL GENESIS OF CHRONOTOPES FROM A DIALOGICAL AND INTERSUJECTIVE POINT OF VIEW THIS MEANS THAT THERE ARE SOCIOPHYSICAL CRITICISM BETWEEN COGNITION AND SOCIAL INTERACTION. THAT IS IN THE EQUILIBRIUM PREDICTED BY DESHAENE AND GIEDION (AND SOCIAL CULTURAL INTERACTION CONDITIONS KNOWLEDGE IN THE NEGATIVE WAY PREDICTED BY PIAGET: WHAT YOU CANNOT DO IN THE PLACE)

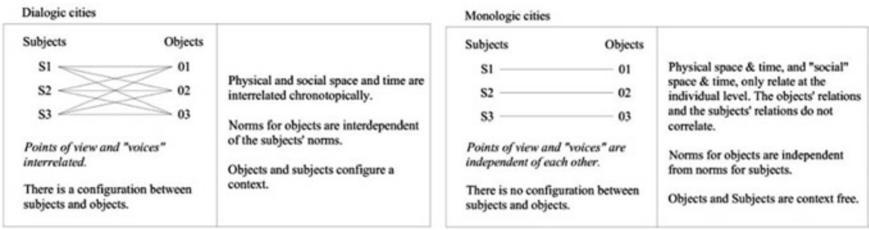
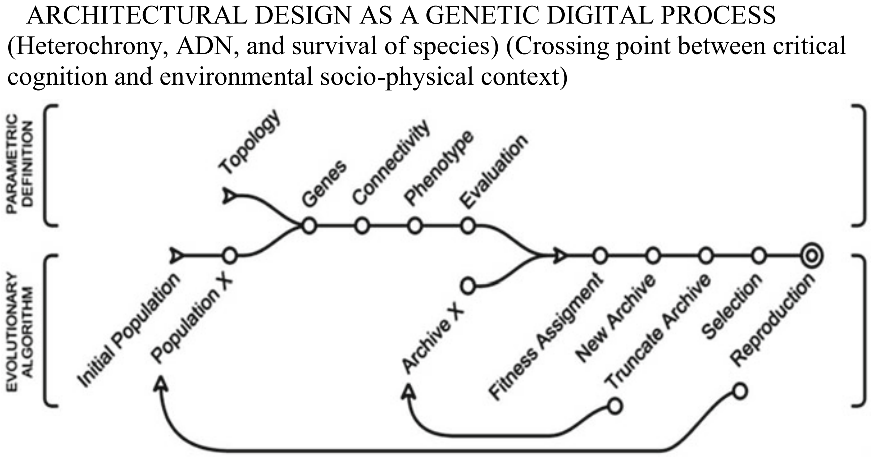


Diagram III (continued)

Diego cognitive center (Kirsh, 2020) And of course, the pioneer enormous work by Lewis Mumford today revisited 30 years after he dies (Sennett, 2019).

But the most important innovative branch of the Langer's Tree today is the topogenetic and computer branch, with an explosive growth as Diagram IVa–c summarized. Then, there is an extremely urgent immediate consequence: the need for the dialogical and social interaction between the machine and the brain. That is: Again, the challenging interaction between the technological basis of the human civilization and the mental and social use of them, in architecture, in health and into politics, totally related to human survival in general terms.

(a)



(b)

Diagram IV **a** The genetic digital models intends to propose an interaction between algorithms to simulate biogenetic studies (see following diagrams) (By Diego Navarro, UIC University Barcelona). **b** Architecture and planning can be analyzed by different digital tools at different fundamental dimensions of the hermeneutic cycle from the physic-logic to the socio-logic spatial structures. **c** The cognitive-computer interactions intend to develop simulations able to be used as an evaluation of future design changes (From R. Koenig and others simulations in SimAUD 2020).

To answer these fundamental challenges, we should enlarge our theoretical philosophical frameworks.

First, the critical distinction between the linguistic code and the social communication of meaning. That is the key point in Bakhtin's and Lotman's philosophies apply to architecture too (Muntañola, 2022; Bakhtin, 1975, 1985; Lotman, 1975, 2005; Gherlone, 2016; Terzoglou, 2018). It is a pity that this distinction impacted the theories of modern architecture very late, despite the efforts of Tzonis and Lefaivre (1990) pertaining to the importance of Mumford's criticism of the international style in 1948. This criticism is beginning to be understood just now when thousands of studies and media publications still follow the same arguments that Gropius and

(c)

AUTHOMATIC EVALUATION OF NEW PROPOSALS (ART AND SCIENCE DIALOGY)

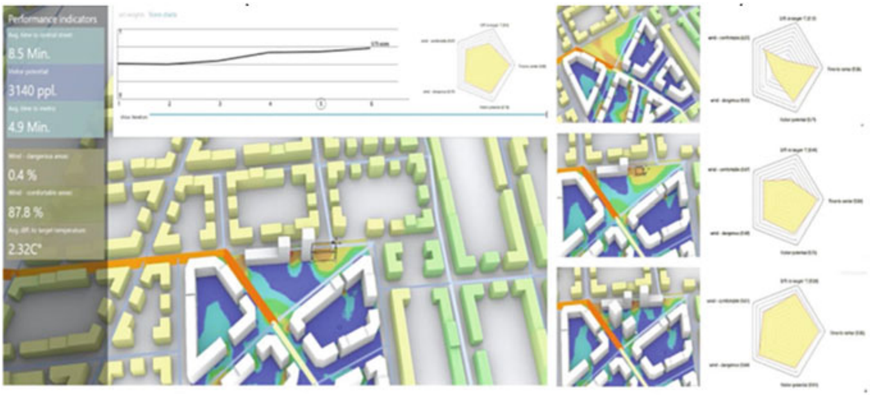


Diagram IV (continued)

Giedion argued in 1948 against Mumford' ideas, underlined the heroic modernity of empty spaces in the absence of functional links to any social use, to increase the power of architecture as an innovative and modern art, without references to dirty old meanings considered as historical "contaminations". Of course, Derrida (1990). Benjamin (1968), Mumford (1937, 1944, 1974) and Ricoeur, insisted again and again about these mistakes because architecture is neither only form, nor only functionality, but always the link between functionalities and forms. This link is the one that the dialogical social theories can analyze, either in "interlocation" or in "interlocution", or in between both social systems of communication (see Diagram I). However, to reduce the link only to the logical dimensions of empty forms is a weak favor to the environmental health of the humanity confronted with climate critical changes. Feelings, functions, and symbols are important dimensions of architecture too, as Sigfried Giedion intended, too late, to point out (Giedion, 1963, 1975).

Finally, it seems clear that the structural semiotic and systematic philosophical relationships between hermeneutics and phenomenology are what artificial intelligence should analyze in the future. This will not be an easy task, and the works by Y. Lotman and P. Ricoeur, and the studies by Zimmermann (2015, 2017) have just opened the door to it. Now, the next generations, with brains and machines, step by step, will have to enter the dialogical racial intersubjective semiotic communicative networks. This could only be done if the humanity has survived the climate changes by then.

3 Chapter Two: Some Examples of Human Interlocation

The examples shown in Diagram V, ABC are based upon the chronotopic power of abstract art totally misunderstood by a lot of studies when they assume that abstract art has no historical references or specific experiential cultural clues. Against this mistake, the work of Lewis Mumford, writing for several years in THE NEW YORKER, defined a totally different chronotropic power of abstract art linked to a history of human culture in a very critical and conceptual way, but never insensitive to it. Then, architectural design can utilize abstract representations of the use of space to link design, construction and use in one semiotic frame and, as Bakhtin indicates, be able to travel socially and physically throughout the humanity.

Other examples can follow the same dialogic and socio-physical point of view in the works by Catalan architect Carles Ferrater (Diagram VIa–c).

Other examples can follow the same dialogic and socio-physical point of view in the works by Catalan architect Carles Ferrater (Diagram VIa–c).

All these examples with or without digital computer tools show us the play between science and art in architectural design and how they can dialogue in a fruitful way. But this can only be done if there is fair play, that is, if the science is science and art is art, without political interferences than hide the cultural interchange and convert it into propaganda in the too fundamental ways of politicization of art or of aestheticization of politics described by W. Benjamin in his books. (Benjamin, 1968).

(a)

FORM AND FUNCTION IN DOUBLE MIMESIS

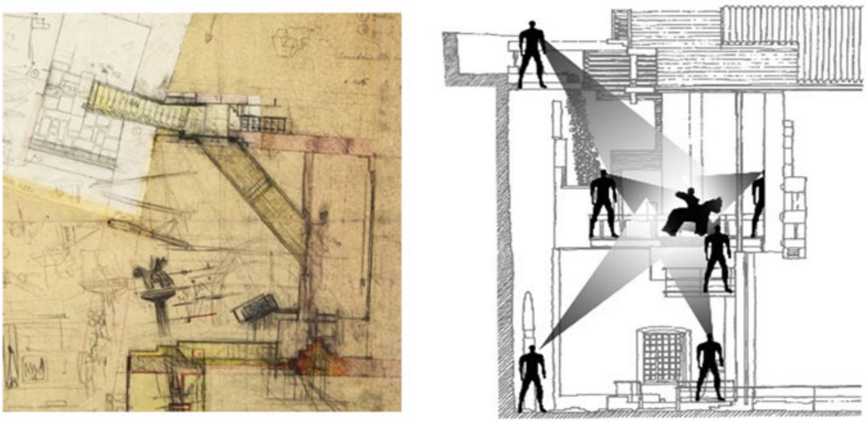
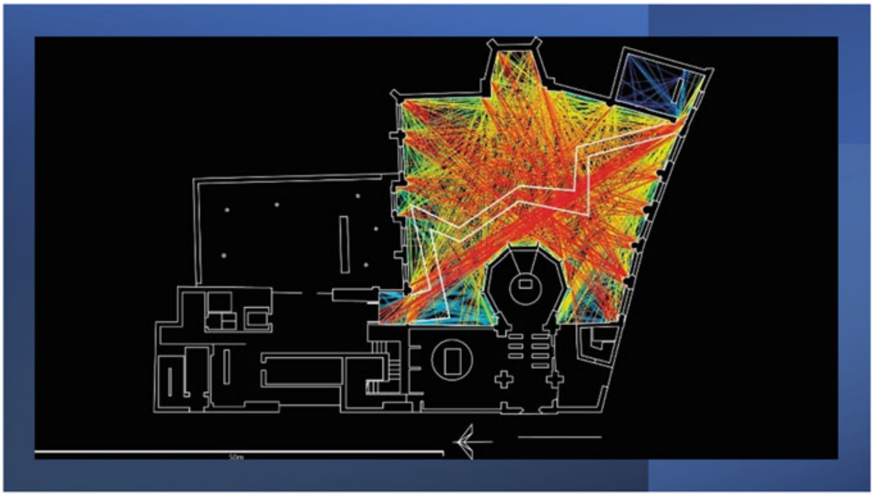


Diagram V **a** Carlo Scarpa design in Castelvecchio as a socio-physical simulation (PhD Dissertation by Nathan). **b** The museum in cologne by Zumthor dialogue between space syntax and design proposal. **c** The museum in cologne by P. Zumthor historical photograph and real photography today

(b)



(c)

MEMORY AS AN INNOVATIVE MEANING OF WHAT COULD HAVE BEEN IN SOCIAL HISTORY

Diagram V (continued)

4 Conclusion

This short analyses of the impact of the computers on architectural design theories and practices uncovers the following fundamental innovative theoretical trends:

First: The monumental philosophical work by Paul Ricoeur making a wide bridge between social phenomenology and general radical hermeneutics offers new concepts that can be useful both for architects and for philosophers. The concept of traces in our brain as specific kinds of signs and of the definitions of the hermeneutic cycle

(a)

(b)

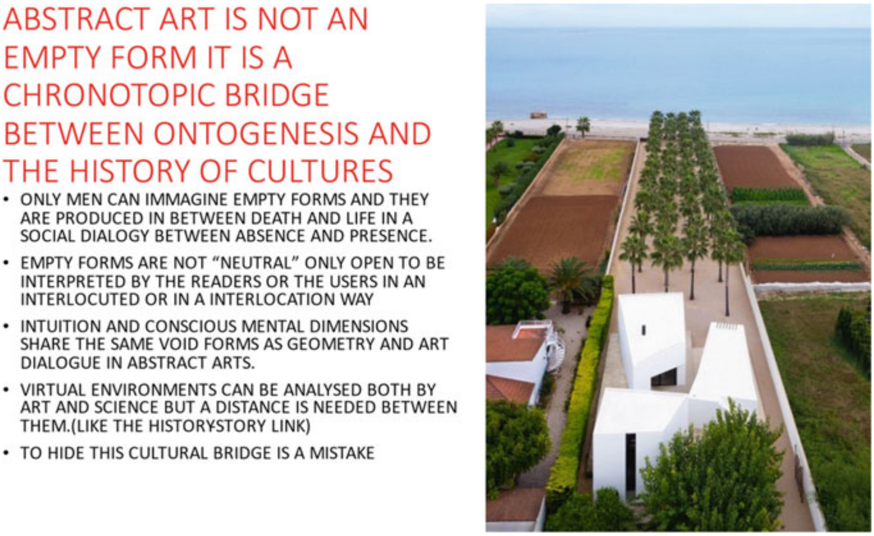


Diagram VI A: Picasso paint of the Horta de Sant Joan village in Catalonia (According to Gertrude Stein these paints are representations of the Catalan Culture of the Urban Forms from the Medieval Times Until Now). The house for a brother, by Carle Ferrater arquitecte. Clearly inspired by Picasso painting about Vernacular Catalan architecture in the same place. Designs by Carles Ferrater as cubist abstractions of vernacular context qualified by gropius in 1948, in Moma New York, as "Contaminations" against Modern Architecture Qualities

(c)

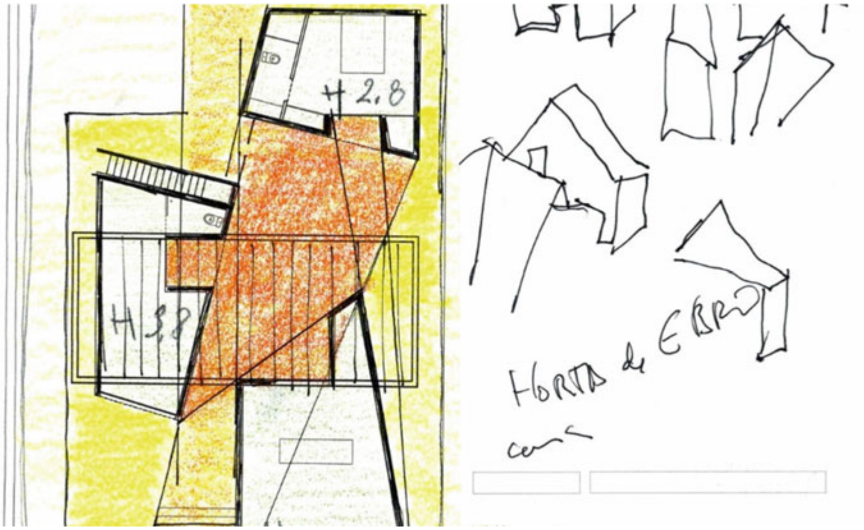


Diagram VI (continued)

proposed in architecture as a complementary interlocative intersubjective communication of the interlocutive power of verbal languages, involve radical changes in the field.

Second: The possibility that art builds a bridge between the scientific knowledge and the social practical wisdom, in general terms, opens in architecture and planning new ways of research. Mikhail Bakhtin with his monumental work supported this possibility with the concepts of social dialogics and architectonics of any work of art in general.

Third: The use in architectural design practices and theories of the artificial intelligence tools implies the need for a social dialogics between the brain and the machines in general, and the computer. Far from to be an obstacle for the two precedent conclusions, the artificial intelligence can be positive if the analyses of each interlocative situation consider the concordance between culture and knowledge as a fundamental dialogical human capability following the Langer's ideas. This can be realized throughout different disciplinary ways, such as the right correlation between the history of culture in concrete physical places, linked with the study of the social distributive knowledge, in order to deduce new emergent codes of cultural evolution, according to Rainer E Zimmermann philosophical propositions.

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The Architectonics of Form: Intelligibility of Space and Form in Space–Time

Sophia Psarra

1 Introduction

As the adjective of form, the terms—formal and formal methods—have usually the intention of addressing the specific architectural properties in works of architecture. But both terms are ambiguous involving a set of complications. Discussing the vocabulary of modern architecture, Adrian Forty explains that form is one of the triads of terms through which architectural modernism exists (2000). The other two terms are 'space' and 'design'. Form is what architects create, evoking the notion of the architect as the form giver, and implying that form exists to transmit meaning. Physically shaping the material objects that surround us, form takes us directly to the question of meaning central in architecture and architectural education.

Forty explains that traditionally form has come to mean the 'shape' of things as we know them through sensory observation (2000). But form has also been taken to mean some kind of substance or essence. I may, for example, see a room shaped as a cube, perforated by doors and windows that provide changing sensations of light and shadow. But I also know the cube is a three-dimensional solid object or a regular hexahedron defined by six square sides with three sides meeting at each vertex. The definition of cube as shape refers to the senses and embodied vision. The definition as essence refers to unchanging properties as these are known to the mind.

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2 The Dynamics of Form and Embodied Vision

I will consider the dynamics of vision into the space–time context of embodied movement by using a distinction made by architectural historian Rudolf Wittcower: that between synchronicity of form showing buildings as the eye can never see them, as when we look at drawings, and vision that is embedded in empirical context. Looking at these two layers of properties, first in plan and second in real context defined what Wittkower called the 'dual method' (1963, p. 46).

In an attempt to reconstruct the intellectual framework of the Renaissance architects, Wittkower (1962) dedicated a body of his writings that were later published in the book *Architectural Principles in the Age of Humanism*, to Palladio's variations on a theme in his villas, his composition of facades as interlocking temple fronts and his use of proportions. Two sections in this book—'The architect as huomo universale' (1962, pp. 57–69) and 'Palladio's optical and psychological concepts: il Redentore' (1962, pp. 97–100)—are based on his 'dual method'. Looking at Palladio's San Giorgio Maggiore and Redentore in Venice, Wittkower drew sight lines on plans from vantage points, arguing that Palladio unified the nave and the centralised part by the creation of corresponding vistas. S. Giorgio Maggiore, he wrote, consists of three isolated units, the Latin Cross with a short nave and a domed area, the rectangular presbytery and the choir separated from the presbytery by a screen of columns. These three units are also separated by steps from one another.

For Wittkower, Palladio's intentions become more obvious in the Redentore where he tackled anew the old problem of the composite type of church in which a centralised domed structure is joined to a longitudinal nave. While Renaissance architects tried to solve this problem with proportional and anthropomorphic devices, Palladio went the opposite way detaching the longitudinal nave from the centralised areas with its three semi-circular apses.

'The visual lines drawn into the ground plan show that from the entrance door the visitor sees at the far end of crossing a half-column coupled with a pilaster, a precise repetition of the same formation under the arch of the nave. Proceeding along the central axis, he views more and more of the farther dome supports, until from a point half-way along the nave a grouping of half-columns and niches closely similar to the bays at the end of the nave appears in his field of vision. By means of this repetition, Palladio created a new kind of coherence between the nave and the centralised part… Thus optical devices, reminiscent of the effect of a stage setting, counterbalance and supersede the objective structural separation' (1962, p. 99).

A similar analysis of the Santa Maria della Salute by Longhena in Venice suggests that the design was indebted to 'Palladio's principle of optical unification' (1963, p. 49) determining vistas across entire spaces. This principle defined a 'subjective scenographic space' (1963, p. 50) anchored and superimposed on an 'objective-mathematical one independent of the beholder' (1963, p. 50). Here Wittkower's dual method refers to direct observation based on embodied vision, what he calls subjective scenographic space, and to the conceptual grasp of the organising principles of architecture, what he refers to as objective-mathematical space. The first one is expressed through analytical diagrams and photographs, while the second one is informed by plans and sections.

Drawing precedents for both of these aspects can be seen in August Choicy's promenades that lead from one space to the next in the Athenian Acropolis, standing for Wittkower's first category, the subjective scenographic space of the observer. Choicy's abstract analysis of ancient architecture, on the other hand, would be representative of Wittkower's second category, conceptual space independent of the observer.

3 Conceptual Space Independent of the Observer

The tradition of formal analysis that emerged from art historian Heinrich Wölfflin and came to Britain through the Warburg historians Fritz Saxl and Rudolf Wittkower owed a substantial debt to Immanuel Kant and his theory on the interaction between two cognitive and interdependent faculties, sensibility and knowledge. Founded on the fusion of the phenomenal and the noumenal, sensual and conceptual qualities, Kant's transcendental aesthetics were translated by these theorists into embodied sensation through direct observation of a building and conceptual understanding through drawings.

Taught by Wittkower at the Warburg Institute, the architectural historian Colin Rowe took inspiration from his diagrammatic plans of Palladio's villas in his comparison of Palladio and Le Corbusier. Rowe framed his discussion of Palladio's Villa Malcontenta and Le Corbusier's Villa Stein using Wittkower's dual method, i.e. the tension between the visual impression of the work and abstract compositional principles the mind knows and sees on drawings.

The second category—the formal logic of composition—has been widely explored in architectural theory and formal analysis. It is beyond the scope of this short text to provide a comprehensive review of this subject. But as an illustration, one can look at William Mitchel's *The Logic of Architecture: Design, Computation and Cognition* (1990); Tzonis and Lefaivre's *Classical Architecture: The Poetics of Order* (1986), Peter Eisenman's *House X* (1982), *Diagram Diaries* (1999); and Eisenman's and Matt Roman's *Palladio Virtuel* (2016) as contemporary examples of work studying the internal forces of architecture and the dynamics of design.

What about the embodied dimension of space and spatial experience?

4 The Three-Dimensional Shape of Embodied Vision in Space–Time—Towards a Formal Method

Like all time-based media—such as music, prose, poetry and film—spatial experience unfolds sequentially through space and time. Yet, the existing body of formal analysis and research in architecture does not provide methods to capture the gradual unfolding of spatial information. The shape of spatial sequences, i.e. how we experience rooms, thresholds and passages, the widening of visual fields, the narrowing of vistas, the expansion of panoramas and the time effects through which views appear in and disappear from our visual fields have so far defied description.

There are two main reasons for this shortage. The first one touches upon our systems of human understanding. Spatial form is a fluid entity that cannot be easily captured by our strategies of representation, categorisation and classification into stable concepts, in the same way individual instances of similar entities can be grouped under a universal concept. We can point to an animate entity, such as a bird or an inanimate one, such as a cube, as discrete entities or objects that can be recognised in the 'birdness' or the 'cubeness' of other similar entities. When it comes to space however, it is not possible to point to a space as an identifiable object of specific shape, size and configuration by which we can recognise other similar spaces.

The second reason for which we do not have methods to account for space as an embodied fluid entity is cultural convention, i.e. customs conditioning our thinking according to a representational tradition. We use orthographic and linear projection to represent space in plans, sections, elevations and perspectives, based on a representational practice that is 500 years old. Approaches such as space syntax rely on representations that capture space from the view point of the observer, such as axial lines and convex spaces, accounting for the one-dimensional and two-dimensional perception of space (Hillier and Hanson, 1984). However, once the representation of plans is established, syntactic analysis reduces the geometrical and conceptual logic of these representations to graph-theoretic measures that quantify and visualise spatial interconnections. A second genealogy of analysis that captures space from the view point of the observer—used in space syntax—concerns the isovist tool. Invented by Michael Benedikt (1979), an isovist is a visual polygon representing the visual field of an observer from a vantage point linking this point with the edges of visible surfaces. However, all these methods of representation and units of analysis—convex spaces, axial lines and isovists—are based on two-dimensional projections in plan. In addition, the spatial properties measured are either about relations of every element to every other element in a configuration (global) or relations to elements that are immediately visible or accessible from each element (local). This way of looking at space is stable and theoretical, allowing us to comprehend how the set of all possible routes in a layout is structured in one grasp. One can use a set of viewsheds (isovists) along a route, but this method is also unable to express the time bound, dynamic, and fluid nature of spatial experience.

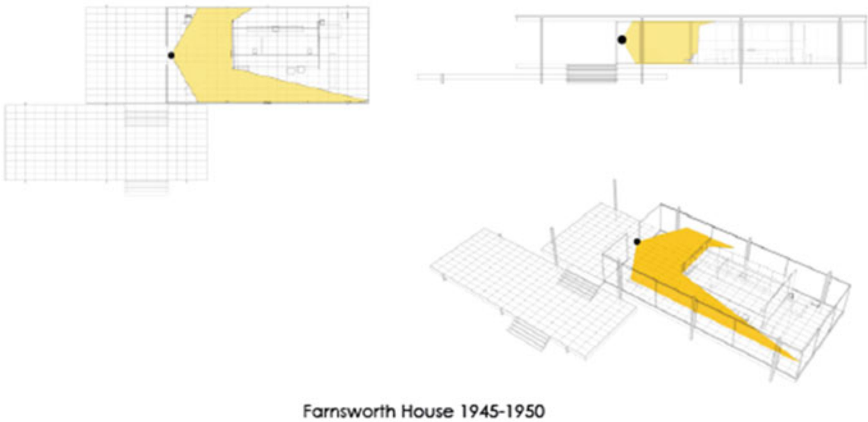

Fig. 1 Farnswoth House, Mies van der Rohe, (clockwise) isovists in plan, section and 3D

Over the last period I have been exploring how selected aspects of three-dimensional spatial experience can be rendered in 3D. We can take isovists along a path and plot in succession the fluctuation of their variables in three dimensions. The work builds on previous research I did with Tadeusz Grajewski (Psarra & Grajewski, 2001, 2003) Athina Lazaridou (Lazaridou & Psarra, 2021) and ongoing work with Gustavo Maldonado Gill. Our findings consist of four prototypes and digital images, each one modelling a building by selected architects (Fig. 1).

The modelling of embodied movement can provide systematic ways to compare a corpus of buildings of different styles, or buildings by the same architect over a period of time. Another advantage of this work is that it can facilitate the study of social factors in terms of interfaces between different categories of people, examining whether spatial experiences look different from the viewpoint of different users.

The process depends: 1. on the selection of points along isovists paths and 2. on isovist features from which we extract the form and shape of spatial experience along this path.

1. The isovist path depends on the functional type of buildings to be analysed and the key interfaces structured by a specific functional type. For houses, for example, it would appear that a path of a visitor from the entrance to the key reception area as opposed to the path of an inhabitant from the private areas of bedrooms to the reception area offers adequate reason for path selection, allowing the representation of the experiences that characterise the interface between visitors and inhabitants. We define 20 points at regular intervals, with each interval being 0.5 m defining an isovist path (Fig. 2).

   The sample consists of houses by two architects that are very different to each other such as Adolf Loos and Mies van der Rohe. Adolf Loos is known for his concept of Raumplan characterised by three-dimensional complexity. In the case of Mies van der Rohe's, we look at few of his houses and compare them to the

Barcelona Pavilion as a way to detect whether the prototypical design of the Pavilion influenced the encounter between visitor and inhabitant (which is more complex and needs privacy) in his domestic designs.

2. The isovist features to use are drawn from the study by Psarra and Grajewski (2001) and Psarra (2003) capturing the complexity of the isovist shape perimeter by measuring connectivity of points along the isovist perimeter. The x-axis captures time along the path, that is, the time it takes to cover the set of points from which the isovists are drawn assuming a regular pace of walking. The y-axis captures a range of metric properties, such as perimeter lengths between the points of inflection in an isovist perimeter along the x-axis, the radials or sight lines or the distance between the vantage point and each inflection point along the isovist perimeter on the y-axis (Fig. 3).

Building types where the key interface is between visitors and artefacts, and where inhabitants remain invisible, such as museums libraries and market places, would point to routes of visitors from the entrance to the exhibition spaces. If these routes are largely sequential the choice of points from which to draw the isovist is obvious. If these routes consist of rings of circulation, isovists can be drawn using the Hamiltonian path, a path that visits as many spaces as possible along a single sequence without returning to the same space twice (Hillier, 2019; Li & Psarra, 2022). In this first experiment, we use simple examples of houses or small buildings or even a section of small buildings as a pilot study (Fig. 4).

The significance of this work is devising a methodology to map the shape of space–time embodied vision and experience. It can provide systematic ways to compare a corpus of buildings of different styles (Renaissance versus Baroque), or a corpus of buildings by the same architect over a period of time (exploring whether an architect opens his work to experimentation or reproduces a certain genotype). Another advantage of this work is that it can enable studying social factors in terms of interfaces between different categories of people. Do spatial experiences look different from the view point of different users?

I have explored a key binary associated with the question of form and formal methods, which lies at the basis of our cognition. This question has been traditionally expressed as a question of architectural form and meaning. I reframed it as a question of dual consciousness, or of two interrelated types of understanding: the properties of buildings we experience through sensory observation and embodied vision, and the properties of composition we use to describe their formal logic. This subject begs for a focussed and intensive inquiry on the interrelationship of these two forms of understanding. It should be conceived in and for itself and used to challenge the preconceptions of formal and spatial analysis.

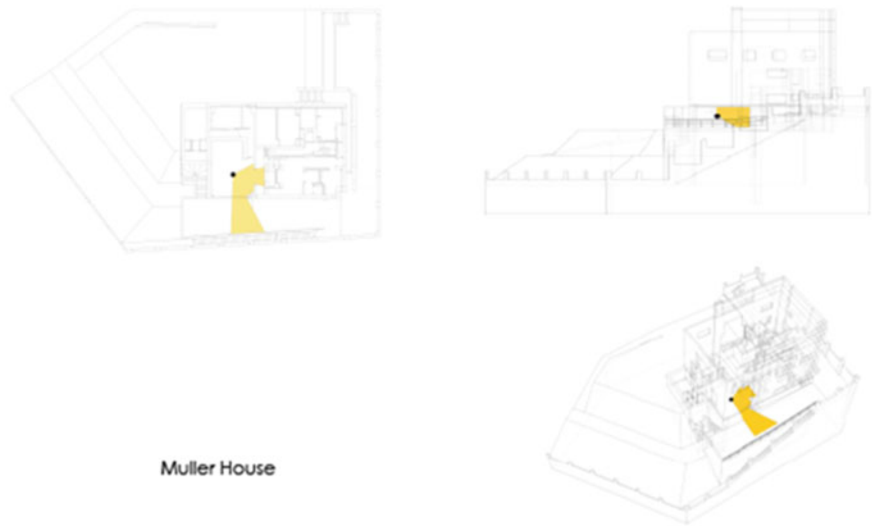

Fig. 2 Adolf Loos. Müller House, (clockwise) isovists in plan, section and 3D

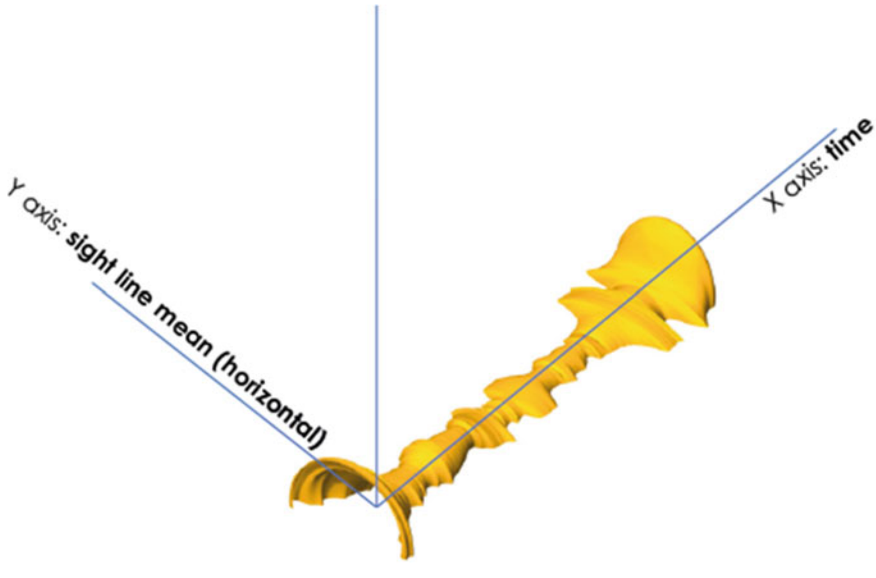

Fig. 3 Representation of isovists' sight lines along a path in 3D

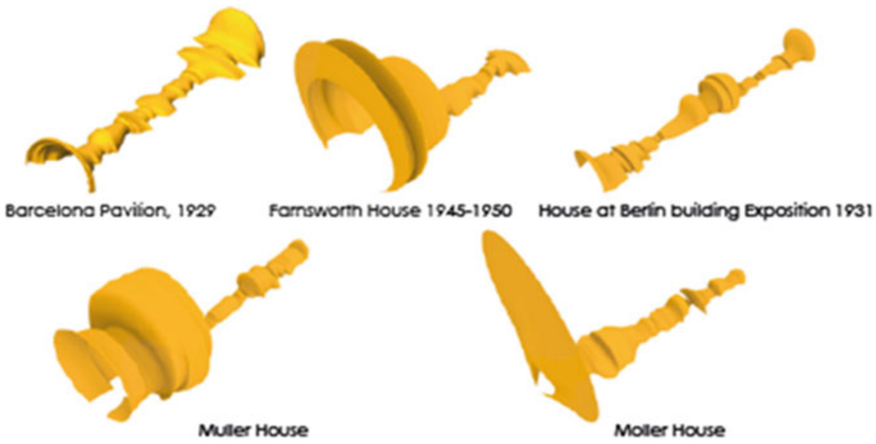

Fig. 4 Representation of isovists' sight lines along a path in 3D, top: Mies van der Rohe; bottom: Adolf Loos

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Research, Diffusion and Transfer in Architecture—The European Context

Pilar Chias

1 Introduction

As successor of the *Horizon 2020 Programme*, the aim of the *Horizon Europe Programme* is to invest in a prosperous future for people and planet based on European Values.[1] To achieve this, the connection between scientific and technical innovation will be strengthened, while the key society challenges set out in the Sustainable Development Goals (SDGs) are tackled.

Rooted in research and innovation, EU objectives are clear, realistic, measurable and targeted. They will increase European leadership in innovation and entrepreneurship, remove barriers to development and foster collaboration between public and private sectors in a broad range of focus areas.

Scientific excellence and world-class research will make it possible, strengthening the European research area and widening participation through three main pillars: excellent science, global challenges and industrial competitiveness and innovative Europe.

According to the Objectives, three types of impact with the corresponding key impact pathways are defined.

The scientific impact aims to promote scientific excellence based on key impact pathways to create and disseminate high-quality new fundamental and applied knowledge, skills and training, by strengthening human capital and fostering Open Science.

[1] *Horizon Europe Guide* 2021. Available at: https://www.catalyze-group.com/horizon-europe-2022/?utm_campaign=Horizon%20Europe&utm_term=Horizon%20Europe%20Application&gclid=CjwKCAjwh-CVBhB8EiwAjFEPGWx16x6Sq2-25Q1vYvB3FGmFoiXK1iARC2a1CghJQGhdo7RecetSjBoCdTcQAvD_BwE Accessed: 2021/07/22.

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The societal impact works for connecting knowledge generation with the implementation and development of European Union policies, and for supporting the uptake of innovative solutions in industry, considering that small and medium-size enterprises (SME) represent 99% of all businesses in the EU.

The economic impact seeks all kinds of innovative solutions by facilitating technological development and knowledge transfer, that will help to create more and better jobs and leverage investments in research and innovation.

The three types of impact are closely related to each other and affect a broad range of focus areas structured across three main pillars: excellent science, global challenges and industrial competitiveness and innovative Europe. As discussed below, architecture is a key actor in promoting EU aims and projects.

2 The Role of Architecture in Horizon Europe

The *Horizon Europe Programme* gives a boost to the global challenges in the EU through six clusters: Health; Culture, creativity and inclusive society; Civil security; Digital, industry and space; Climate, energy and mobility; and Food, Bioeconomy, natural resources, agriculture and environment (Fig. 1).

Clusters have their own areas of intervention where architecture has many research and innovation opportunities, especially in the fields of health; of culture, creativity, inclusive society; of single digital market; and of climate, energy and mobility (Fig. 2).

Fig. 1 The *Horizon Europe* framework (*Source* the author)

Fig. 2 Some research and transfer opportunities in Architecture within *Horizon Europe*. (*Source* the author)

In fact, much of the research and innovation supported by Horizon Europe may serve as a cradle for the *New European Bauhaus*,[2] which is about designing sustainable ways of living, situated at the crossroads between art, culture, social inclusion, science and technology. This includes research and innovation on manufacturing, construction, advanced materials and the circular economy approaches. According to the President of the European Commission, Ursula Von der Leyen, 'If the European Green Deal has a soul, then it is the New European Bauhaus which has led to an explosion of creativity across our Union' (Fig. 3).

Under mottoes such as 'breaking boundaries', 'beautiful & sustainable', 'beautiful solutions for the most vulnerable', 'beyond human perception', 'regenerative design in the built environment', 'do more, buy less', 'education and the New Bauhaus', 'soundscapes' or 'how to rethink fashion', a huge number of activities were performed, that can serve as an inspiration for architects and creators.

The COVID-19 pandemic evidenced the need for a recovery plan for people and communities, to make society more resilient and health systems better prepared to any future public health emergency. According to this, the health cluster entails supporting the twin digital and green transitions by unlocking the full potential of data-enabled research and innovation for digitised health systems, that will increase their capacity to deliver more personalised and effective healthcare, with less resource wasting. But there are other expected impacts in this area to be considered as 'staying healthy in a rapidly changing society', 'living and working in a

[2] The New European Bauhaus. Available at: https://europa.eu/new-european-bauhaus/index_en Accessed: 2022/06/05.

Fig. 3 The Festival of the New European Bauhaus, Brussels 9–12 June 2022. (*Source* European Union)

health-promoting environment' and 'ensuring access to innovative, sustainable and high-quality healthcare'.[3]

Repercussions of these targets in healthcare architecture are evident. Among the areas of intervention within the Health cluster, 'health throughout the life course' has a strong relation with architectural and urban design, because today's society demands healthy accessible buildings and cities. Environmental and social health determinants are currently a focus of attention. Moreover, life expectancy has risen tremendously over the last decades and has created an unprecedented demand for end-life architecture and buildings adapted to elderly and disabled people. Finally, considering the design methodologies, the users' centred approach becomes an essential strategy to be applied during the project definition, construction and management.

Culture, cultural heritage and creativity are part of the traditional core activities of many architects and urban planners. *Horizon Europe* gives a new perspective to architectural practice by attaching great importance to social and economic transformations and welcomes proposals and actions that might result in an inclusive society.[4] Among its aims, to promote better access and engagement with cultural heritage and to improve its protection, enhancement and restoration are an integral part of architects' professional activity. Moreover, research and innovation across

[3] *Horizon Europe—Work Programme Health.* Available at: https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/wp-call/2021-2022/wp-4-health_horizon-2021-2022_en.pdf Accessed: 2022/06/01.

[4] *Horizon Europe—Work Programme Culture, creativity and inclusive society.* Available at: https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/wp-call/2021-2022/wp-5-culture-creativity-and-inclusive-society_horizon-2021-2022_en.pdf Accessed 2022/06/01.

the cultural and creative sectors can foster their inbuilt innovation potential and can offer innovative, integrated, sustainable and participative management and business models for museums and other cultural institutions, fostering intercultural cooperation. Accordingly, the need for a universally accessible Cultural Heritage draws attention not only to the importance of knowledge dissemination but also to the heritage as a means to build the European identity.

On the other hand, the sustainability of Cultural Heritage is a priority for energy transition, that shares some interventions with the climate and energy cluster. Materials and methods for the conservation and restoration of cultural heritage can often be energy-consuming, not environmentally friendly or even harmful to the environment and the health of users. Green technologies application and use of recycled materials are part of a wide field of research that not only aims to meet the needs for efficient construction and management, but to achieve the desired goal of Zero Energy Building (ZEB), and of climate-neutral smart cities at the urban scale. We should not forget that energy consumption is at its highest in urban areas.

The overarching driver of the climate, energy and mobility cluster[5] is to achieve climate neutrality in Europe by 2050 by transforming the energy and mobility sectors, including the habits of the population. Urban and land planners are expected to enhance multi-level cooperation and alignment of research and innovation on sustainable urban and land development across and within cities, regions and countries. Priority focuses on critical urban sectors are positive energy districts, accessible, connected urban mobility and urban greening and circularity, their interrelations and interplay with cross-sectorial issues such as governance, digitisation, resilience land use, infrastructures and public spaces for sustainable, liveable, inclusive and resilient cities and territories.

Within the areas of intervention for architects and expected results are the solutions designed for sustainable mobility, that affect clean, safe and accessible transport, as well as urban design, land planning and rural development. They may even tackle environmental observation and circular systems.

Progress in digital technologies currently shape all sectors of the economy and society, and human-centred innovative solutions and applications of the Technologies of Information and Communication (TIC) can be integrated into each cluster. By way of example, healthcare buildings and facilities are being deeply transformed due to the introduction of eHealth and Tele-Health systems that permit to free up storage spaces previously occupied by medical histories and reduce on-site visits of patients. Wayfinding apps design and development, and interactive signalling become interesting research areas that are closely related to the Digital, the Health, and the Culture clusters.[6]

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[5] *Horizon Europe—Work Programme Climate, Energy and Mobility*. Available at: https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/wp-call/2021-2022/wp-8-climate-energy-and-mobility_horizon-2021-2022_en.pdf Accessed 2022/06/01.

[6] *Horizon Europe—Work Programme Digital, Industry and Space*. Available at: https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/wp-call/2021-2022/wp-7-digital-industry-and-space_horizon-2021-2022_en.pdf. Accessed 2022/06/01.

In short, all the intervention areas focus on reaching fully integrated balanced societies, and on building a European sense of identity, without sidestepping the challenges of the global climate crisis.

3 Impact Assessment

As we have seen, *Horizon Europe* is an impact-driven framework programme based on objectives. Accordingly, the expected impacts must deal with the general, specific and operational objectives of the research.

General objectives should have long-term wider effects on society, environment, economy and science, while specific objectives must evidence medium-term effects such as uptake, diffusion, use and deployment of the research results by direct target groups. Finally, operational objectives evidence short-term results produced during the research implementation, such as innovative solutions, patents, prototypes, new business models, guidelines and policy recommendations, methodologies, publications, etc. (Fig. 4).

In all cases, impact tracking of research results applies some specific criterion that must be considered.

Firstly, the credibility of the pathways to achieve the expected outcomes and impacts must be specified in the research project work programme, as well as the likely scale and significance of the expected contribution.

And secondly, the suitability and quality of the measures to maximise the expected outcomes and impacts, including communication and dissemination activities, must be set out in the dissemination and exploitation plan.

Fig. 4 Expected outcomes of specific and operational research objectives. (*Source* the author)

However, there is a strong tendency to change the criterion applied to research assessment that is currently led by DORA,[7] that focuses on promoting quality rather than quantity, on stabilising criteria and on limiting the effect of changes in long scientific careers. Moreover, the impact factor of scientific journals should be complemented with other qualitative indexes, giving priority to Open Science. Finally, assessment should foster transdisciplinarity, collaboration and scientific networks.

4 Conclusions

The *Horizon Europe Programme* tackles policy priorities, including green and digital transitions and Sustainable Development Goals, fuels the EU's scientific and technological excellence, and boosts Europe's innovation uptake, competitiveness and jobs.

Within this framework, specific innovation can no longer be seen as the result of predefined and isolated innovation activities, but rather as the outcome of complex processes involving transdisciplinary teams of researchers, as well as economic and social environments. In this context, users are in the spotlight and must become a part of the value creation processes. Moreover, citizen participation and social inclusiveness can effectively contribute and help the EU progress towards multiple SDGs.

The times of individual research are over, and architects cannot ignore this reality. Now is the time to step up to the new reality and give an imaginative response to the needs, demands and expectations of the European and global contexts.

Finally, the *New European Bauhaus* initiative provides an interesting overview of the possibilities that creative and transdisciplinary collaboration bring to architects and creators, by bridging between the world of science and technology, art and culture, and connecting the European Green Deal to our daily lives and living spaces. Inspiration is at fingertips!

[7] *Declaration of Research Assessment* (DORA). Available at: https://sfdora.org/read/. Accessed: 2022/01/20.

Some Controversies Around Formalization in Architecture

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1 Formalization as a Current Path of Cognitive and Methodological Evolution

Formal Methods is a designation that has its origin in the computer sciences, where it is widely used. Due to the increasing importance of computer systems, and their growth in scope and complexity, formal methods are expanding within these disciplines.

The purposes for this expansion are clear—to develop methodologies for specification, development/deployment and verification, which strengthen the computer products to fulfil both functional requirements (what they do—those functions that ensure the effectiveness of the project/application in fulfilling all our desires) and

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non-functional ones (taking as an example some that can also be applied to the practice of architectural design—accessibility to all stakeholders, compliance, efficiency (fewer resources, namely cost, and lifecycle cost), and auditability).

Those requirements are certainly directed to the final application/product, but also to the production process of the application. The above-mentioned formalization is both theoretical and methodological. Declarative knowledge and operational methods (theories and methodologies) are represented in formal languages, separately or together, but with a tendency to become autonomous of each other.

These goals are achieved through an increment in formalism, carried out by the introduction of mathematical meta-theories over the theories and methodologies already in use. The use of mathematics appears to be well founded in the historical experience of human knowledge, and of science in particular, as capable of achieving these objectives of effectiveness and efficiency. This ability to increase formalism in a series of disciplines is a must of mathematics, which in turn is in an incessant process of self-formalization. This process of formalization is a global trend of all sciences and technologies, on a historical scale.

It is no longer just mathematics that is used directly for the task of formalizing a domain. There is a group of sciences and technologies, generally called formal sciences, that perform this task. In particular, digital technologies, which allow increasingly intelligent tasks to be delegated to automatic tools, are, today, the main ways to implement the development of this path toward formalization. They also take the role of the main means of increasing work productivity, considered to be the main indicator of civilizational development by many social scientists.

1.1 Formal Is not Digital

"Computer science is no more about computers than astronomy is about telescopes" is an aphorism commonly and mistakenly attributed to Edsger Dijkstra, well known among computer scientists. We could say analogically: "Formal methods are no more about digital architecture than biology is about microscopes".

Geometry, the first fully formalized method applied to architecture was introduced some millennia before the first digital computer.

We insist on speaking of formal methods in architecture and not digital architecture. Digital is a machine way of doing something. Something that needs to be formalized, as the machine cannot understand otherwise. But the formal is the explicitation of the way of thinking, prior to digitalization.

2 What About Architecture?

We are talking about disciplines that were born formal. What about architecture?

Mathematics is very old in architecture. Any regular architecture student can say something about the golden ratio when talking about the Parthenon. But does he know why?

3 Architecture Is Historically Defined as a Discipline of Deep Abstract Thinking

3.1 Spatial Organization of Human Life

Archaeological discoveries have found *Homo Erectus* settlements dated to about one million nine hundred thousand years ago, in which traces of terrain arrangement remained. Everything suggests that those arrangements were intended to spatially organize the dwelling activities of those early humans.

It can be assumed that this behavior of this extinct species of archaic humans presupposes new and very special characteristics, in relation to other biological species.

The first is that the biological strategy toward the environment was not that, common in other species, of Darwinian biophysiological self-adaptation to the environment. Rather, it was a matter of carrying out major transformations in the environment to adapt it to the characteristics and needs of the human being.

The second is the ability to perform a complex explicit mental representation of reality, mediating behavior from stimuli to actions. *Homo Erectus* is also associated with the first manifestations of geometric engravings (the oldest found being around 0.5 million years ago), molded or carved shapes and the manipulation of colored pigments. Everything suggests that there is some evidence of symbolic thinking, associated with modern cognition and behavior, what we call rationality. These mental processes, required by the most incipient architectural activity, denote the first signs of conceptual formality.

3.2 Construction and Environmental Control

Homo erectus is also associated with the first constructions carried out by a species of the genus Homo, dating from around 1.75 My. Construction (where spaces are defined through physical limits) allows a much more accurate modulation of activities than the minimal arrangements previously practiced, such as stone circles for fires, excavated holes, beds of leaves, search for shading, and activity distancing. And it allows to add a second functionality to architecture, which is a very effective environmental control of the spaces in which human activities are carried out.

If we consider the spatial organization of human life as the primary function of architecture, and the activity of construction as just one of the possible materializations of this organization, then architecture is around 2 million years old. Then, architecture has preceded the start of construction by a few hundred thousand years.

The third phase of architecture dates from the neolithic period, when sedentarization allowed construction to become heavy and permanent. This brought two new problems: construction became of such importance, in the mobilization of natural and human resources, that it was no longer a tool to support other human activities, and became an activity in its own right (one that we must remember that, in our days, uses the largest share in mass and volume of the natural resources used by all humanity), and it became an activity in the control of nature that involves great difficulties and complexity—just as an example, the considerations related to the maintenance of building shapes in an environment full of forces (such as gravity) and movements that tend to bring down buildings forced the development of formal knowledge about what we today conceptually call structure.

We see that from the most incipient level of architecture, it needs formal thinking. Raising a megalith or organizing a bedroom requires this structured conceptual thinking. The process of complexification of its task could only lead to the promotion of this effort.

If we talk about the spatial organization of human activities, we are talking about space. One of the first formal sciences is precisely the science of space—geometry—the first formal method used by architecture. At a very primordial level of the design of shapes by architecture, a certain degree of geometrical knowledge was absolutely necessary. And at a time when human development led to the creation of written languages that assertion was already a very established reality. It is not by chance that some of the oldest written records state that architects were among those who possessed the highest levels of mathematical knowledge. Although Imhotep is a very vague historical figure, the established fact of his glorification and deification[1] is enough to demonstrate this. And the more than proven connection of ancient buildings to astronomy (which required humans with the same mathematical skills) demonstrates this once again.

3.3 Abstract Thinking in Architecture Becomes More Complex, Assumes Other Roles, and Gains Autonomy

A minimal analysis of ancient constructions allows us to verify that the complexification of human relationships with nature throughout history, and particularly of human social relationships, led to a constructive complexification and differentiation not immediately related to spatial organization, environmental control, or construction techniques. For example, the aforementioned relationships with astronomy (a

[1] Yes, architects can become gods!

fundamental science for agriculture, the main human activity at the time) made buildings to also become representations (albeit in non-discursive languages) of historical knowledge and values, if not instruments of scientific development. Also, the social relations start to appear clearly in the constructions through linguistic tropes that manifest the various social ideologies in presence.

Thus, architecture assumes another role, that of conveying, through buildings, a whole other great set of symbolic functions. This is achieved through multiple means, among which we cannot ignore the formal ones. For example, the geometric complexity and rigor of the various heritage buildings allow for perceiving immediate social distinctions.

3.4 The Self-autonomization of Architectonic Languages

We know with certainty that the Pythagoreans knew the relationships between string lengths and the pitches they produce. This mathematics applied to acoustics still holds its validity today. But the Pythagoreans also built a musical poetics based on this mathematics, advocating the excellence of certain conjugations of notes (related to each other by small integers) that we designate by the term harmony: the use of the harmony was supposed to produce the music that most appealed to the listeners.

So, we have documented evidence that mathematics was used consciously by the Greeks of the classical period, at least in music.

Given this, it is not difficult to believe that the architects consciously used mathematical rules in the Parthenon. Many studies point in this direction, although some do not seem to pass the sieve of empirical verifiability. There are numerous studies by art historians about the coincidences between built shapes and some geometric configurations that are only possible with advanced knowledge of geometry. In particular, there has been a search for the golden number in all classical architecture. Of course, if we try to discover geometric patterns to study the Acropolis or something else, with thousands of mathematical possible schemes, some of them will work. Many natural phenomena obey mathematical rules. Some even say that mathematics is the language of nature. Therefore, any construction in the real world will be mathematical, whether or not there is awareness of it.

But certain results defy the statistical probability of pure chance by a large margin, what compels us to think that geometric intentional patterns exist.[2]

We are not sure about the use of the golden ratio in the Parthenon. But after a few centuries, in the oldest architectural treatise that has come to our days, Vitruvius already focused on more complex semantic abstract constructions on geometry used

[2] Since we've talked about music, let's take a small example there. Someone has noticed that there are 11 repetitions of "Herr, bin ich's" in the area where Jesus announces "Einer unter euch wird mich verraten", in St. Matthew Passion by the divine Johann Sebastian. It seems credible that Bach chose the number judiciously: it is the number of apostles who are surprised, since the other was the traitor. But many other semiological observations by scholars about other numbers appearing in the Passion, 3, 7, various multiples, 22 and its sacred and esoteric derivations seem far-fetched.

in architecture—for example, symmetry (modulation and rhythm) and proportion. He reasoned about these new concepts, establishing some identification with the measurements of the human body.

But this use of formalizations in music or architecture appears with the germs of what seems to be two novelties. The first is the advanced nature of the mathematical language, with a developed structured internal semantics—the harmony, the symmetry, and the proportion. The second characteristic is the evaluation criteria that appeared far from the previous material motivations, seeming to be linked to the pure enjoyment of humans, who here also assumed a new role in relation to the product—that of spectator, an autonomous relationship between the piece of work and the viewer or listener, alien to the rest of the world around them. But this evaluation criteria had also a new feature: the evaluation was made not only considering the effect of the work on the world or the spectator, but also the very internal qualities of its language. Developments of these ideas constitute some of the positions of a discipline we now call aesthetics.

4 Struggles

We can perceive a new problem here. In its primordial roles, the methods used by architecture could be fairly well evaluated by their material results. With the new role of transforming, not the reality, but the perception of reality by human beings, the results appear much more confused and mediate. The transmitted values can appear as the goals and, many times, reified in the linguistic forms themselves.

For example, and in the case that interests us, geometry has the possibility to constitute a normative ideal of creating forms with meanings that seem disconnected from material reality. Geometric constructs can assume ideal value of the most diverse types—sacred, moral, political, and ideological. And they can even assume a value intrinsic to the geometrical language itself—for example, the Vitruvian proportion or symmetry.

So much so that the word form is currently associated in architecture with the geometric form or shape, making architecture an activity that transmits values through shapes.[3] Form appears throughout this text also with this meaning. But other meaning is used that should not be confused with that of form in "formal methods". Formal methods are methods that use formalisms from formal sciences such as mathematics. Architecture uses formal methods to produce construction projects, which will necessarily materialize in assemblages of materials with certain geometric shapes. But neither architecture nor formal methods are by any means limited to geometry.

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[3] That this is a common and current assumption can be seen, for example, on the "mathematics and architecture" page of a widely used digital encyclopedia (https://en.wikipedia.org/wiki/Mathematics_and_architecture), where mathematics appears to be reduced almost exclusively to the use of eye-catching geometric shapes.

4.1 Normative Versus Rational Methods

At the end of the thirteenth century, Jean Mignot was engaged as consultor for the construction of Milan's cathedral, whose dimensions/proportions were motive of great dispute.

It's said that, criticizing the work already done, Mignot claimed the famous sentence "*Ars sine sciencia, nihil est*"—art without science is nothing. This sentence can be misleading, as semantics has changed with history. When he said "*Ars*" he was referring not to the nowadays liberal arts, but to the know-how of the "*maître-d'oeuvre*", the technique, the empirical science of those days. The "*Scienca*" was then the mathematics, embodied in several theories of proportions in the plan, in the elevation and between plan and elevation, such as the medieval *ad quadratum* and *ad triangulum.*

Although those theories were not completely exoteric, they embodied several considerations deviated from reality, and filled with platonically objectified rules of a religious, ideological nature, obeying the symbolic needs of the Church.

What this kind of normative was proposing was the obedience of the constructor to the speculative proportions of something as the Solomon's temple or a divine proportion. In this case, of the gothic cathedral, we can see how a perfect formalism arrives to a perfect error. The proportions in debate were central to a major problem—the stability of the structure. Fortunately, the stone masters continued to apply that knowledge made of experience that had led their activity for centuries.

In the fifteenth century, Leon Battista Alberti[4] understood perfectly what this was all about. And he repeatedly insisted in the architect's need to know mathematics, but not for the sake of mathematics itself, nor the sake of speculative ideologies.

The renaissance could not coexist with the previously dominant neo-platonic Agustinean aesthetics and, instead, imported the Poetics of Aristotle. It was Alberti's historical job to translate what Aristotle made for literature to the field of architecture (and other arts, as he is well known for his treatises in painting and sculpture). And he translated the trilogy of Aristotle keywords—mimesis, metaphor, and catharsis—in the concept of *Concinnitas*, the aesthetic achievement of architecture, and the reflection of the order of the world in the order of architecture. In doing so, he cut with the old Vitruvian *venustas*, which Alberti called *pulchritude*, not without some despise.

This struggle between those key ideas of architecture (the formal based in reality and the ideological abstract formal) continued for centuries and is perfectly current even nowadays.[5]

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[4] Alberti, which is the object of one of the exhibitions in our 6FMA ("Alberti Digital—tradition and innovation in the theory and practice of architecture"), was one of the first that extended the formal methods to design automation. For example, he invented the premises of what we now call shape grammars.

[5] Of course, we have to add yet another strong paradigm—the informal or irrational approach, gaining force in the eighteenth century and having many worshipers in the present time, with the war cry "between poetry and reason, I choose poetry". But that's a topic for another time.

4.2 *"Be Tolerant in the Use of Linguistic Forms"*

We have already seen that abstract formalizations can harm architectural practice. Formal methods have to be seen inside a global rational methodology, one that uses advanced formal means for explicit reasoning, but applied to a certain domain of reality—the edification, and with a clear goal—promoting the accomplishment of the desired futures.

The golden number has been used throughout this text as a synecdoche for formal abstractions without a rationale. (a) At first, it is so widely misused as a formal normative that it transformed itself in a cliché, a platitude. (b) Second, there is no real empirical evidence that it has ever been used, in most of the reported cases. And there are even fewer demonstrated cases of intentional use. (c) Third, the intentional use seems to be irrelevant to solve the problem it is embedded in. The reason for the use of the golden ratio is because. (d) And fourth, the reasons listed for its use appeared to be weak and some even unfounded.

But we must not be radically restrictive. Rudolf Carnap, very wisely, wrote something like this: "Let us be cautious in making claims and critic in examining them, but tolerant in the use of linguistic forms".

So, let us be tolerant and see how the manifestation and dissemination of mathematical theses through architectural work may very well be the creation of representative and lasting examples of cultural assets.

This can be greatly strengthened if the forms used are not random but have some form of semantic relationship with other important domains of human life, or if they have semantics internal to the language itself that justify their use.

4.3 *Denotational Semantics*

A very successful case of external semantics is the aforementioned relation of architecture with astronomy.

Going back to the golden number, the (disputed) argument that it can be found in the proportions of the human body is a very good semantic relation, especially if you are also a supporter of the thesis of Greek architecture based on a human scale, as opposed to Egyptian.

Also, an external semantic relation is taken by the thesis of some psychologists (since the nineteenth century) that the golden ratio is perceived by humans in some way related with the concept of beauty. This one would be a very good argument in favor of the use of golden ratio. Unfortunately, later experiences with more accurate and modern methods did not confirm the thesis.

4.4 Denotation Through Connotation

Shapes possess a semantic network inside the formalization. For example, the simplest of those relations: If you want to provide quick access between two points, provide a straight path, because a straight line has that connotation with the shortest path between two points. Or a more complex one: the catenary is the optimal structural curve for a rope suspended on both sides, which serves as a base for the geometry of suspended bridges. However, and in many cases, the relationship can work both ways, from knowledge to reality and from nature to knowledge. The rectilinear movement of humans is little more than instinctive. And the ancients did not know infinitesimal calculus—the ropes of the old suspension bridges, as they are deformable structures, assumed the catenary shape, which is the geometry in which energy is minimal, obeying the physical laws of nature.

The pyramid shape is used by several civilizations to construct big things. Most of those civilizations had no contact with each other. Why had they built the same shape? Beyond the extraterrestrial explanation, there is the scientific one: the level of technological development did not allow otherwise, for structural reasons. That is the very good reason why, when someone needed to pass a message of great power, he made something so big no one else could do the same. But natural reasons limited the options to a pyramid. So, pyramid became the sign of the referent power. So it was, that many dynasties after the construction of the great pyramids, many tomb monuments of powerful people in Egypt were pyramids, although little ones.

A short parenthesis: all the theses defended in this chapter seem to destroy the Saussurean principle of the arbitrary nature of the sign, at least when applied to architecture. Reasoning processes conduct the creation of meaning. For this particular case, the arbitrariness of "pyramid = sign of power" is completely ragged by a multi-step operation of connotational and denotational semantics.

Some authors also discovered the gold number in the Egyptian pyramids.[6] Their slope appears to be close to the value of its arcsec which is approximately 52°. However, it is a documented fact that the Egyptians used the rule of construction of right angles by the triangle 3:4:5, where one of the angles is about 53°. In this case, there is no reification of the angle, it follows naturally from the constructive processes, in a connotational network that we now know.

The golden ratio has a very large semantic network. Some of those relations could very well be the basis of its successful use in architecture. For example, the golden ratio is a number related to the Fibonacci series. This series is highly invasive in most mathematical fields and natural sciences. It even deserves a periodic scientific journal. One of the possible uses of the internal semantics of the golden ratio could very well be in a evolutive construction expanding in a Fibonacci sequence, very frequent in natural phenomena. For example, a rabbit hutch.[7]

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[6] Which seems to contradict the aforementioned thesis of the non-human scale of Egyptian architecture.

[7] This caricatured example carries some irony in trying to apply to this very text some of the principles that we have been enunciating. We leave it to the reader to discover.

4.5 Interlacing Multiple Languages

There is a famous example of multiple formal reasons to the determination of geometric shape: the gothic ogive. At least three independent theories converge: the cultural symbolism (the upward direction with strong religious denotations), the structural (greater height for the same span reduces the stresses applied to the structural material), and the constructive (the intersection of two ogival vaults is almost circular, making the construction easier). When we reach this level of symbiosis, we are facing a masterpiece.

4.6 Development and Experimentation of Languages

The rational agent tries to optimize the solution, using fewer resources. He uses his decision skills based on what he knows. But he must be aware of what he does not know. In AI, the most sophisticated artificial agents reserve a part of their resources to do side work—in search of new and better knowledge, in permanent learning, to accomplish even better solutions next time.

In this way, all experiments around language development are welcome. In fact, mathematics itself does nothing else, often neglecting its immediate applicability.

One of the most used ways is that of generalization, which leads to methods or languages that respond to a larger set of problems, but can be expensive in terms of resources and less accurate in solutions. Introducing language restrictions is another way.[8]

It is what is done by the musical Pythagorean poetics of harmony, mentioned a few pages ago. No one will deny that this poetic rule, inscribed in broader musical syntaxes, modal, and tonal, used as a canon in Western classical music for many centuries produced wonderful music. On the other hand, its promotion to an irreplaceable aesthetic rule seems to be condemned by the acknowledgement of non-Western classical music trends and by the evolution of Western erudite music itself, especially in the last 100 years. Pythagoras has lost neither validity nor relevance in the science of sounds. Simply, now we know a little more on acoustics. But he lost poetic topicality, and he lost aesthetic validity—demonstrating that cultural values have an historical context of validity.

Returning to our leitmotif, there is nothing to oppose the use of the golden ratio (or any other normative) as a formal restriction to a very broad set of possibilities.

Another great historical example of methodological development:

[8] To be more accurate we should say that generalization of languages is only rarely carried out in major scientific, especially mathematical, advances. In most cases, our ideas or their materialization in actions are always carried out in restricted languages. In particular, all artistic objects or events are produced in a context of linguistic restriction. Popular culture even speaks of the artist's style. This is not to say that art does not do linguistic research. Some even say that this is the very griffe of art. What is meant is that the introduction of restrictive rules to language constitutes an inevitability of development.

Alberti's friend Filippo Brunelleschi invented the principles of linear perspective, with profound consequences for architecture and the fine arts. This method of drawing was a great aid to the design process in three main ways: in this new type of drawing, what you see is very similar to what you will see in reality, which makes the design more intelligible to an inexperienced observer; it makes it easier to correct the proportions between real and perceived; and finally, it helps to ensure the invariance of the proportion with the angle of view. This was another (as Alberti's shape grammars) great contribution of formal methods not directly to the convenience of the project resulting from the design process, but to the process of design itself, comparable to the CAD of our times.

We must stress that linear perspective is a method that brings together two ways humans have to understand space, the sensory and the conceptual, showing that there is no opposition between the intellect and the sensible.

4.7 Positioning Is not Arbitrary, but Socially Engaged

To complete the topic, we must say that explanations for the adoption of one or another methodological thought, as well as of one or another normative model, cannot be found within pure architectural theory. The various sciences have a say. There are reasons to make a commitment to one side or the other. Positioning is not arbitrary. For example, the social sciences claim that the various positions are supported by the social forces confronting in society, explaining why rational methods are prevalent in revolutionary times and norms are conservative.

It is not by chance that the famous manual by Giacomo Barozzi da Vignola, "*Regola delli cinque ordini d'architettura*", is a concatenation of strict geometric norms, with little or no elucidation of their reasons, which is known to have constituted a tool of the Counter-reformation to standardize the building under a single political and religious direction in times of great instability—the reformation, the rise of the capitalist mode of production, with all its enormous economic and social upheavals. Vignola's body of rules does not exist because it is a normative primer on crystallized beauty or perceptual delight. There were even material instruments that forced compliance with the rules—for example, the fires of the Inquisition.

Alberti and Brunelleschi are precisely on the opposite side, that of the revolutionary forces that were launching capitalist beginnings against the feudal order. Trust in rationality can be seen in the craziest act of trust in the entire history of architecture. The construction of Florence Cathedral began in 1296. The plan features a large hole in place of the crossing of the transept with the main axis, over 40 m in diameter. The hole was conceived without any concrete idea of how it would be covered. Only more than a hundred years later, in 1418, did Brunelleschi present his proposal for a solution to plug the hole, which was not completed until 1446. Only technological and scientific development, well intertwined with the knowledge of reality, to which rationality is not alien, allows for such adventures.

5 The Need for an Autonomous Architectural Formalization

Brunelleschi is also the actor of a determining historical fact. When he abandoned the corporation of constructors, he signed the certificate of birth of architecture as an autonomous profession.

And we must take this in mind: when he left, he took mathematics with him, to architecture, leaving to construction a few empirical and much less theorical knowledge.

After Alberti's "*De re aedificatoria*", many architectural treatises were given to press. Most of them dealing with geometry and mathematics.

Of course, history did not finish there. In 1638, Galileo published "*Discorsi e Dimostrazioni Matematiche, intorno a due nuove scienze*". One of the two new sciences was structural engineering. Galileo gave birth to the modern engineer, with its own mathematics, creating a more or less profound divorce from architecture that remains till nowadays.

Since then, engineering has deepened and deepened its links to mathematics. Architecture has its own way of ups and downs.

Certainly, the overall panorama has changed in architectural practice. And we must honestly say that the main reason of the spread of new techniques is due to the construction sector's pressure over the architect's office. Besides the old CAD, now BIM and GIS are widely spread digital tools.

But this favorable (to formalization) trajectory brings a very big problem. Architecture is bringing formalization from the outside, and not thinking architecture with autonomy. For example, BIM is very important to the industry and all its professionals. But it has nothing to do with the core thinking of architecture. BIM does not know what space is. Neither it knows what people or society are. Simply, space or people or humans in space or space for humans don't belong in BIM language. And without humans in space, or places, spaces for humans, we don't do architecture.

Today's professional architect is in charge of the tasks that the social division of labor has given him in the construction sector, in particular: the global framing of the project satisfying all kind of human needs,[9] the spatial organization of human life, the transmission of cultural values. All of these tasks are prone to formalization.

The needs of our epoch direct architecture to find new paths, paving the ground with new formal methods. What may we wish, as a final word: that our work in this symposium can be useful for the millenary epic of the permanent construction of architecture.

[9] What qualifies the architect, in this age of intense division of labor, as one of the last professionals who must be a polymath renaissance man.

Developments in Space Configuration, Accessibility and Visibility Analysis

A Spatial Analysis Proposal for Activity Affordance in Exhibition Halls

Mariana Yollohtzin Tafoya García

1 Introduction

If we think of a furnished room, it is usually possible to identify patterns of occupancy that happen inside. In a bedroom, for example, there are areas, such as the bed or a desk, that need to be reached to attend specific activities. There are also inner corridors, which are better kept unobstructed so that the bed, the wardrobe, and any other area of activity within the room can be reached. Given the disposition of the furniture, some corners may appear less fit for human occupation; these areas are commonly used for decoration or storage, when they don't remain vacant at all. What has been said of a bedroom is also true for many other places such as offices, living rooms, stores, and even individual exhibition halls inside museums. This paper shows some of the progress made in a master thesis that aims to understand if differences in an occupation like those described above can be explained through quantitative analysis and be related to attributes of the architectural space.

The problem at hand is one of spatial analysis constrained to a single room. A room is defined as "a part of the inside of a building that is separated from other parts by walls, floor, and ceiling". Thus, a room constitutes one single architectural environment into which the users then introduce additional elements that constrain perception and possibility of action to accommodate their needs. In this scenario, traditional spatial analysis methodologies appear to be insufficient. In the case of the two classical representations of space used by Space Syntax—the axial line and the convex space—the whole area of a room would be represented with too few spatial compounds. Visibility Graph Analysis (VGA) increases the resolution of analysis to analyze finer relations of inter-visibility. However, depth values indicate the number of steps among inter-visible spatial compounds named e-spaces; once again, no

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more than a couple of e-spaces are needed to describe a room. Convex mapping, axial mapping, and VGA methodologies are useful to describe visual complexity and probability of co-presence inside a building, but they do not necessarily explain affordances for activity.

A new analysis of inner space is proposed, which aims to describe the affordances of “being in a room” and “using a room”, in opposition to the traditional perspectives of “understanding space” and “navigating through a building”. The model is based on a regular hexagonal grid with topological and metric attributes that account for immediate accessibility and range of movement. An initial test is driven in five exhibition halls within two museums in Mexico City to examine the functionality of the model and its immediate outputs.

2 Literature Review

2.1 Quantitative Representations of Architectural Space

Space Syntax methods are used to divide space into discrete portions which can be described in terms of their topological relationships; that is, in terms of their relations of adjacency and permeability (Behbahani et al., 2014). These methods are a practical application of an area of mathematics called graph theory, where systems are constituted by independent components (nodes) and connections among them (edges). The set of techniques in Space Syntax includes convex analysis, axial analysis, and Visibility Graph Analysis. Each of these methods partitions the space in a different way, as will be briefly explained.

In the Space Syntax literature, *convex spaces* refer to areas in which no straight line drawn between any two points goes outside the space (Hillier & Hanson, 1984). Consequently, a *convex map* is defined as a near-minimal set of the biggest, non-overlapping convex spaces that cover the area of study (Turner et al., 2001). Since many rooms have an orthogonal shape, they can be considered as one single convex space that breaks at the door. Even in cases where the geometrical definition of convexity is not met, some researchers use the social function of the room to define the spatial entity (Behbahani et al., 2014). Therefore, when used on the architectural scale, convex map analysis mainly explains configurational relationships between rooms.

Axial mapping represents affordances for orientation in space and is closely related to problems of navigation. Axial lines refer to the longest lines of sight available, and an axial map is objectively constructed with the “fewest longest lines of sight and access in the system which traverse all the convex spaces (…) thus form a set of intersecting lines which represent all nontrivial rings of circulation” (Turner et al., 2001). In a primal axial map graph—where lines of sight are considered nodes and intersections are considered edges—axial lines normally run across different convex spaces. In a dual axial graph, where intersections are considered nodes and lines are considered edges, not all convex spaces are always captured (Behbahani et al., 2014). Overall, while axial maps are good for representing streets and corridors, they do not provide much information about the attributes of a room.

Visibility Graph Analysis (VGA) was designed to increase the resolution of analysis and portray subtle differences in spatial geometry. Turner et al. (2001) proposed to perform graph analytics over an orthogonal grid of points with an ideal spacing of around one meter, to represent human scale. In VGA, each point is represented by a node, and edges represent inter-visibility among them. For large sets of points, Turner et al. propose to cluster the points into endpoint partitions; the resulting e-spaces correspond to a minimal set of *isovists*—as defined by Benedikt in 1979—required to cover the area. It is important to notice that VGA does not portray physical adjacency between points of analysis; in consequence, a visible point on the opposite side of the analyzed area will be considered "lower" in depth values than a point that is situated closer but lies behind a visual obstruction.

The fine resolution of VGA indicates subtle differences in the geometry of space relative to the position of a viewer. The outcome is, for several metrics, a gradient of value consistent with the concept of visibility field suggested by Benedikt (1979) when he defined the concept of isovist. Visibility fields are nearly continuous and present more difficulty to illustrate regularities than former syntactic analysis. When used for the analysis of a whole building, mean values are obtained to synthesize a single visibility measure for each convex space. Koutsolampros et al. (2018) recognize the difficulty to relate presence to visibility metrics when analyzing small offices.

In summary, actual Space Syntax analysis provides a measure of our chances to become aware of space. Previous studies suggest a correlation between this degree of awareness potentiality and the proportion of people found in the proximity. However, not much has been clarified about the uses we give to the spaces that we have already become aware of. While there are some programmed activities which rely heavily on the inter-visibility of space—for example supervising or exhibiting, or in inverse attributes of visibility, when holding a private meeting—it may be erroneous to assume that every action of the occupants depends on visual attributes or centrality values that encourage copresence.

2.2 Considerations for Room Analysis

Traditional methodologies are useful to describe the degree of complexity in space when trying to apprehend it in detail. On the other hand, they do not represent intuitively the affordances of space for the development of activities. The distinction between occupying (being in) and circulating (navigating through) space demands some reflection on the premises of analysis:

1. The classic Space Syntax methodologies, whether based on axial lines or convex spaces, represent the relationships between different rooms. This leads to notions

about privacy and control but provides no information on the occurrences inside the social units of space, despite the intricacies of its own geometry.

2. VGA gridding system overcomes this issue. However, while trying to minimize the load for computing, the analysis focuses on the minimal covering set of isovists. As a result, depth metrics describe the complexity of the space only in terms of the difficulty to hold a visual grasp of it. This too might help understand how we grasp and navigate space, but not how we use it.
3. When analyzing the Farnsworth House, Turner et al. (2001) suggest that once inside the house, the glass walls can be considered as containing our sense of enclosure, and thus interpret them as borders for a visibility analysis. This approach may be taken also when "being in" a room, in opposition to "navigating through" it. In this scenario, people can be expected to comply with a program of activities for as long as they stay inside a room. In the meantime, the general configuration of the building diminishes in importance, in the same way that happens to the urban structure once we enter a building. This paper does not go further into the existence of local autonomy of behavior settings—as defined by Roger Barker (in Popov & Chompalov, 2012)—for each room in a building layout but explores the possibility of syntactic analysis given that premise.
4. VGA analysis states a difference between *visual accessibility* and *permeability.* When a graph is discussed in terms of visibility, it accounts for the inter-visibility of points at eye level. The permeability graph is a special case of a visibility graph constructed at the floor level, in such a way that furniture and other obstacles may be included in the system (Turner et al., 2001). In most cases, the permeability graph will be a subset of the visibility graph, which represents the points that are visible *and* can be walked into in a straight line. This means that the floor behind a desk will not be considered as directly permeable from the point of reference. In the way the analysis is constructed, the farthest corner of the room will appear more permeable than the floor behind the closest desk, for it requires less changes of direction while walking from the point of reference.

3 Methodology

A new representation of space is suggested to portray non-visual attributes of space, such as the immediate range of movement. Following the ideas of Turner et al. (2001), a cell of one-meter diameter is considered as a good representation of peripersonal space, where objects and our own body can be manipulated without requiring a change of position.

3.1 Construction of the Grid

The model is discrete, so there is a finite number of available positions in the area of study, corresponding to the center of each cell. Cells are arranged to form a hexagonal grid. Cells are addressed with two axes oblique coordinates indicating Row and Column, like those used by Luczak and Rosenfield for image processing (in Asharindavida et al., 2012). As a result of overlapping, the distance for columns and diagonal rows of the grid is 0.866 times the cell diameter.

3.2 Adjacency and Valency

A cell is considered contiguous to another if it is no more than one row and one column away, meaning that they share borders. Each cell has six contiguous cells which are labeled with the letters *A* to *F* according to their relative position (Fig. 1). A cell is considered adjacent to a contiguous cell if a straight line can be drawn from the vertex of one to the other, without any permeability obstacles. All adjacent cells are contiguous, but contiguous cells may not hold a relationship of adjacency. If the model was to be represented as a graph, each one of these cells would correspond to a node, and edges would express a relation of contiguity and permeability onto immediate cells.

Each cell has a valency that equals the number of adjacent cells. If the valency equals 0 then the cell is inaccessible. Valency from 1 to 6 illustrates the affordance of displacement for a person occupying a cell. Cells next to a wall will typically have valences averaging 4 points and narrow corridors will have valences as low as 2 points, signaling a determinate path for navigation.

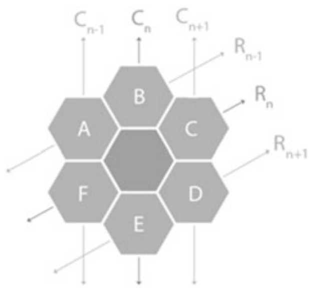


Fig. 1 Contiguous cells labeled according to their relative positions to a reference component

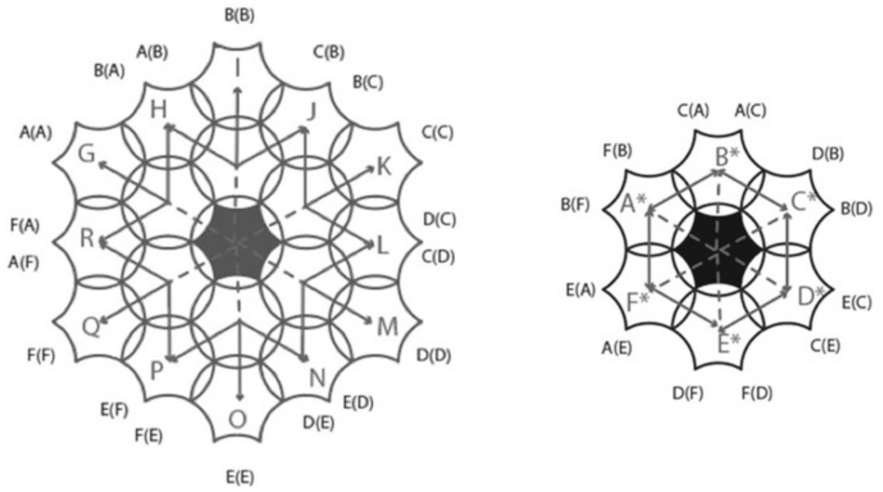


Fig. 2 Cells labeled from A to Q are accessible in a maximum of two steps when there are no obstacles. In case there are any obstacles within this area, accessibility in radio two can be inferred from the relations of adjacency of each node to the contiguous cells

3.3 Accessibility and Second-Degree Valency

A cell is accessible from another cell if there is an unobstructed path that allows it to be reached. Adjacent cells are accessible in one step. Contiguous cells which are not adjacent may be accessible in more than one step, given that the obstacle between them may be avoided. In this paper, a radio analysis of two steps is surveyed to evaluate the variability of the outputs. Second-degree valency is defined as the number of cells that can be reached with one or two steps from the position of reference. Second-degree valency may be derived from adjacency relationships as shown in Fig. 2. Note that different paths allow access to some of the modules. The least value for this metric is 0 for an inaccessible cell and the maximum is 18 for a cell with no obstacles in the vicinity.

3.4 Computation of Connections and Valences

Each accessible cell is computed into an Excel data sheet (Fig. 3), indicating its oblique coordinate address (columns A to C). In this case, a particular *id* was assigned to each cell, but such address may be replaced by the coordinate address as the combination of row and column is particular for each node (columns D and E). By adding or subtracting one column and one row to the oblique address (columns F to K), it was possible to retrieve the *id* of contiguous accessible cells by using the

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK
Hall	Column	Row	Address	Id	C_A	C_B	C_C	C_D	C_E	C_F	A	B	C	D	E	F	A*	B*	C*	D*	E*	F*	G	H	I	J	K	L	M	N	O	P	Q	R	1st V	2nd V
N1	12	23	C_1223	216	C_1122	C_1222	C_1323	C_1324	C_1224	C_1123	190	215	242	243	217	191	190	215	242	243	217	191	165	164	189	214	241	268	269	270	244	218	192	166	6	18
N1	12	24	C_1224	217	C_1123	C_1223	C_1324	C_1325	C_1225	C_1124	191	216	243	244	218	192	191	216	243	244	218	192	166	165	190	215	242	269	270	271	245	219	193	167	6	18
N1	12	25	C_1225	218	C_1124	C_1224	C_1325	C_1326	C_1226	C_1125	192	217	244	245	219	193	192	217	244	245	219	193	167	166	191	216	243	270	271	272	N/A	N/A	N/A	168	6	15
N1	12	26	C_1226	219	C_1125	C_1225	C_1326	C_1327	C_1227	C_1126	193	218	245	N/A	N/A	N/A	193	218	245	N/A	N/A	N/A	168	167	192	217	244	271	272	N/A	N/A	N/A	N/A	N/A	3	10
N1	13	01	C_1301	220	C_1200	C_1300	C_1401	C_1402	C_1302	C_1201	N/A	N/A	246	247	221	194	N/A	N/A	246	247	221	194	N/A	N/A	N/A	N/A	N/A	273	274	275	248	222	195	169	4	11
N1	13	02	C_1302	221	C_1201	C_1301	C_1402	C_1403	C_1303	C_1202	194	220	247	248	222	195	194	220	247	248	222	195	169	N/A	N/A	N/A	246	274	275	276	249	223	196	170	6	15
N1	13	03	C_1303	222	C_1202	C_1302	C_1403	C_1404	C_1304	C_1203	195	221	248	249	223	196	195	221	248	249	223	196	170	169	194	220	247	275	BRK	BRK	250	224	197	171	6	16
N1	13	04	C_1304	223	C_1203	C_1303	C_1404	C_1405	C_1305	C_1204	196	222	249	250	224	197	196	222	249	250	224	197	171	170	195	221	248	BRK	BRK	BRK	251	225	198	172	6	15
N1	13	05	C_1305	224	C_1204	C_1304	C_1405	C_1406	C_1306	C_1205	197	223	250	251	225	198	197	223	250	251	225	198	172	171	196	222	249	BRK	278	279	252	226	199	173	6	17
N1	13	06	C_1306	225	C_1205	C_1305	C_1406	C_1407	C_1307	C_1206	198	224	251	252	226	199	198	224	251	252	226	199	173	172	197	223	250	278	279	280	253	227	200	174	6	18
N1	13	07	C_1307	226	C_1206	C_1306	C_1407	C_1408	C_1308	C_1207	199	225	252	253	227	200	199	225	252	253	227	200	174	173	198	224	251	279	280	281	254	228	201	175	6	18
N1	13	08	C_1308	227	C_1207	C_1307	C_1408	C_1409	C_1309	C_1208	200	226	253	254	228	201	200	226	253	254	228	201	175	174	199	225	252	280	281	282	255	229	202	176	6	18
N1	13	09	C_1309	228	C_1208	C_1308	C_1409	C_1410	C_1310	C_1209	201	227	254	255	229	202	201	227	254	255	229	202	176	175	200	226	253	281	282	283	256	230	203	177	6	18
N1	13	10	C_1310	229	C_1209	C_1309	C_1410	C_1411	C_1311	C_1210	202	228	255	256	230	203	202	228	255	256	230	203	177	176	201	227	254	282	283	284	257	231	204	178	6	18
N1	13	11	C_1311	230	C_1210	C_1310	C_1411	C_1412	C_1312	C_1211	203	229	256	257	231	204	203	229	256	257	231	204	178	177	202	228	255	283	284	285	258	232	205	179	6	18
N1	13	12	C_1312	231	C_1211	C_1311	C_1412	C_1413	C_1313	C_1212	204	230	257	258	232	205	204	230	257	258	232	205	179	178	203	229	256	284	285	N/A	N/A	233	206	180	6	16
N1	13	13	C_1313	232	C_1212	C_1312	C_1413	C_1414	C_1314	C_1213	205	231	258	N/A	233	206	205	231	258	N/A	233	206	180	179	204	230	257	285	N/A	N/A	260	234	207	181	5	15
N1	13	14	C_1314	233	C_1213	C_1313	C_1414	C_1415	C_1315	C_1214	206	232	N/A	260	234	207	206	232	N/A	260	234	207	181	180	205	231	258	N/A	N/A	N/A	261	235	208	182	5	14
N1	13	15	C_1315	234	C_1214	C_1314	C_1415	C_1416	C_1316	C_1215	207	233	260	261	235	208	207	233	260	261	235	208	182	181	206	232	N/A	N/A	N/A	N/A	262	236	209	183	6	14
N1	13	16	C_1316	235	C_1215	C_1315	C_1416	C_1417	C_1317	C_1216	208	234	261	262	236	209	208	234	261	262	236	209	183	182	207	233	260	N/A	N/A	N/A	263	237	210	184	6	15
N1	13	17	C_1317	236	C_1216	C_1316	C_1417	C_1418	C_1318	C_1217	209	235	262	263	237	210	209	235	262	263	237	210	184	183	208	234	261	N/A	N/A	291	264	238	211	185	6	16
N1	13	18	C_1318	237	C_1217	C_1317	C_1418	C_1419	C_1319	C_1218	210	236	263	264	238	211	210	236	263	264	238	211	185	184	209	235	262	N/A	291	292	265	239	212	186	6	17
N1	13	19	C_1319	238	C_1218	C_1318	C_1419	C_1420	C_1320	C_1219	211	237	264	265	239	212	211	237	264	265	239	212	186	185	210	236	263	291	292	293	266	240	213	187	6	18
N1	13	20	C_1320	239	C_1219	C_1319	C_1420	C_1421	C_1321	C_1220	212	238	265	266	240	213	212	238	265	266	240	213	187	186	211	237	264	292	293	294	267	241	214	188	6	18
N1	13	21	C_1321	240	C_1220	C_1320	C_1421	C_1422	C_1322	C_1221	213	239	266	267	241	214	213	239	266	267	241	214	188	187	212	238	265	293	294	295	268	242	215	189	6	18
N1	13	22	C_1322	241	C_1221	C_1321	C_1422	C_1423	C_1323	C_1222	214	240	267	268	242	215	214	240	267	268	242	215	189	188	213	239	266	294	295	296	269	243	216	190	6	18
N1	13	23	C_1323	242	C_1222	C_1322	C_1423	C_1424	C_1324	C_1223	215	241	268	269	243	216	215	241	268	269	243	216	190	189	214	240	267	295	296	297	270	244	217	191	6	18
N1	13	24	C_1324	243	C_1223	C_1323	C_1424	C_1425	C_1325	C_1224	216	242	269	270	244	217	216	242	269	270	244	217	191	190	215	241	268	296	297	298	271	245	218	192	6	18
N1	13	25	C_1325	244	C_1224	C_1324	C_1425	C_1426	C_1326	C_1225	217	243	270	271	245	218	217	243	270	271	245	218	192	191	216	242	269	297	298	299	272	N/A	219	193	6	17

Fig. 3 Fragment of the data sheet used for computing valences in first and second degree for cells arranged in a hexagonal mesh

XLOOKUP formula (columns L to Q). Border cells are immediately signaled when some of the contiguous cells are not to be found ("N/A" is retrieved instead).

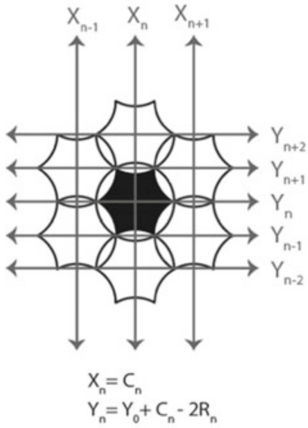
In terms of graph theory, the labels A to F in the data sheet do not try to represent the actual nodes, but the edges of connection to contiguous nodes. Since not all contiguous cells can be considered adjacent, obstacles must be represented to override some of the relations of contiguity retrieved in the data sheet. These broken links were manually introduced in this exercise using the label "BRK". Once the correction is made, it is possible to sum up the valid connections using the COUNT formula to obtain a 1 to 6 valency for each cell (column AJ).

Using XLOOKUP, accessibility in up to two steps can be evaluated for cells A* to F* and G to Q, following the logic shown in Fig. 2. If any of the available two-step paths is positive, then the id of the cell in the correspondent position is retrieved (columns R to AI). Once again, it is possible to sum up valid connections using the COUNT formula to obtain a 1 to 18 s degree valency for each accessible cell (column AK).

3.5 *Translation of Hexagonal Coordinates into Rectangular Coordinates*

The available programs for syntactic analysis are built using rectangular coordinate systems. To correlate the measures of adjacency with previous metrics, it is necessary to be able to identify the Cartesian position of the analyzed cells. The Cartesian position for each node can be derived from the oblique coordinates following a simple procedure. Coordinates are obtained for a reference cell in the first column. First, a row number is assigned for the cell; this is calculated from the original column and oblique row assigned. Cartesian x-coordinate is obtained by multiplying the column identifier by the distance between columns and adding it to the x-coordinate values for the reference cell. In the same way, Cartesian y-coordinate is obtained

Fig. 4 Transformation of the oblique address into rectangular coordinates using one point of reference (Y_0)



by multiplying the row identifier by the distance between rows and adding it to the y-coordinate value for the reference cell (Fig. 4).

Once Cartesian coordinates are calculated, it is suggested that each accessible cell can be weighted according to the single value closest to its center. Several visual metrics can be retrieved from the open software *Isovist_App 2.4.6* by exporting the available *CVS* (McElhinney, 2020).

4 Data

A total of five exhibition halls belonging to two contemporary art museums in Mexico City were assessed to evaluate the proposed model. The architectural layouts of Museo Universitario Arte Contemporáneo and Museo Jumex were redrawn from plans available on the web (Butler, 2013; Llamosas, 2016), while the temporary layouts and the disposition of art pieces was retrieved by means of a survey on site.

Each point within the area of study receives a set of non-orthogonal coordinates which describe its row and column. The area of study includes every cell accessible according to the architectural project. Then, obstacles are manually introduced into the chart by overriding the relation of adjacency with a tag indicating the broken links as identified in Fig. 5.

Three data sets were obtained for each hall:. First, the space as defined by the architectural designers; all circulations in the area are considered accessible; Second, the space redefined by temporary walls for the current exhibition, circulations, and other facilities behind closed doors is considered inaccessible; Third, including non-architectural obstacles, such as furniture or art pieces.

Fig. 5 Accessibility analysis of five exhibition halls. Colored lines represent edges or adjacencies broken by means of a permanent architectural element, temporal walls, and objects

5 Statistical Results

Figure 6 shows the summary of valency values observed for each hall in each of the three scenarios. The upper chart shows the cell count for each valency in the first degree. The lower chart shows the cell count for second-degree valences. First- and second-degree valency were statistically correlated for each of the 15 scenarios, showing a strong positive relation between 0.901 and 0.974 points.

Cell counts for first-degree valences (Fig. 7, left) show an average reduction of 9.2% for accessible space due to the segregation of vertical circulations and adjustments in the shape of the exhibition halls and segregation. An average of 2.7% of total cells became inaccessible due to the disposition of art pieces on the floor. Within

Cell count for first degree valency															
	S7			S8			N1			N2			N3		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
0	0	34	37	0	41	48	0	82	104	0	75	97	0	191	291
1	1	1	5	0	2	6	8	12	12	7	9	15	4	9	11
2	3	3	4	4	2	8	13	9	11	13	10	19	13	15	19
3	17	17	23	28	28	35	97	88	98	97	85	103	79	86	89
4	35	33	37	53	61	70	173	169	180	157	144	160	127	153	175
5	14	12	34	26	27	37	124	104	126	111	101	166	89	98	122
6	245	215	175	395	345	302	836	787	720	868	829	693	984	744	589
TOTAL	315	315	315	506	506	506	1251	1251	1251	1253	1253	1253	1296	1296	1296
Cell count for second degree valency															
	S7			S8			N1			N2			N3		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
0	0	34	37	0	41	47	0	82	104	0	74	96	0	191	291
1	0	0	0	0	1	1	0	2	2	0	2	2	0	2	2
2	1	1	1	0	0	1	1	1	1	0	0	0	0	1	2
3	1	1	2	0	0	0	0	1	1	0	0	1	0	0	0
4	0	1	2	0	1	1	3	3	3	3	2	2	3	3	4
5	1	0	2	1	1	5	4	3	4	5	3	8	5	8	9
6	1	2	4	2	3	8	15	8	8	16	8	17	14	6	5
7	2	3	2	4	4	9	7	6	8	5	4	11	6	11	15
8	3	3	2	6	6	7	17	18	21	23	17	17	18	21	23
9	1	1	10	5	5	14	58	54	57	54	53	50	43	53	56
10	16	13	15	24	23	24	79	80	87	80	77	90	62	79	80
11	32	29	26	41	43	41	63	60	69	53	47	63	55	54	62
12	14	15	15	25	30	30	79	85	84	75	79	94	56	75	86
13	0	1	9	7	6	16	82	81	85	76	77	76	61	74	92
14	2	0	20	5	4	16	68	50	64	55	41	59	40	44	54
15	43	40	37	59	66	63	116	107	115	105	96	114	85	83	91
16	0	0	14	8	8	20	75	59	72	60	51	124	34	43	66
17	12	12	31	24	25	37	89	73	100	87	79	134	61	68	79
18	186	159	86	295	239	166	495	478	366	555	542	294	753	480	279
TOTAL	315	315	315	506	506	506	1251	1251	1251	1252	1252	1252	1296	1296	1296

Fig. 6 First- and second-degree adjacency cell count for each of the cases of study. S7, S8, N1, N2, N3 refer to the hall, “1st” refers to the bare architecture space, “2nd” refers to modifications in layout and access permissions, and “3rd” represents additional obstructions caused by the display of art pieces

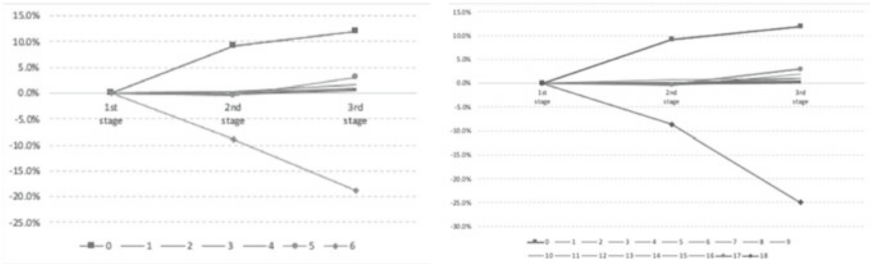


Fig. 7 Average variation in first- (left) and second- (right) degree valency for five exhibition halls in the following stages: 1st in the permanent layout as defined by architectural designers, 2nd considering the temporary partitions and enclosures specific for the exhibition, and 3rd including exhibition objects sitting in floorspace

each exhibition hall, there is stability in cell counts for second-step valency values between 1 and 5, with variations averaging up to 2.1%. On the other hand, cell counts for maximum values of 6 decrease by an average of 9% for the hall redefinition and a total of 18.9% for the final layout of the exhibition. Standard deviations are under 5.5 percentile points for valences of 0, under 2.1 percentile points for valences between 1 and 5, and under 7.2 percentile points for valences of 6.

The same analysis over second-degree valences (Fig. 7, right) shows identical values for valences of 0. An average of 2.7% of total cells became inaccessible due to the disposition of art pieces on the floor. Within each exhibition hall, there is stability in cell counts for second-step valency values among 1 and 17, with variations averaging up to 3%. On the other hand, cell counts for maximum values of 18 decrease by an average of 8.6% for the hall redefinition and a total of 25% for the final layout of the exhibition. Standard deviations are under 2 percentile points for valences between 1 and 17, and under 9.1 percentile points for valences of 18.

Several field analysis options available in *Isovist_App* were run against the halls of Museo Jumex to compare outputs. The graphic output shown in Fig. 8 suggests that the most similar metric within Visibility Graph Analysis is *Variance (Tv)*, defined as the mean of the square of deviation between all radial lengths and the average radial length of an isovist (Benedikt, 1979), which represents either complexity or eccentricity of an isovist (McElhinney, 2020). To correlate this value to the valences of the proposed analysis, each hexagonal cell was assigned the value of the *variance* of the closest coordinate exported from Isovist_App. Second-degree valences and variance had a correlation coefficient of −0.19 showing a weak negative relation among values.

In *DepthmapX-030*, most similar results were obtained by running a VGA map restricting visibility distance to 1 or 2 and retrieving the point first moment for the attribute of connectivity.

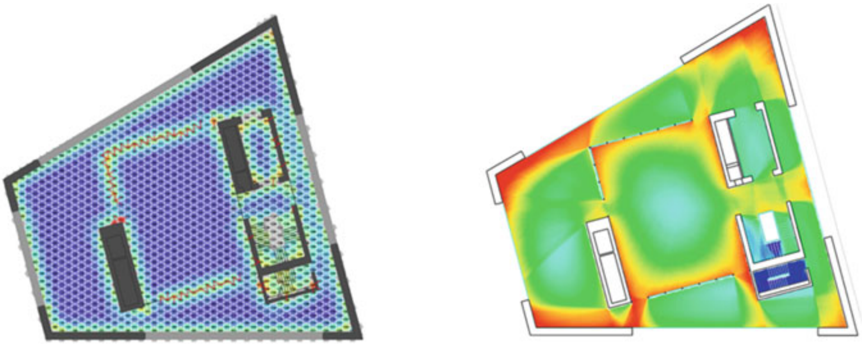


Fig. 8 Shows a graphic representation of second-degree valences (left), and variance of visibility as retrieved by *Isovist_App 2.4.6* (right) for hall N1

6 Discussion

The statistical tests show that the suggested representation is useful for illustrating the minimal areas left for occupation and inner transit in the assessed exhibition halls. In the 15 scenarios assessed, under 1% of the cells have a second step valency of 1 to 4, suggesting a minimum range of movement necessary for occupation and transit in exhibition halls. The reduction of higher valences in the adaptation of exhibition halls illustrates a possible preference to locate obstructions in the central locations of the available area.

An increase in the radius of analysis (second-degree valency) emphasizes the disturbances in accessibility caused by architectural or non-permanent obstacles. Nevertheless, the correlation coefficient described in (5.1) and the similarity between graphs shown in Fig. 7 suggest that the distribution of first-degree valences—expressing an immediate range of movement—might be a sufficient indicator for the general configuration of accessibility in a room.

As shown in Fig. 8, valences help to illustrate the position of different obstacles within the plan, indicating comprehensible portions of space (such as borders and corridors) which could be analyzed against the human presence of other syntactic attributes. Statistical information showed a weak correlation between valences and spatial attributes defined by Visibility Graph Analysis run with Isovist_App.

7 Conclusions and Future Work

This study examines the limitations of classic Space Syntax methodology to represent the spatial order in single environments. While Visibility Graph Analysis solves the problem of resolution, we found that visual attributes are insufficient to explain all spatial behaviors. A new representation is proposed based on the existing VGA, which addresses new types of accessibility relations among cells. The model arranges cells according to a hexagonal lattice and evaluates the relationships of adjacency using an oblique coordinate system.

An initial test was driven on simple spaces to understand the output. Even though data is not yet enough to establish statistically significant correlations, the results suggest some possible patterns. In the future, new data may be added to address other exhibitions that take place in the same museums. While the evaluation is now focused on museums, this kind of analysis may be carried out in other indoor spaces. Different patterns are expected according to context and architectural genre. This method might allow us to understand behaviors on the furnishing and inhabiting of spaces that are partially constrained by spatial configuration.

The suggested representation and mathematical relations were useful to account for accessibility metrics. Nonetheless, the visual recognition of obstacles and broken links is a slow procedure subject to errors. New strategies are needed for the automatization of this procedure. Also, other dimensions for the cell diameter may be tried to increase resolution, but accessibility metrics will also vary, so this variable should remain constant to allow comparison among studies.

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VISSOP: A Tool for Visibility-Based Analysis

Christoph Opperer

1 Introduction

The relationship between visuospatial properties and psychological response and behavior is among the most important considerations in architectural design. Visibility-based spatial analysis is a way to explore and understand these relations. From a conceptual and computational point of view there are currently two main approaches. The first approach is called isovist analysis, the second is based on the intervisibility of points and summarized under the term visibility graph analysis (VGA). Whereas isovists deploy geometric-spatial information for a particular position in space, VGA unfolds the relationship of different positions in space to each other.

Visibility-based analysis is typically divided into several actions, such as geometry generation and preparation, data calculation, visualization, data evaluation, geometry modification, and so on. Built upon Houdini's highly optimized data generation and manipulation capabilities, VISSOP provides the opportunity to perform all these different steps very efficiently within a single software environment. Most algorithms are therefore fully multi-threaded and have been written either in VEX, Houdini's internal high-performance scripting language running on the CPU, or in OpenCL to take full advantage of today's GPU processing power. To ensure a maximum of flexibility and customizability, only a few algorithms have been written in C ++ based on the Houdini Development Kit (HDK) due to performance reasons. Researchers who would like to implement their own custom algorithm or rely on VISSOP for prototyping new ideas and comparing results have full access to all the underlying geometrical and numerical data such as isovists, visibility graph, occluding edges,

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and so on. People who are not concerned with the inner workings can simply select those measures in the user interface which should be calculated. Due to the scope of the paper, it is not going too much into the technicalities but rather intends to point out what makes VISSOP different from already existing applications such as Depthmap/depthmapX (depthmapX, 2017), Isovist App (McElhinney, 2021), and DepthSpace3D (opo'arch, 2018) and demonstrates this in some examples.

The paper is divided into three parts. The first part provides a short overview of the basic background of visibility analysis and space syntax research. The second part explains what VISSOP is and how it works. The third part tries to highlight some of the possibilities offered by the software and shows what it is currently used for.

2 Background

An isovist is a geometric concept and was discussed first in relation to landscape architecture by Tandy (Tandy, 1967). In architecture, the term isovist fields were introduced some years later in a seminal paper by Benedikt in 1979 (Benedikt, 1979). Geometrically, isovists are a way to represent the amount of space (directly) visible from a particular vantage point and describe spatial properties from an egocentric perspective within the environment. Benedikt believed that isovists could quantify space to establish an "objective" method for understanding spatial qualities in terms of information associated with a static location in space. Derived from various geometric properties, he proposed several measures such as area, perimeter, compactness, skewness, variance, etc. to achieve a quantitative description of spatial environments. If the vantage point is not static but moving, the isovist changes continuously in relation to its position in space and the surrounding environment.

A further development of the concept of isovists within the field of space syntax research is the term visibility graph (Turner et al., 2001). Originally introduced by Braaksma and Cook (Braaksma & Cook, 1980) for measuring human orientation in transportation terminals, it was later rediscovered and methodologically developed by Turner et al. (Turner & Penn, 1999; Turner et al., 2001) and implemented as visibility graph analysis (VGA) in Depthmap (Turner, 2001). As opposed to isovists, a visibility graph describes space in terms of relations and in measures associated with global properties of space. Mathematically, a visibility graph is a discrete topological structure and, as such, expressed via graph theory. Conceptually it shows many similarities to models of spatial memory from cognitive science (Franz et al., 2005a). On the conceptual and computational level isovists and visibility graphs are fundamentally different and thus there is a clear distinction between these two approaches in the space syntax literature as noted by Psarra and McElhinney (Psarra & McElhinney, 2014). Even when both concepts are used in combination, as it is currently implemented in (depthmapX, 2017), this distinction is clearly reflected in the software.

3 How VISSOP Works

The motivation for developing VISSOP was twofold. On one hand there was the intention to bring space syntax research closer to architectural design practice by incorporating it in the early design phase. On the other hand, it was the idea to develop and establish a software application that is not a "closed" system, but "open" and flexible enough for developing, testing, and evaluating new ideas and concepts fast and simple. At the very core any visibility analysis application has to deal with three demanding requirements: (1) fast ray casting for visibility calculation, (2) data evaluation and manipulation, and (3) data visualization. Since all these requirements are perfectly met by SideFX Houdini (Houdini | 3D Procedural Software for Film & TV Gamedev | SideFX., 2022), it was the logical choice for using it as software framework on which VISSOP was developed upon. Although VISSOP is implemented in Houdini, it could be integrated in pretty much any software application by creating a custom plug-in with Houdini Engine (Engine & | SideFX., 2022). Beyond that and in addition to exchange data by simply importing and exporting it, Python, which is deeply integrated in Houdini can be utilized as "link" to any other application supporting it.

Most measures and tools provided by VISSOP are dedicated to the exploration and analysis of (architectural) interior space. For that reason, the focus is on isovist analysis, although visibility graph analysis is supported as well. Isovists are strongly associated with visuospatial properties and are an invaluable tool in understanding the relationship between spatial structures in relation to human experience and perceptual responses. However, to explore space to its full extent, it is imperative to apply three-dimensional isovist analysis in supplying its typical two-dimensional complement. To provide such a software environment for visibility-based analysis, VISSOP uses three different approaches which are: (1) geometry-based, (2) topology-based, and (3) image-based methods.

3.1 Relational Isovists

On the conceptual level, VISSOP follows the proposition of Psarra and McElhinney (Psarra & McElhinney, 2014) in discarding the distinction between isovists and visibility graph in favor of reinterpreting a combination of both concepts as a "*relational framework*" (Psarra & McElhinney, 2014) of geometric entities. In this context, the term relational does not refer to the mutual visibility of points in a graph; Instead, it refers to how isovists relate to each other in terms of overlapping areas (Psarra, 1997). Because VISSOP prioritizes the use of (geo)metric properties as much as possible it follows this approach. However, instead of relying on sub-sets of points (Psarra & McElhinney, 2014) and hence still capturing topological information, these sub-spaces are described solely geometrically based on sub-isovists. Mathematically

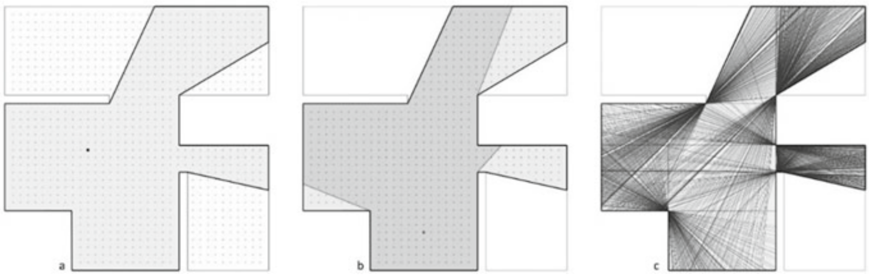

Fig. 1 Sub-isovist generation in favor of a geometric and continuous approach to visibility-based analysis. **a** Isovist; **b** sub-isovist from a single point within isovist; **c** sub-isovists from all points within isovist

it is a continuous approach and thereby it is independent of the number and distribution of vantage points. Topology-based calculations are thus replaced to a large extent, not least, in order to achieve consistency between the conceptual and the computational framework of VISSOP.

An example of briefly describing the aforementioned process is the measure of the clustering coefficient (Turner et al., 2001). The clustering coefficient is an important relational second-order measure describing the intervisibility between all points visible from a particular vantage point and is usually calculated on the visibility graph. Referring to the concept of overlapping isovists, it is the mean overlapping area between an isovist and all the isovists visible from it (Turner et al., 2001). Instead of calculating the clustering coefficient based on the visibility graph, VISSOPs approach is entirely geometric. This is done for the following reasons: (1) accurate geometric representation and computation, (2) calculation is not dependent on point distribution, (3) it is a mathematical and conceptional continuous method, and therefore (4) maintains consistency between computation and conception. For each point visible from a particular viewpoint, or in other words, for each point within the boundary of an isovist, VISSOP computes sub-isovists by interpreting the isovist boundary as new environment. Consequently, the more concave the shape is, the larger is the difference between the original isovist polygon and its sub-isovist polygons. The mean area of all sub-isovists divided by the area of the generating isovist is finally a measure for the relative intervisibility and thus the geometric equivalent to the clustering coefficient computed on the visibility graph (Fig. 1).

3.2 Visibility-Based Analysis Methods

The very heart of VISSOP is the generation of two- and three-dimensional isovists based on (vantage) points given by the user. It doesn't matter how these points are arranged. It can be anything: a single animated point moving through space, many points along a path, a two- or three-dimensional pointset, and so on. Usually,

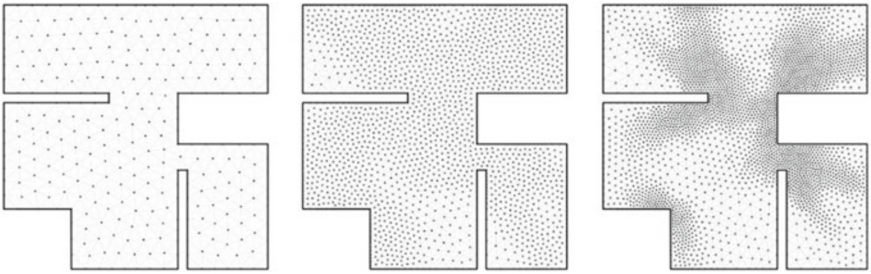

Fig. 2 Three iterations in which the distribution of vantage points is refined based on the measure of area during the analysis

points are arranged in the form of an equidistant grid superimposing the geometry of the environment. This, however, is not mandatory as VISSOP is able to handle irregularly distributed pointsets as well. Since most calculations are geometry-based as described above, this works without any loss of accuracy. VISSOP also provides the possibility to adaptively refine the input pointset based on several attributes and thresholds. The example illustrated in Fig. 2 shows three iterations in which a rather coarse distribution of points is iteratively refined during the analysis. In each iteration new isovists are generated and relevant measures are derived. The threshold for refinement is calculated based on the average difference between the local neighborhood in relation to the average difference for the entire pointset. In Fig. 2 it is based on the proportion of visible space (area) and hence comparable to the measure of revelation (Franz et al., 2005b; Dalton 2011). Therefore, the distribution corresponds to informationally stable/un-stable regions in space as described by Peponis et al. (Peponis et al., 1997). However, if it is nevertheless necessary to perform topological calculations on a graph, VISSOP computes for each input point the corresponding local area, or respectively volume (Meyer et al., 2003) based on adjacent triangles or tetrahedral and stores it as an attribute. When performing intervisibility checks, VISSOP then does not only count the number of visible points but also takes their assigned area and volume into account in order to compensate for irregular point distributions.

3.2.1 Two-Dimensional *Isovists*

To generate two-dimensional isovists, VISSOP uses a radial sweep line algorithm (Asano, 1985) and relies on the connectivity structure, rather than on point positions to circumvent precision errors. The resultant isovist polygon consists of vertices and edges only at the exact intersection between the isovist plane and the three-dimensional geometry of the environment and is an accurate two-dimensional representation of visible space around the vantage point. Several isovist measures, such as the mean radial distance, statistical data like variance and skewness (Benedikt, 1979), the calculation of autocorrelation and entropy (Stamps, 2005), and so on are dependent on an equiangular vertex distribution around the vantage point. If needed, VISSOP automatically generates a second, evenly vertex distributed isovist to calculate the particular measure. Once generated, it is kept in the internal cache for potential later use. Conventionally, an isovist represents a 360 degrees view around a static observer location. To account for movement, however, the user might want to use partial isovists (Conroy 2001) which are restricted by the field of view. In VISSOP, this can be achieved on a per point basis simply by providing a direction vector together with an angle.

3.2.2 2.5-Dimensional Isovists

2.5-dimensional isovists are technically the same as two-dimensional isovists and everything described above also applies to them. Based on a paper by Conroy-Dalton and Dalton (Dalton & Dalton, 2015) (even though it is concerned with the representation and not so much with the generation of isovists), the user can choose between the generation of tri-planar or contour isovists. As the name implies, a tri-planar isovist is the combination of three two-dimensional isovists lying in the x, y, and z plane whereas a contour isovist is the combination of several horizontal isovists from different heights. In both cases measures are derived from the single two-dimensional polygons which are then combined and averaged to get the final result at the particular vantage point.

3.2.3 Three-Dimensional *Isovists*

Isovists are naturally three-dimensional as Benedikt pointed out (Benedikt, 1979), yet most commonly their two-dimensional equivalent has been used so far in space syntax research. In VISSOP both versions are methodologically very similar in terms of how they are being generated. Like in two dimensions, VISSOP can either (1) generate an exact polyhedral representation of visual space or (2) generate an approximation by sampling the surrounding geometry in all directions from the vantage point (Fig. 3a, b). The former method relies heavily on geometry intersection calculations which are computationally expensive. The latter is based mostly on ray casting and is therefore much faster and computationally very robust. The directions in which rays are cast into the three-dimensional environment are typically uniformly distributed over the unit sphere. By providing a direction vector, however, the user has the option to weight the distribution, for instance, to emphasize the horizontal direction (Krukar et al., 2021). This results in isovists having a higher resolution in a particular direction which allows to capturing people's field of view in a more natural way.

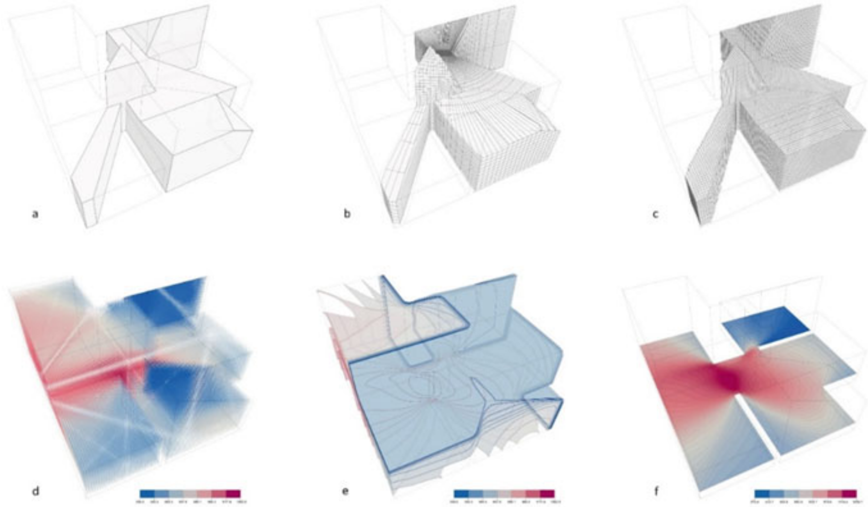

Fig. 3 **a** Accurate isovist; **b** approximated isovist; **c** visible points (voxels) from the vantage point. Amount of visible space visualized as **d** points (voxels) and as **e** isosurfaces. **f** Amount of visible space from vantage points at a height of 1.7 m above floor level

3.2.4 Visibility Graph

Conceptually and computationally, there is no difference between a two- and a three-dimensional visibility graph. Either way, it is based on the intervisibility of points in space (Fig. 3c). In VISSOP the user has the option to input a second set of points with a different distribution and density. Therefore, it is possible to use a very dense, high-resolution pointset as vantage locations but use considerably less points as "target points" for checking intervisibilities and constructing the graph. Varying densities such as adaptively (re)sampled volumetric grids are possible as well.

3.2.5 Image-Based Method

This method works technically the same as rendering an image. But instead of displaying a perspectival picture from a virtual camera, VISSOP uses raytracing to generate 360 degrees spherical panorama images from each vantage point given by the user. Such images are widely used in virtual reality applications, for example, to simulate an immersive environment. In the space syntax field, however, they have been used comparatively rarely with some exceptions (Chirkin & Pishniy, 2018; Christenson & Foobalan, 2012; Ünlü et al., 2019). Computationally, this method is similar to the generation of isovists. The main difference, however, is how ray directions are distributed and particularly how visible space is represented. Spherical images are typically either in equirectangular or in cube-map format. Because of its simplicity, VISSOP uses the former which is a simple way of representing a

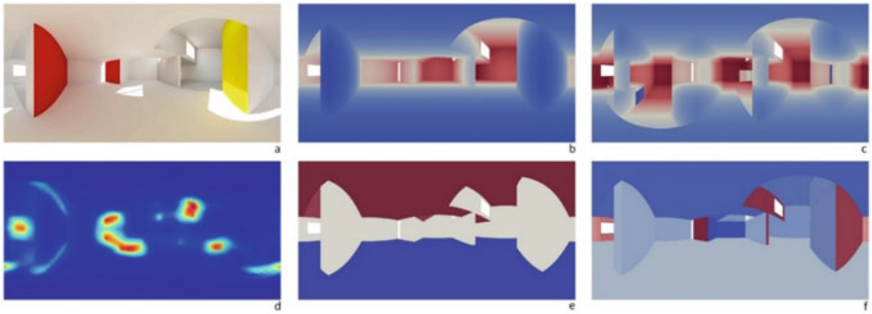

Fig. 4 Some examples of spherical panorama images showing **a** lighting and surface color; **b** radial distance to vantage point; **c** diameter distance; **d** saliency map; **e** surface normal; **f** surface class

sphere as a flat two-dimensional image. It works basically by mapping planar coordinates to angles in polar coordinates around the vantage point at its center. After casting rays in the directions of these angular coordinates, VISSOP either returns (geometrical) data from the ray intersection or initiates further calculations at this particular point in space. Any derived information from this ray will be stored in the corresponding pixel of the image. This might be the distance from the vantage point to the first ray intersection position. But it could be any number and type of data, such as the surface normal, surface luminance, color, etc. which will then be stored in multiple layers in the image. Figure 4 shows some examples in which scalar data is stored as grayscale pixel values whereas vector data is encoded as color values.

3.3 Measurements

VISSOP is able to calculate a large number of isovist and visibility graph measures as proposed in the space syntax literature. This includes typical measures, such as radial distance, area, circularity, etc. but also less commonly descriptors such as angular autocorrelation, fractal dimension, and so on are provided to the user. Each calculation could be performed based on first- and second-order visibility relationships (Turner et al., 2001) and many work in the two- as well as in the three-dimensional setting. Additionally, it is also possible to calculate local measures in relation to isovist in the (close) neighborhood to incorporate the notion of movement. Methodologically it works quite similar to the measure of revelation (Franz et al., 2005b; Dalton 2011) which describes how much visual space is revealed when moving from one location to another. In addition to already existing measures, several new spatial descriptors have been implemented and are currently being evaluated in an ongoing study. Due to the scope of this paper, they couldn't be described but some results are shown in Fig. 5.

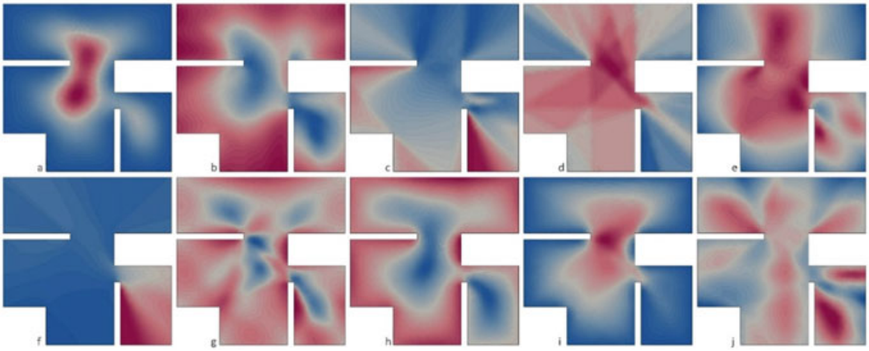

Fig. 5 Some isovist measures provided by VISSOP: **a** flow through, **b** isovist similarity, **c** wideness, **d** branching, **e** elongation, **f** occlusivity, **g** radial correlation, **h** drift, **i** through vision, **j** local symmetry

4 Applications and Possibilities

To demonstrate the potential of VISSOP due to its open framework of tools, it seemed important to give some examples. However, it should be noted that the following study is based on a hypothetical setup and several factors have been simplified for the purpose of demonstration. It is mainly intended to show what VISSOP is currently used for and to illustrate some possibilities in the field of visibility analysis by using it.

4.1 Case Study

Several studies have shown a significant relationship between visual properties such as color, texture, changing luminosity, etc. and the human perceptual response to physical space. Especially with respect to the experience of spaciousness and openness, light and color are fundamental factors (Stamps, 2010, 2011; Ünlü et al., 2019). A room, for example, might appear larger when it receives more light even though it is quantitatively smaller (Houser et al., 2002). Such attributes like color, light, and intensity are also often those visual features that are particularly eye-catching. The main tool for identifying those visual features that attract people's attention is saliency (Itti & Koch, 2000, 2001). Within the field of space syntax research the effect of saliency has rarely been studied and investigated mainly in relation to wayfinding and navigation (Bhatia et al., 2013; Psarras et al. 2019; Yesiltepe et al., 2021). This study, however, proposes a more general approach on how isovist analysis could be supplemented by saliency as a measure of human attention. Therefore, a simple three-dimensional geometric model is used as test-environment for incorporating a saliency detection algorithm (Hou & Saliency, 2007) from computer vision.

4.1.1 Texture-and Light Map Generation

In this study texture- and lightmaps are utilized to incorporate visual properties, such as natural light in the visibility-based analysis. Such a map is a simple way to store, for example, pre-calculated surface information like lighting and shadows of a three-dimensional scene as an image in texture coordinates. Texture coordinates are representing a three-dimensional model in a way, that surfaces (polygons) are basically unfolded and laid out flat in a two-dimensional plane. To calculate the lighting and rendering of the scene, Houdini's integrated render engine Karma was used together with a custom lens-shader to compute the texture- and lightmap (Fig. 7a, b). In addition to illumination, also the surface color and surface normal were calculated and stored in the map. Once the map is generated, rays that are cast into the scene for visibility calculation can return the texture coordinates from the intersection point between the ray and the three-dimensional model of the environment. These coordinates can then be used to lookup the corresponding pixel values in the texture- and lightmap to include this information in the analysis (Fig. 7c, d).

4.1.2 Saliency Map Generation

As a basis for the visibility analysis, 5000 points with a mean distance of 0.25 m between them were distributed uniformly in a two-dimensional plane 1.7 m above the floor level. Generating isovists based on ray casting is generally very fast in VISSOP, calculating a saliency map, however, is significantly slower and also does not have to be done from each position in such a dense distribution of points. Therefore, the number of locations from which a saliency map has been calculated was reduced to 100 points with a proximity distance of about 1.75 m. For each of these 100 points and relying on the pre-generated texture-/lightmap, a spherical panorama image with a resolution of 800 $\times$ 400 pixels was generated. To better reflect human vision, the vertical field of view has been restricted to an angle of 135 degrees, whereas the horizontal view was still covering 360 degrees around the observer point. Based on the image resolution, 320.000 rays for each of the 100 vantage points were cast into the three-dimensional scene to check for intersections between the ray and the environment. Texture coordinates, surface color, surface normal, and distance were returned from the intersection point and stored in a NumPy array representing the equirectangular panorama image for one point (Fig. 7e). Overall, this resulted in 32.000.000 data samples for the three-dimensional model of the architectural environment stored in 100 spherical panorama images as shown in Fig. 6.

Equirectangular images are stretched horizontally at the top and bottom. These regions of the image correspond to areas near the poles and are the result of unwrapping a sphere into a two-dimensional plane, or more precisely converting spherical coordinates to planar coordinates. Due to these distortions, saliency detection might fail and find visually outstanding regions in the image which do not exist as such in the "real" three-dimensional environment. To prevent this from happening saliency detection was not applied directly on the equirectangular panorama image. Instead,

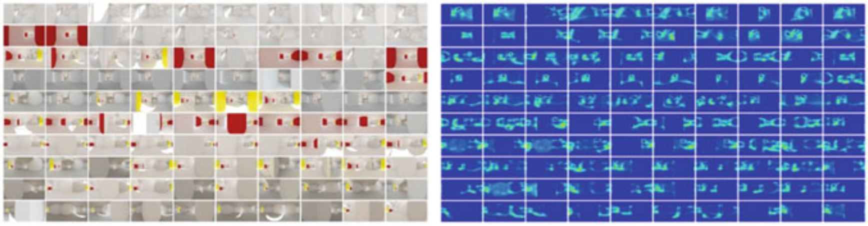

Fig. 6 Equirectangular panorama images (left) and corresponding saliency maps (right) generated to 100 vantage points

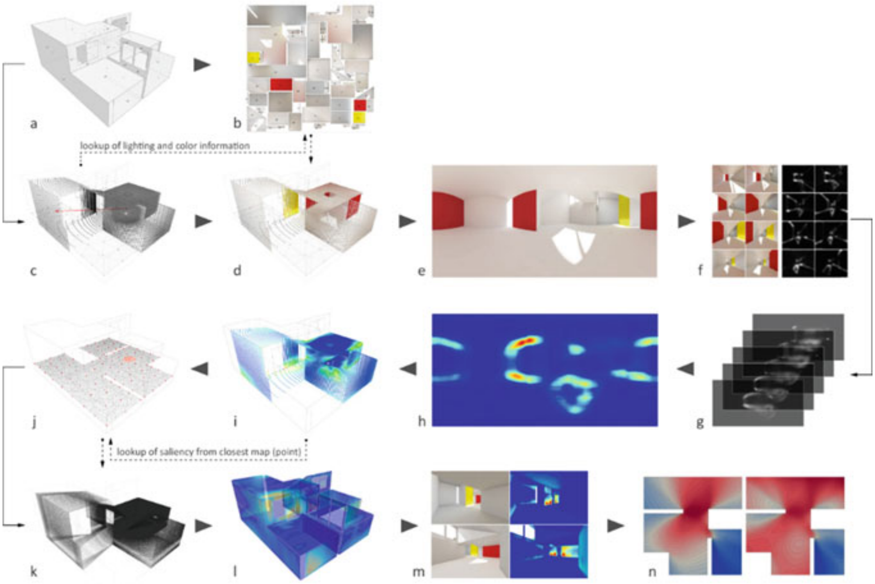

Fig. 7 Diagram illustrating the different processing steps described above. **a** Simple three-dimensional model as input for the entire process. **b** Texture- and lightmap which is generated by rendering the scene. **c** Lookup of lighting and color information, based on the texture coordinates at the ray intersection. **d** Lighting and color information for all ray intersections for a particular vantage point. **e** Spherical equirectangular panorama which is generated by mapping polar to planar coordinates; **f** Perspective images are extracted from the equirectangular panorama for saliency detection. **g** Saliency maps are converted back into the equirectangular format. **h** Heatmap visualization of the combined saliency map. **i** Pixel values from the saliency map are stored at the corresponding ray intersection point. **j**–**l** Isovist generation and lookup of closest saliency values. **m**, **n** Weighted isovist measures

the image has been processed in parts similar to the method described by Startsev and Dorr (Startsev & Dorr, 2018). To achieve this, a perspective image with 150 degrees horizontal and 135 degrees vertical field of view was extracted from the equirectangular panorama which was then used as input for calculating the saliency map. Once the map had been generated, it was converted back into the equirectangular format. This step was repeated for 30 iterations while the image's region to be extracted was shifted horizontally by 12 degrees. The resultant overlapping saliency maps were stored in a multidimensional NumPy array and combined by taking the highest value along the third axis to get the final map corresponding to the original equirectangular panorama image (Fig. 7f, h).

4.1.3 *Isovist Generation and Saliency Weighted Measures*

For each of the initial 5000 vantage points, a three-dimensional isovist with 32.768 vertices was generated. Usually, all vertices of an isovist are treated as equally important. However, this might not always be meaningful since people perceive visible space differently when salient features are in the field of view. To take such visual characteristics into account, the saliency maps were used as a weighting factor in calculating several isovist measures such as visible volume, area, longest line of sight, and so on. Each ray that was cast into the scene corresponds to a vertex of an isovist, respectively, a pixel in the spherical saliency map. This value was used in a simple linear weighting function to incorporate human attention in the calculation of isovist measures for better reflecting the experienced qualities of visual space. Since the weighting function was selected primarily for the purpose of demonstration, further studies are necessary to find an appropriate weighting scheme that relates to human perception (Fig. 7k, n).

4.1.4 Saliency-and Distance Weighted Ray Distributions

Referring to the proposition of building a "… sophisticated model of isovists that structures them variably across their extents, weighting them in different directions to capture differences in where people actually look" (Montello, 2007), this part of the study describes a simple way how saliency and distance maps can be used for weighting the distribution of ray directions for the generation of isovists. Usually, the rays which are cast into the environment are almost evenly distributed over the unit sphere. However, the problem is that areas of the environment that are farther away from the vantage point are captured in less detail whereas nearby regions are represented very accurately by the isovist. In order to compensate for this, an uneven distribution of ray directions is necessary. For each vantage location the distance- and saliency map from the closest point (the points which have been used in the saliency map generation described above) was selected and combined in a new weight map. This map was then normalized and used to weigh the distribution in such a way that more rays are cast in the direction of strong weight values, corresponding to distant and salient regions in the environment. Methodologically this process is very similar to the concept of importance sampling from statistics, which is used extensively in rendering (raytracing) for image generation.

5 Discussion and Future Work

Utilizing spherical panorama images for visibility-based analysis could open new possibilities and advantages, especially when they are combined with isovist and visibility graph generation. Techniques from computer vision and image analysis, such as saliency detection, object recognition, image segmentation, and so on, enable an enriched notion of isovist measures and could greatly facilitate space syntax research in relation to human experience and perception. As Ervin and Steinitz pointed out, being visible and being seen are not necessarily the same (Ervin & Steinitz, 2003). Saliency detection could be a way to account for and incorporate this fact in visibility-based analysis. Moreover, visualizing and interpreting three-dimensional isovists is not an easy task due to the rather abstract representation and the amount of data (Dalton & Dalton, 2015). Panorama images might be one step closer to a solution for this problem since images are a very common way to represent space; people are used to understand and interpret them effortlessly. When using a VR engine or a VR player, a panorama image is also a great way to give the user an interactive and fully immersed first-person experience of the surrounding environment by viewing it in the egocentric perspective from any vantage point. However, because people react differently to features in a spatial context than they do when inspecting images of scenes in a non-spatial context, further research in this direction is necessary. For that reason, image-based calculations are only used to support isovist analysis in VISSOP and not to replace it. The results of these studies are therefore to be evaluated and investigated in further research.

For performance reasons, geometry generation in VISSOP is currently mainly implemented in C++ . However, this is not ideal in terms of VISSOPs customizability. Since C ++ code has to be compiled, it is no longer (human) readable and therefore cannot be easily adapted to new requirements. To compensate for this lack of flexibility, VISSOP also supports ray casting and geometry generation using VEX, which is unfortunately slower. Various alternatives are currently being investigated.

6 Conclusion

This paper presented a new software tool that combines different approaches to visibility-based spatial analysis. Instead of developing a completely new program, VISSOP has been implemented in SideFX Houdini which is best known for its procedural geometry generation, data manipulation, and simulation capabilities. This decision was based on the consideration that (1) VISSOP, on one hand, should be simple and straightforward to use in architectural practice and design and (2) on the other hand it should also provide as many features possible to be used extensively for research as well. A key aspect of VISSOP is that it is not only intended as an analysis tool but also as a design tool within the early architectural design phase. So it is for instance possible to use VISSOP in combination with PDG/TOPS (PDG | Side FX) to automatically create and simultaneously analyze a large number of different design variants. A very similar setup can also be used to apply design optimization based on several constraints and requirements given by the user. Because of the scope of the paper, many of the features that VISSOP offers couldn't be described or are only briefly mentioned. VISSOP is able to calculate a large number of different measures from the space syntax literature which are not listed here due to the scope of the paper. Besides, many technicalities have been covered only superficially, not least because this is primarily a software paper. Nevertheless, we hope that VISSOP will be a valuable application in the field of space syntax research as well as within the field of architectural design.

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Restructuring Urban Form Through Restructuring Accessibility: An Integrated Urban Network Approach

Chen Yang and Zhu Qian

1 Introduction

Urban form, or the physical structure of cities, has attracted scholarly attention over a long time, especially that of urban morphologists (Gauthiez, 2004; Oliveira, 2016; Whitehand, 2018). According to Oliveira (2016), research on urban form deals with the "main physical elements that structure and shape the city—urban tissues, streets (and squares), urban plots, buildings, to name the most important" (p. 2). The built environment, while being created by people, also reinforces human socio-economic activities. Hillier (1997)captured this interaction vividly through the concept of "movement economy," which serves as the theoretical underpinning for the "circular causality" between physical structure and human activities (Omer & Goldblatt, 2016). Yang and Qian (2022) argue that urban form should not only be interpreted as a process in the space syntax approach but should be comprehended as a transect from a relatively micro and real-time perspective. Capturing the interplay between subjective (human) and objective (urban form) forces has thus been a flourishing intellectual battlefield for architectural and planning studies.

One interesting observation of the existing literature is that there is a glaring omission of underground morphological elements in understanding the interplay mentioned above. This is much more problematic especially when it comes to metropolises whose underground space is highly developed (Cui et al., 2012). Underground space includes many functional spatial elements such as metro systems, pedestrian underpasses, underground spaces of shopping malls and office buildings, and other functional spaces. Montreal's underground city is representative of this

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space. While the composition of urban form elements on the ground has been investigated at length (Kropf, 2009; Osmond, 2010; Scheer, 2001), the underground counterparts need further exploration (existing attempts include Chiaradia et al., 2005; Law et al., 2012). This research is not intended to provide a comprehensive analytical framework of underground morphology, rather, it serves as an entry point for further research in this realm. This work paid special attention to the metro system, especially its function of spatial connection (transportation) that facilitates direct connections between relatively distant locations. This research adopts space syntax to examine how the metro system contributes to the existing urban form through reinforcing accessibility. In addition, it seeks to highlight the importance of incorporating underground morphological elements in modeling urban form to make informative design and planning decisions.

Since this research uses accessibility as the proxy of investigation, it is necessary to elaborate on the relationship between accessibility and urban form. The attempt to understand cities through abstractions/modeling has been a long tradition, e.g., works done by the Chicago school (Burgess, 1935; Harris & Ullman, 1945; Hoyt, 1939). The space syntax theory focuses on street networks and uses graph analysis to predict the intensity of socio-economic activities of different spatial locations. The pre-assumption lies in that regardless of functional magnets, the configuration of street networks leads to spaces with diverse accessibility. The higher the accessibility, the more human flows and opportunities for socio-economic activities to take place. Therefore, the urban form can be analyzed through the quantitative indicator of accessibility (Papa et al., 2016; Srinurak et al., 2016; H. Zhou & Gao, 2020). While the concept of accessibility has been a key subject of research on measuring and interpreting the connections of urban spaces (Batty, 2009; Hansen, 1959), the space syntax approach focuses on the topological links of the street network. The approach has been challenged from different aspects, such as that it is over-reliant on relational connections and ignores physical geometry, and it is too theoretical (Batty, 2010; Jiang & Claramunt, 2002; Ratti, 2004; Turner, 2007). Nonetheless, it is still the most widely used and acknowledged spatial analysis and modeling approach in investigating urban form, given that it has also evolved for years with new metrics and theoretical innovations emerging (Hillier et al., 2012). Previous applications of space syntax mainly deal with urban street networks with scare attention paid to the physical structure of underground space, especially that of the metro system. As it is believed the diversity and density of human activities help determine local land use and built form, it is essential to capture how accessibility is redistributed through metro links.

This essay makes a novel contribution by proposing a preliminary approach to constructing an integrated urban network to investigate urban form. The remainder of this essay is organized as follows. The research methodology section offers step-by-step elaborations on how this research is undertaken to inform further research that builds on this work. The findings section presents the results in the form of both the conventional space syntax maps and quantitative statistics. The discussion and conclusion section respond to our research questions and point to the limitations of this work.

2 Research Methodology

The development of spatial technology has equipped urban scholars with more tool kits to capture the complex urban system. Tools like Depthmap (Turner, 2004), Urban Network Analysis (Sevtsuk & Mekonnen, 2012), sDNA (Cooper & Chiaradia, 2015), and Form Syntax (Ye et al., 2017) have already facilitated prior research in many ways. The emerging geographic information (GIS) system offers an integrated platform for conducting spatial analysis. The Space Syntax Toolkit (SST) of the QGIS platform (https://www.qgis.org/en/site/) is a handy and effective apparatus for performing space syntax analysis.

Traditional urban form research is often constrained by the availability of cartographic data. In the past decades, the trend of Web 2.0 is leading the paradigm shift in terms of data generation and data collection. The OpenStreetMap (OSM) emerged in this context and soon became one of the most successful Volunteered Geographic Information (VGI) projects (Fan et al., 2014). In addition to the traditional map dataset, crowdsourcing can provide a mass of spatial–temporal data through various sources, including social media, the point of interest, and location-based services. These two datasets provide urban morphologists with information about their key research interests: the physical pattern of the urban fabric and the socio-economic activity pattern in cities. Furthermore, the crowdsourced data is an important complement to the conventional datasets generated from the top-down system and offers a new lens to understand the city organism. The data quality of OpenStreetMap (OSM) has improved substantially in recent years in the Chinese context (Zeng et al., 2017; Zhang et al., 2015). As such, the street network and metro network of Xi'an were retrieved from OSM using plugins in QGIS. This research only focuses on the inner-city of Xi'an which is bounded by the second ring road (Fig. 1). This area reflects the historical spatial patterns of ancient Chinese cities. This specific boundary is determined on the consideration of Park's (2009) recommendation on boundary selection to refrain from edge effects.

Since this research also considers the socio-economic activities of cities, POIs data are introduced as a proxy for such non-physical factors. POIs data have been an important indicator for measuring urban vitality (Jin et al., 2017; Ye et al., 2018; Yue et al., 2019). In this sense, it is plausible to deduct that it reflects the intensity of human socio-economic activities. The POIs used in this research were collected from the web map API of the Chinese Baidu Map (equivalent to Google Map). A total of 14,959 geotagged POIs were collected. Although they are categorized under different groups based on their functional variances, we regard them as homogenous since it is not this research's objective to differentiate functional effects (interested readers can refer to Yang and Qian, 2022).

Figure 2 shows the workflow of this research. We borrowed the method of creating an integrated network from Law et al., (2012) but with a few updates to better suit our case. Law et al. used a short segment at metro stations to link two networks. We also use this technique but take advantage of particular intersections as the natural links, where we did not specify the "unlink" point in unlink layers (refer to Al-Sayed et al.,

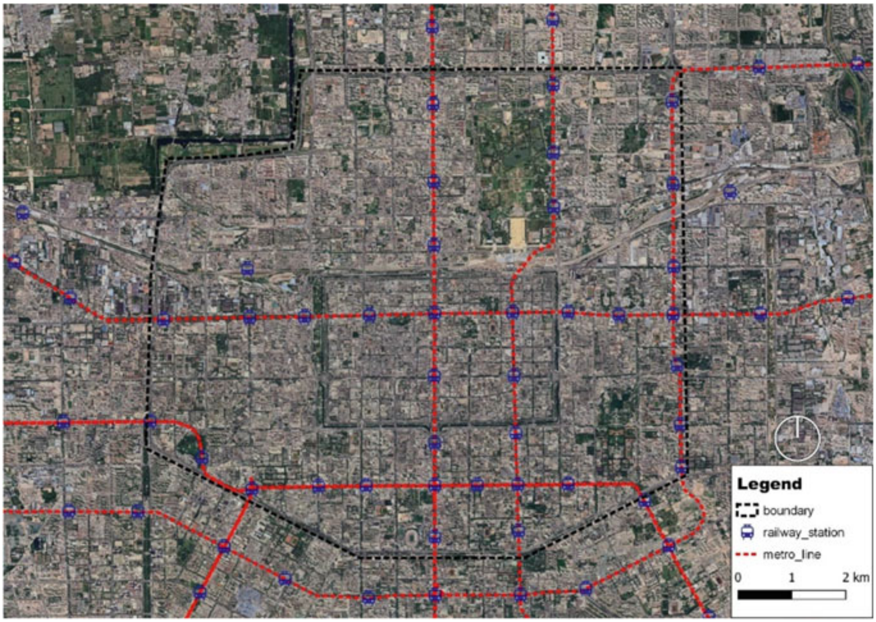

Fig. 1 Research area and boundary

2014). As Fig. 3 shows, we first constructed two axial maps for the two networks and transformed them into segment maps in QGIS through SST. Subsequently, we specify the unlink points at relevant intersections of two lines, so the two lines are considered disconnected. We use segment analysis and specify the radii at 400 m, 800 m, 1200, and n to examine the structure at different scales, from local to global. We used the two most widely used and credible indicators of the analysis output, normalized angular choice (NACH) and normalized angular integration (NAIN) (see details in Hillier et al., 2012). In principle, the NACH value corresponds with movement flows through spaces and the NAIN value indicates the degree to which people clustered at the spatial location. Therefore, the former can be used to predict human movement patterns and the latter can be employed to identify urban core areas. We performed spatial join in QGIS to calculate the sum of POIs within 400 m (around 5 min walk) of each metro station. Then, we used bivariate correlation analysis to validate which network fits more closely to the real intensity of socio-economic activities as reflected through POIs counts at 36 metro stations.

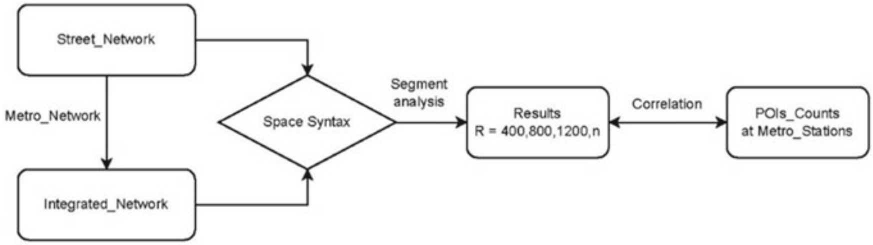

Fig. 2 The workflow of the research

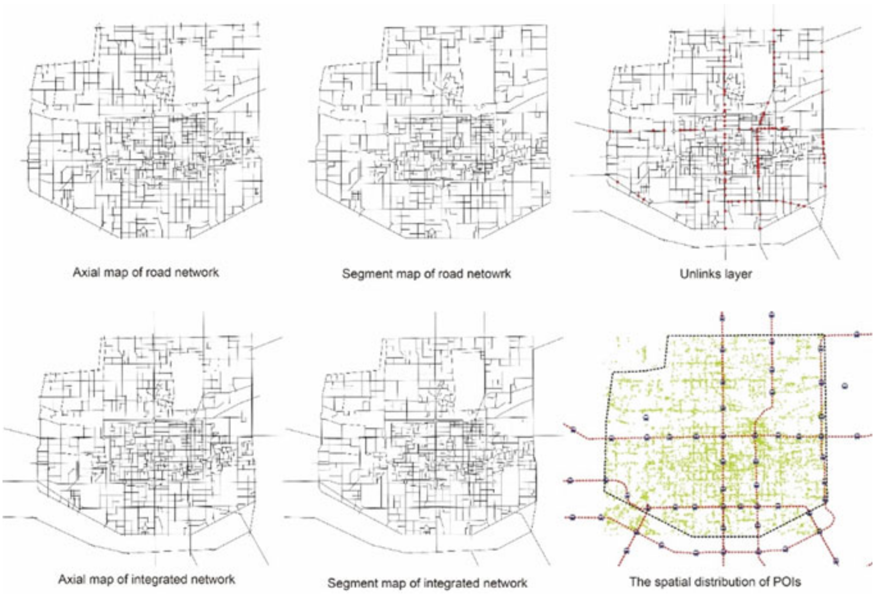

Fig. 3 The construction of spatial models

3 Research Findings

3.1 The Qualitative Spatial Patterns

We used the traditional red-blue contrast color range as the symbology to show the different urban form patterns. Figure 4 shows the results of NACH at different radii. The result of radius at 800 m is not presented since it did not make a substantial difference. We consider the three radii of n, 1200 m, and 400 m as macro, meso, and micro scales, respectively. Both 4_a and 4_d capture the primary routes of travel in Xi'an. While 4_a highlights some vertical and horizontal thoroughfares in the city, there is no clear pattern of these red lines. In contrast, red lines in 4_d evidently cluster along the metro lines. Moreover, the pattern of red lines in 4_d is reinforced based on that in 4_d by metro lines. This is quite comprehensible as the location choice of metro stations is often determined by the intention of linking existing core urban areas. It can therefore be inferred that the metro network significantly influences human movement patterns at the macro scale. We attribute this to a cognitive technique adopted by travelers in daily life: "it is never to our knowledge how the real underground rails traverse in our city, but we always plan our trips according to the topological metro diagram that is posted everywhere" (Yang & Qian, 2021, p. 5). The population of Xi'an proper is around 8 million, and the ridership of the Xi'an metro system was around 2.8 million per day in 2021. This sheer magnitude of human flow through the metro system makes it increasingly important to incorporate the metro network into the urban network system.

As for the meso scale, neither 4_c nor 4_f shows effective results. Considering that the distance between two metro stations ranges from 800 to 2000 m, the use of a radius of 1200 m may only capture partial effects exerted by the metro network onto the integrated one. If we take a closer look at 4_f, we can find only metro line 2 (the vertical one at the center) is less segregated from the whole network. Other metro lines are mostly in blue, which indicates there are less likely to be chosen for through-movement. The observation may lead to a conclusion that when dealing with analysis with a radius larger than 1200 m, the metro network's contribution to the overall system is limited. In fact, the average distance between the two stations of the Xi'an metro is from 1.21 km to 1.43 km. This also supports our assertion above. Further, 4_b and 4_e have almost identical patterns since the analysis at the radius of

Fig. 4 The spatial patterns based on NACH

400 m reveals only local facts. The Metro network may even have negative impacts on the whole system. Looking closely at the inner-city, many red lines disappear, suggesting a decrease in NACH value (we will discuss this in the following sections).

Figure 5 shows different patterns based on NAIN value. The cluster of lines with high integration value (red cluster) points to the cities' urban core or integration core (Hillier et al., 1993). However, if we interpret 5_d through this conceptualization, it may lead to a paradox since underground spaces like metro lines cannot serve as space for people's gathering. Then, what should we deal with the red lines that have been deemed as "destinations" in conventional space syntax analysis? Since it only makes sense to consider metro stations in a metro-related network, we hereby interpret the NAIN map based on the proposed concept of "red cross node" (highlighted in the black circle). Notably, this concept only works for the global scale analysis since such nodes are not seen in other maps (5_e and 5_f). The result at the meso scale, especially 5_f offers new insights. Similar to the NACH results at the meso scale, the metro network only has limited effects on the road network. Yet, the metro network in 5_f is more integrated into the road network compared to that in 4_f, as fewer blue lines are displayed. While it is hard to provide theoretical accounts for this examination based on the existing data, we deduct that this is because of the functional synchrony between the metro network and the functional attractors spatially dispersed in cities, especially with a spatial spacing of around 1200 m. The results of NAIN at 400 m (5_b and 5_e) report analogous findings to that of NACH: considering the potential effects of the metro network is not necessary.

Fig. 5 The spatial patterns based on NAIN

3.2 The Urban Spatial Structure

The above section qualitatively presents our findings. This section uses the star models (Hillier et al., 2012) to help construct a quantitative understanding of the two networks based on comparative analysis. According to Hillier et al., (2012), the high and low points on the vertical axis are the mean of NACH (top) and NAIN (bottom), while the left and right points on the horizontal axis are the maximum of NACH (right) and NAIN (right). The means (vertical axis) represents the background network and the maxima represent the foreground network (see deep discussions in Hillier, 2014, 2016). While Hillier uses the star model to make comparative studies on different cities, we invoke the model to provide further elaboration on the two networks used in this research.

Figure 6 illustrates the spatial structure of the two networks at three radii. It is evident from 6_a that our model's foreground is much stronger than the background. This is consistent with Hillier's findings on Beijing's spatial structure. Both Beijing and inner Xi'an city are capital cities of ancient Chinese dynasties and share the same traits of spatial layouts. Given that the foreground shaped by long axial lines represents the urban transformation driven by microeconomics while the background constructed by short lines indicates local socio-cultural activities (Yang and Qian, 2022), the current form of Xi'an is heavily influenced by historical legacies. There are slight increases in both NAIN_max and NACH_max in 6_b in contrast to 6_a, whereas there are small decreases between 6_d and 6_c as well as 6_f and 6_e. Such changes imply the integrated network while reinforcing the foreground at the macro scale, weakening the foreground at the meso and particularly the micro-scale. The increase in NAIN_mean and NAIN_max in 6_b indicates the increase in the accessibility of the whole system, whereas the decrease in both indicators in 6_f points to the opposite. In other words, the integrated system is conducive to city-level planning, but such planning may undermine the local neighborhoods. This reminds us of the battle between Jane Jacobs and Robert Moses in the 1960s. The planning aims for a city's overall structure may not serve the people in small neighborhoods.

3.3 Implications on Land Use Planning

The final stage of this research is to investigate whether the proposed integrated network can have practical usage in informing urban design and planning practices. We performed a bivariate correlation between the outputs of space syntax and the intensity of socio-economic activities (POIs). Table 1 lists the results. In terms of the road network model, NACH_400 is the only indicator that shows a significant correlation. As for the integrated network model, both NACH and NACH_1200 report statistically significant correlations with the intensity data. It is worth noting that the four integration metrics all fail to predict the intensity of human activities in the selected metro stations. This is an interesting finding which is completely

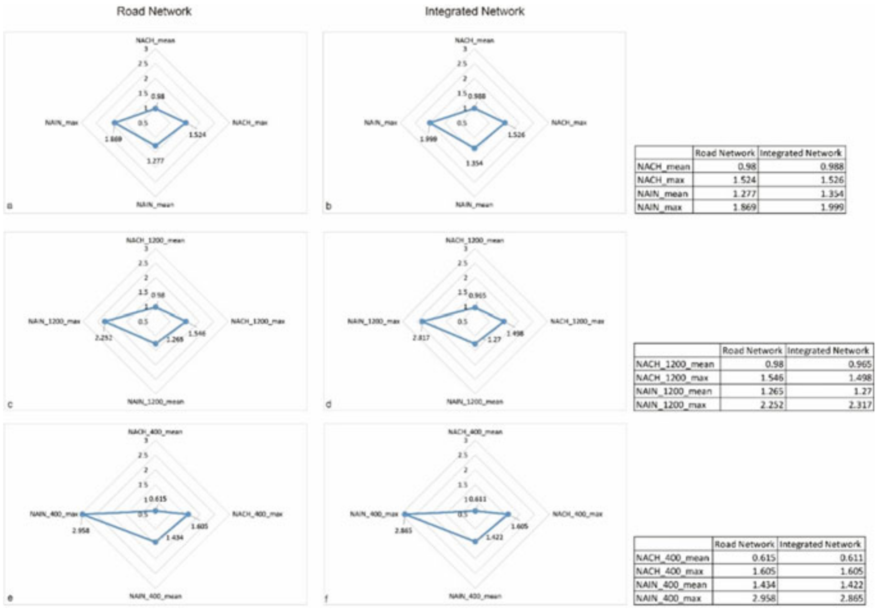

Fig. 6 The star models of the two networks at different scales

different from our findings in the qualitative patterns (Sect. 3.1). The possible explanation for this variance may lie in the essential difference between the road network and the metro network: The former travels through the space of human activities continuously, while the latter can only be connected to the space of human activities at discrete nodes. To wit, while in theory, high integration captures the most clustered space for human activities, it does not speak for underground space since the only place that is capable of housing human activities are metro stations. This pre-defined spatial arrangement goes against the basic assumption of the application of integration metrics. On the contrary, the choice is a more suitable quantitative metric.

Table. 1 The correlation results

	NACH	NACH_ 1200	NACH_ 800	NACH_ 400	NAIN	NAIN_ 1200	NAIN_ 800	NAIN_ 400
Road network	0.195	0.268	0.164	0.393**	0.231	0.076	−0.125	0.023
Integrated network	0.377*	0.283*[a]	0.264	0.274	0.251	0.04	−0.008	0.128

Notes *indicates significance at the 0.05 level (2-tailed). **indicates significance at the 0.01 level (2-tailed). [a]significant at 0.05 level (1-tailed).

Then, what do these significant correlations imply? Our interpretation points to a suitable scale for the selection of models. As we argued above, the integrated network best captures the urban spatial structure at the macro scale (radius at n), may partially explain the structure at the meso scale (radius at 1200 m), and completely dysfunctions at the micro-scale (radius at 400 m). The data of POIs count represent the socio-economic activities around specific locations, which is more of a force that shapes the background of cities. It should also be noted that we also count the POIs within a 400 m radius of metro stations. In this sense, the correlation between NACH_400 and the intensity is easy to understand. When it comes to the integrated network, the correlation at the macro scale reveals that the metro network has been an integral part of urban spatial structure regarding reconfiguring people's movement patterns city-wide. But is this conclusion biased since the "gates" are metro stations that are originally arranged based on the metro network? This question can be responded by that there is no correlation between NACH_400 and the intensity based on the integrated network model. That is, if the integrated network exerts no effect on the road network, there should be a significant correlation between NACH_400 and the intensity. Since there is no such correlation reported, the metro network does have a potential impact on the road network and this impact is not at the micro-scale.

Another question raised regarding the results is that while the indicator NACH_400 has already provided a relatively effective prediction for the intensity, why do we need the additional integrated network? We should revisit Hillier's concept of the dual-structure generic city. In megacities, the transit system especially the rapid railway system has become an essential tool for connecting within the expanding urban areas. The development of the foreground is driven mainly by microeconomics. In traditional urban morphology studies, the foreground system tends to remain stable and durable throughout history, like the axial avenue of a city (Champs-Élysées in Paris, Yonge Street in Toronto, Qianmen Dajie in Beijing). Because of the difficulty in promoting massive reconstruction to the foreground system, they have become the symbol of a city. However, by incorporating metro lines into the morphological system, the path of metro lines becomes an integral part of the foreground system. The key point is that metro lines are rapidly expanding in many fast-developing cities, including many megacities in China and future cities in other developing countries. This phenomenon challenges the epistemology adopted by space syntax researchers and urban morphologists in broader terms. As such, the additional lens of the integrated network is imminent, especially for the planning efforts that address sustainable development through facilitating high mobility and accessibility by the advanced transportation system.

4 Discussion and Conclusion

This essay is among early attempts to conceptualize underground morphology and investigate its potential implications for future cities' urban design and planning practices. In doing so, this research proposed an integrated network based on the space syntax approach and uses POIs data to validate the model. The findings of this research shed light on future studies on urban form in the following aspects. First, with the development of subway facilities in urban areas, more people's travel patterns will be impacted by the availability of transit services. Although the locations of metro stations are pre-defined, the human flow directed by the metro network is bound to influence the intensity of socio-economic activities around such nodes. As our qualitative results suggest, the existing urban spatial structure is reinforced by the metro structure. Second, the integrated network is more applicable for the analysis at the macro scale. The threshold for an effective integrated network may be hinged upon the average distance between two metro stations in reality (between 1.21 km and 1.43 km in our case). This should be a prerequisite in applying the integrated network in urban modeling. Furthermore, the metro network may even negatively impact the road network on the local scale. As we indicated above, an integrated view may be conducive to city-level planning but may disrupt local neighborhoods. Third, we argue that the metro network is an essential component of cities' foreground. The foreground of cities is often considered as the historical legacy that is less likely under reformation. However, in many emerging cities, the embracement of the railway system has been underway. This micro-economic force that drives the restructuring of cities' spatial structure warrants heightened attention. Nonetheless, the metro system should also be viewed with caution since it is physically inaccessible to its surrounding space and human activities. Therefore, the integrated network may create discrete patterns and need tailored interpretation in contrast to traditional explanations based on the color pattern created by space syntax.

While this research provides insights into underground morphology, it has some limitations that are not adequately addressed. We only focus on the urban areas bounded by the second ring road in Xi'an, which makes it hard to include all the existing metro lines in our model. This problem should be addressed in future by constructing a city-wide model. Second, conventional space syntax analysis often uses pedestrian movement intensity gleaned from gate observation to verify model results. Using POIs as the proxy for socio-economic activities may not be ideal. Other indicators based on new urban data (Y. Zhou & Long, 2016), such as POIs density, land use diversity, or mobile data may be more effective. Lastly, it is necessary to point out the limitations of building an axial map model in the space syntax approach. The only available way to distinguish the metro network from the road network is to specify "unlinks" at every intersection of two lines. This process is very time-consuming. Our model only captures major roads in the inner area of the city, but we have to manually input more than 150 unlink points. Constructing an integrated model of larger spatial coverage would be a daunting task.

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Urban Design, Architecture and Space Syntax in the Conception of Public Spaces—A Look at Luanda'S Revitalization

Ana Cristina Inglês, Luísa Cannas, and Teresa Heitor

1 Introduction

This paper is part of Ana Cristina Inglês's ongoing PhD research that investigates ***How Public Open Spaces can serve as catalytic tools for city centres' urban revitalisation*** using Luanda's city centre as a case study. The goal is to propose an adaptive model to intervene in Luanda's city centre, contribute to its revitalisation based on sustainability principles and take Public Open Spaces (POS) as an urban fabric tool to promote vibrant public life and social inclusion.

Cities are layers of architectural built forms around public open spaces. Each structure carries its meaning in time and relates to historical events and socio-cultural practices set on a given site. Furthermore, the visual and natural qualities of the site contribute to one's delight in the place. There is no city without the urban network of buildings, roads, parks and infrastructure, but all of that means nothing without people. The poetry of architecture, the forms, shapes, architectural styles and languages produce different effects on its surroundings and set the public space 'wallpaper'.

It is essential to acknowledge that urban revitalisation poses an opportunity to rethink the urban fabric to improve social interactions, socio-economic conditions of the community and urban sustainability in a broad sense (Taherkhani, 2021).

Promoting downtown living is one of the proven avenues to achieve positive city centre revitalisation (Ito et al., 2019). Decades of research have focused on public life

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and public space (Carmona, 2021; Gehl & Svarre, 2013; Grodach & Ehrenfeucht, 2016). Evidence in the literature indicates that some of the most critical features of POSs that promote pedestrian walkability and public life are land-use diversity, commercial ground-floor façades and the layout of POSs (Lamour et al., 2019). Furthermore, pedestrians' perceived safety, the reduction of space dedicated to cars and increased space dedicated to pedestrians are also essential characteristics (Ibid.).

Historically, urban revitalisation projects and the use of public space in globally known cities are well documented (Carmon, 1999; Lamour et al., 2019). However, there is still a novelty in documenting revitalisation processes and POS interventions in less affluent cities, especially in the developing world (Jaszczak et al., 2021), such as Luanda in Angola.

Some studies suggest recent trends that urban tourism gives priority to public spaces and that public spaces used in urban revitalisation function as symbols of the city and proved helpful to revitalisation strategies (Muneerudeen et al., 2016; Ramlee et al., 2015). Moreover, as is the focus of the ongoing research, the importance of public spaces is documented as essential to increasing leisure-time walking and social interactions (LTW) in high-income countries, but with a dearth of evidence in middle-income countries. (Florindo et al., 2017). Functionality and the appealing aesthetics of the architecture and urban design improve the quality of experiences of POS.

The proposed argument is that a model of intervention that creates a network of public open spaces in Luanda's downtown that promote vibrant public life needs analyses and understanding of the local socio-economic and socio-cultural context and its spatial configurational properties.

The paper uses the revitalisation of the Bay of Luanda as a starting point, one of Luanda's prominent landmarks. Over time, it has served as the city's most important public open space. However, the Bay lacks connectivity with the inner city.

This paper has two parts. The first introduces the theoretical approach that combines Urban Revitalization theories, the importance of Public Space to public life and Space Syntax as the welding element. Space syntax, as a methodological approach and a set of tools, provides insights into POSs potentials and their dialogue with their surroundings within the hosting city from a configuration point of view. These insights, in turn, allow analysing and measuring the impact of public space interventions in an urban revitalisation strategy.

In the second part, we apply a speculative academic exercise to Luanda's Central Business District (CBD) using space syntax methodology and tools to understand the existing fabric. The main parameters analysed are walkability and pedestrian movement patterns that inform the positioning of commercial activities to promote and optimise social interactions. Space syntax makes it possible to think of space differently by focusing on the organisation of spaces, movement patterns, and their social meanings (Bendjedidi et al., 2019). This approach is chosen for the current research because it links physical configurations and people's spatial behaviour.

2 Theoretical Framework

2.1 Urban Design Theories and Practices

Urban revitalisation poses an opportunity to rethink the urban fabric to broadly improve social interactions, community socio-economic conditions, and urban sustainability (Taherkhani, 2021). In the ongoing research, the focus is the fostering of social interactions and social inclusivity.

The need to intervene in the urban fabric dates from the 1930s, with western industrial cities in the United Kingdom (UK) and the United States (US) facing precarious conditions of sanitation and insalubrity. Governments acted to provide better housing conditions and implemented zoning separating working, housing, commercial and leisure areas (Carmon, 1999; Gehl & Svarre, 2013).

Urban revitalisations of the 1930s, 1960s and 1980s vary in strategies. However, the experiences accumulated over the years have improved each new generation of revitalisation, and this process continues today. The improvement of urban living conditions is not a new topic. The clearance of slums and physical determinism marked urban interventions from the 1930s. Modern movement ideology of zoning, bedroom neighbourhoods and long commuting hours prevailed in the 1960s. Lastly, micro revitalisation interventions and neoliberal approaches took over from the 1980s onwards (Carmon, 1999; Carmona, 2021; Gehl & Svarre, 2013). The constant need to maintain and improve the built fabric is the theme of numerous studies and research.

From a historical perspective, urban redevelopment policies in the western context had the United Kingdom and the United States as leaders in the policy design and implementation process. These strategies spread within and across continents, with countries such as Canada, France, Sweden, Holland, West Germany, Israel and Australia following suit. However, each country adopted changes appropriate to its economic and social realities. The commonalities in the implementations of these policies '*are partly attributed to international policy transfer, but to a larger extent, are related to similarities in the socio-economic and socio-political developments in Western countries, particularly after World War II*' (Carmon, 1999:145).

The introduction of the sustainability debate surfaced in mid-1980s (Gehl & Svarre, 2013). The need for humankind to reconcile its existence with nature and learn from it gave a new twist to contemporary interventions to become mindful of using low carbon and low embodied energy materials (Ferrão & Fernández, 2013). The construction industry is increasingly searching to strengthen regional economies while fostering the spread of technical-scientific knowledge developments globally (Almy et al., 2021; Ferrão & Fernández, 2013).

It is essential to recognise the importance of the introduction of neoliberalism in the 1980s (Harvey, 1989, 2006), which surfaced with reduced funding from governments in urban interventions and the private sector taking over the management of basic urban services; governments took a more legislative and monitoring stance. Neoliberalism impacted interventions on POSs by being increasingly directed at profit gain and less socially oriented (Carmon, 1999).

Another theme surfaced during this time, governance (Bevir, 2016; Brogan, 2020; Fainstein, 2020) which introduced a multi-stakeholder and co-participatory approach to urban interventions. Contemporary urban revitalisation interventions largely involve state-citizen and public–private partnerships (Carmon, 1999; Watson, 2009). However, by 1990s urban revitalisations failed to reduce the gap between the haves and have-nots and produced islands of revitalisation around seas of urban decay (Carmon, 1999; Harvey, 2006), and this perception lingers on.

The are some considerations worth noting. Firstly, the scale of interventions of urban redevelopment projects has reduced over the years, as has state investment. Another vital aspect to point out is the travelling aspect of these policies amongst western cities and the global south.

For example, colonial powers have experimented with modernist urban planning in colonised cities (Maia, 2019; Milheiros, 2012). In fact, Luanda´s downtown urban plan revised in 1960 by Architect Simões de Carvalho, anticipated a Civic Centre (Maia, 2019:99), Largo da Mutamba, further discussed in the Luanda´s Space Syntax analysis´s section of this paper. Civic Centres are characteristic of Le Corbusier´s modernist Public Space design (Sequeira, 2012:4). An example of the civic centre as a public space, is found in Le Corbcusier plans for the new city of Daint-Dié in France between 1945 and 1946 (Sequeira, 2012:2).

Neoliberalism's positive impact on western realities did not reflect in the global south and the sub-Saharan African context specifically (Pieterse, 2002; Watson, 2009). Some of the challenges in the sub-Saharan African countries relate to the lack of strength of the private economy sector (Castells, 1983) and the centralised nature of the majority of the national governments in place coupled with extensive areas of 'informal settlements' (Pieterse, 2000, 2002, 2004; Myers, 2011). Investments in unproductive sites of high population density, concentrated poverty and overall national economic dependency are a longstanding challenge to independent African nations (Castells, 1983). Furthermore, navigating between political-administrative structures and understanding the operation of visible, invisible and hidden interests in power is as important or even more than technical expertise to achieve gradual change (Pieterse, 2004). Nevertheless, citizen agency, passive resistance from government officials, and urban governance have been able to fend off unwanted changes in the urban fabric of African cities (Croese, 2018; Bekker et al., 2021) and push for meaningful transformations.

Luanda's population density registers more than 7 million inhabitants (GPL et al., 2015). Its unique urban culture and characteristic informal appropriation of public space by informal traders or the pop-up markets and cultural music and dance events call for a strategy that takes advantage of these initiatives for the city's urban life.

2.2 *Public Space and Public Life*

Lessons from decades of urban revitalization stress the importance of professionals in urban design and architecture to understand everyday life dynamics (work, leisure,

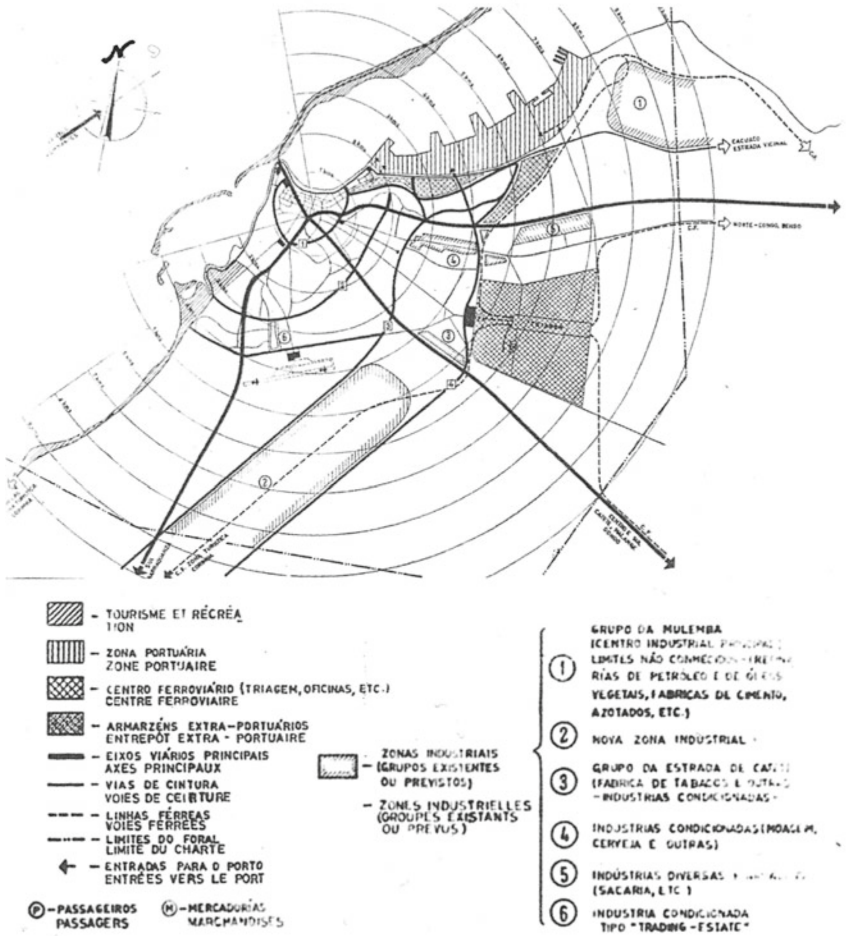

Fig. 1 Schematic diagram showing the study of the road network for Luanda´s 1961–6 Master Plan by Architect Fernão Simões de Carvalho. The two axes intersecting in the city centre correspond to Rua Amílcar Cabral (North-West to South-East) and Avenida de Portugal (South-West to East). The point of intersection is Largo da Mutamba. (Photo from the archive of POR-ARQ, FA-UL in Maia, 2019:97)

entertainment, shopping, health and education and public social interactions broadly). This understanding serves as the basis for the design process to create spaces that respond to the need and aspirations of the community (Gehl & Svarre, 2013) rather than merely produce an urban aesthetic add-on to the city.

Understanding people's behaviour in space, the way they use and inhabit space, is essential to building pleasant public spaces (Bendjedidi et al., 2019) that attract residents, tourists, investment and employees with a direct impact on cities economies and intercity competition (Gehl & Svarre, 2013). The argument is that preferred

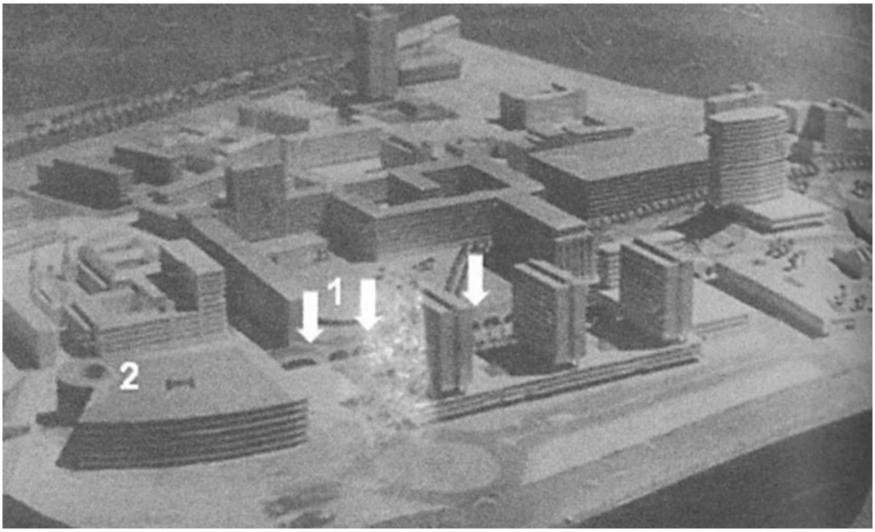

Fig. 2 Study model of Luanda´s CBD for the 1961–6 Master Plan by Architect Fernão Simões de Carvalho. Number 1 represents arcades under which a tunnel would link to the Island of Luanda. Number 2 represents the proposed exclusive pedestrian Piazza. Number 3 represents a multistorey parking building proposed. (Photo from the archive of POR-ARQ, FA-UL in Maia, 2019:100)

Fig. 3 A collage of photos of Largo da Mutamba from the 1970s on the left (Maia, 2019:100) and 2021 on the right (Ana Cristina Inglês)

spaces are those characterised by the most attractive visual properties experienced by the stationary person and a good variety of activities (Carmona, 2021).

Direct observation is one of the methods explored by Jan Gehl for more than three decades (Gehl & Svarre, 2013). Other tools include the dialogue–based tool, an interdisciplinary approach based on interviews, workshops and community involvement developed by Project for Public Spaces rooted in William H. Whyte's studies and founded by Fred Kent in the 1970s (Ibid).

Computer-aided methods for studying public life emerged during the 1980s, including GPS tracking and Space Syntax. Hillier (1996) stresses the importance of the correlation between the visual properties of a given space and people's behaviour around it statically or dynamically.

When referring to urban space, Hillier (2005) considers the city to be composed of two cities: the physical city (with buildings and physical elements) and the experiential city (the space experienced between buildings), in which the spatial network and space are the shared medium. Social interactions and human behaviour associated with perceptions of public spaces and the presence of people in public spaces is the crucial feature of public spaces that urban design can improve and encourage through the physical planning (Gehl, 2011).

3 Methods

3.1 Space Syntax and Public Open Space Revitalization

It is amid criticism about the modern movement zoning urban planning and urban design that at the end of the 1970s, space syntax was first put forward and applied by Bill Hillier and colleagues (Almy et al., 2021; Bendjedidi et al., 2019). Henceforth, many scholars used syntax analysis in various fields, such as studies on urban traffic, urban street layout, and urban space design, the latter of interest for this research. Through Space Syntax is possible to think of space differently by focusing on the configuration of spaces, movement patterns and their social meanings (Bendjedidi et al., 2019). The method is chosen for the current research work because it provides techniques and tools that allow spatial analysis to understand the link between spatial and physical configurations and people's behaviour (social aspect).

The space syntax research field started to be developed in the early 1970s by Bill Hillier, Julienne Hanson and colleagues at the Bartlett School of Architecture, University College London. Hillier and colleagues are considered the forerunners of this field. The first published bibliographic records are in the article entitled 'The man-environment paradigm and its paradoxes ' (Hillier & Leaman, 1973). However, the publication of detailed information about the name and theoretical basis intended to develop with space syntax appeared in the article 'Space Syntax' (Hillier et al., 1976). The books 'The Social Logic of Space' (Hillier & Hanson, 1984) and 'Space is the Machine' (Hillier, 1996) present further published information on Space Syntax analyses.

Apart from being an effective tool to identify and simulate human spatial systems, potential uses of space, their social interpretation and the impact that form has on its function, space syntax relies on a synthetic and expressive visual representation of space, the so-called axial map. The axial map consists of a web of a small set of axes—called axial lines—illustrating the whole spatial system covered by a road network. This graphic representation of urban fabric or buildings is called the 'syntactic model', which is considered an abstract representation of how spatial systems configurations.

The simplistic nature of the representation reduces the importance of geometric configurations of architectural and urban features and focuses on the cognitive processing of spatial information. Syntactic representation thus aims to represent the physical and visual continuity experienced by the users of a spatial network. The axial map does not portray visual obstacles but rather the potential of accessibility based on the observer's visual perception.

From the perspective of public space, the axial analysis allows the visualisation of the entire network and the accessibility patterns it displays. There is evidence of using Space syntax to enhance economic performance (Yamu et al., 2021). Based on the axial analysis, for example, it is possible to position commercial activities (hotels, restaurants, shops) in locations of the road network that show a high probability of pedestrian movement. On the other hand, positioning health and educational facilities in locations offering quieter and safer surroundings becomes facilitated through an axial analysis of the site.

'Syntactic analysis is based on rigorous mathematical descriptions using a set of algorithms developed within the graph theory. The axial graph of an axial map is a graph in which the vertices or nodes correspond to the axial lines, and two vertices are adjacent if and only if the corresponding axial lines intersect. The axial graph contains information about the connections of each axial line with all the others that constitute the system and allows analysing the relative position of each line concerning all the other lines' (Heitor & Silva, 2015:149).

Therefore, each line's properties obtained do not vary according to their conditions but with their inserted position (topological) in the system.

3.2 Axial Analysis

Amongst all measures developed and tested by the spatial syntax community, two have become the reference when analysing urban configurations: Choice and Integration. These two syntactic measures related to the concept of 'natural movement', i.e. the proportion of urban pedestrian movement determined by the grid configuration itself (Hillier et al., 1993) and allow to establish a parallelism between the value of 'integration' of a space and its potential to be understood as a destination in random movements (to-movement) and between the value of 'choice' and the probability of a space to be used as a crossing point in such journeys in which it is neither origin nor destination (through-movement) (Heitor & Silva, 2015).

Choice (called Betweenness Centrality in graph theory) measures potential passing traffic (mainly pedestrian) motion. The programme calculates the least cost (angular; accumulated change of direction) path between all possible source origin/destination (OA) pairs (in the map/graph, the analysis considers each element as a possible origin and destination to determine the choice (Hillier et al., 1993; Heitor & Silva 2015; Yamu et al., 2021). Thus, those elements (axial lines/roads) that cumulatively belong to the lowest cost paths between all source/destination pairs will often present higher choice values (Hillier et al., 1993; Heitor & Silva, 2015). Note that this sum is divided by the total number of possible trips (Ibid). On the contrary, elements that cumulatively meet less frequently on the sum of all least-cost paths will have lower choice values.

Integration (called Closeness Centrality in graph theory) is the second relevant measure for analysing urban configurations. It measures the degree of centrality and usually emphasises those spaces in the city that the ordinary citizen would call the main streets, where a large part of specialised commerce positioning is often associated with an urban centre's functional concept (Yamu et al., 2021). Typically, integration analysis uses the axial map as a medium. However, since there would be an advantage in using this measure in the segment map, the algorithm used in the axial map had to be updated. Moreover, as in the case of 'choice', when one moves from the analysis of the axial map to the analysis of the segment map, the 'counting' the depth in topological terms changes to angular terms (where large high angles imply high expenditure) (Heitor & Silva, 2015) (Fig. 4).

4 Methodology of Analysis

In this section, we apply axial analysis to aid in understanding how the road infrastructure as a network links peripheral neighbourhoods to the city centre. The first analysis looks at connectivity, integration and choice to interpret current mobility patterns within the CBD. The second analysis looks at possible impacts of pedestrian movement on the road network due to altering access to the city centre by creating a built public square amenity.

As part of the exercise and based on the analysis outcomes, different amenities are positioned in locations that would benefit both the user and the service performance. For example, the locations chosen for commercial services (restaurants and shops) envisage the optimisation of investment returns and social interactions based on the high probability of pedestrian activity. On the other hand, educational and health services prioritise areas that offer lower pedestrian traffic and safety.

To better understand the site's historical context, the next section of this paper describes the political and technical objectives of revitalising the Bay of Luanda.

4.1 The Revitalization of the Bay of Luanda

From a historical background, Luanda lacked an effective local government structure since colonial administration (Croese, 2016). Luanda served as the base for centralised colonial Portuguese rule before independence and as the base for the Popular Movement for the Liberation of Angola (MPLA) in the years following Angola's independence in 1975 because of a longstanding civil war motivated by political party rivalry (Croese, 2016, 2018).

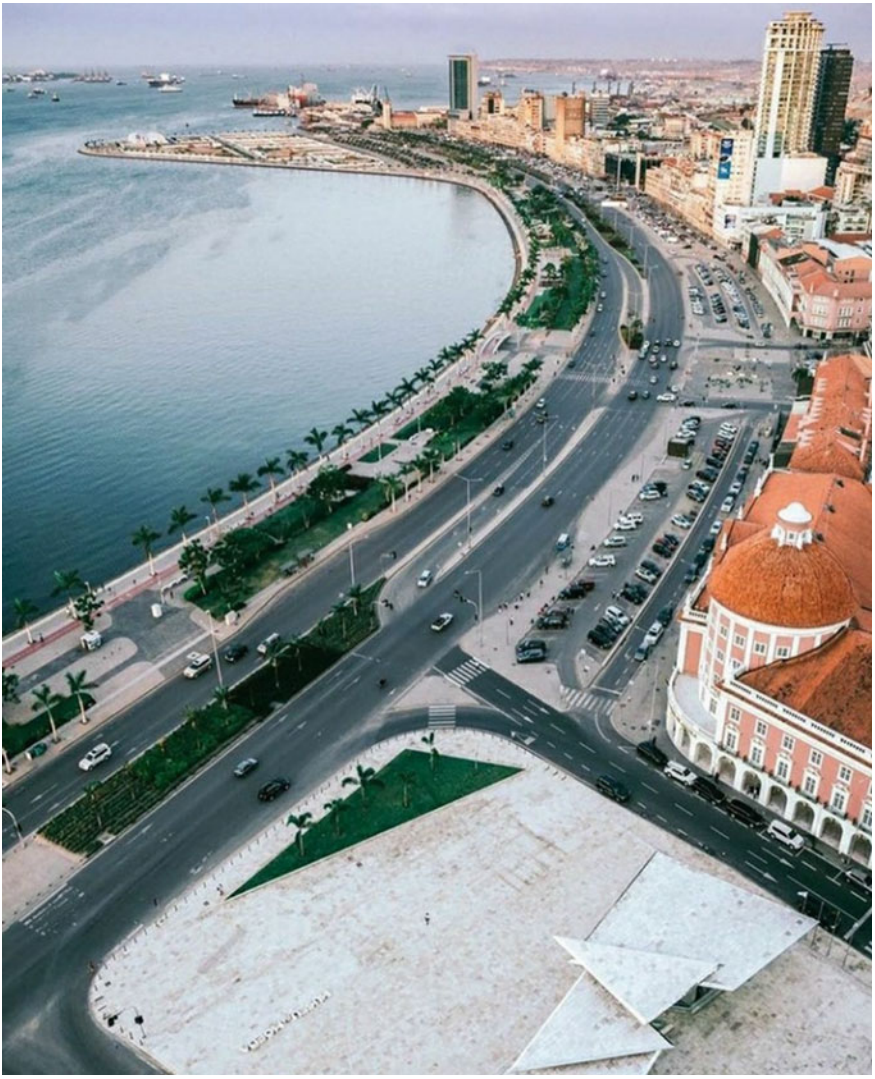

Fig. 4 A view of the Bay of Luanda (2021). Photo by Ana Cristina Inglês

Ten years after the end of the country's civil war, in 2012, Angolan President José Eduardo dos Santos inaugurated the first phase of the redevelopment of the Bay of Luanda (Croese, 2018). From a country devastated by war, Angola demonstrated capacity and effective economic recovery supported by the oil industry, becoming the third-largest oil producer in Africa. In addition, the country launched urban transformation projects, especially in Luanda, considered 'The Postcard' in narratives of the African Renaissance.

Internally, it was one of many projects carried out by public motivations to mark the beginning of a new era of state prosperity and investments to improve living conditions for the population. Internationally, the redevelopment of the Bay reverberated as a successful waterfront redevelopment project with extensive state marketing as Luanda's 'new face' (Lopes, 2011 in Croese, 2018).

Until the national elections of August 2017, President José Eduardo dos Santos exercised power at central and sub-national levels with a knit political web well settled in the country. However, until today, this ideology remains blurred between local administration and local ruling party structures as local administrators have to be approved by the president or 'indicated' by politicians within the party structure (Croese, 2016).

The initiative to redevelop de Bay of Luanda and the definition of the project's objectives came from central government administrative authorities (Croese, 2018). With little public consultation, initial proposals resembled Dubai-like artificial islands and high-tech architectural paradigms (Croese, 2018, 2021). However, at the time of submission for approval, professional organisations and prominent members of the society came to the rescue of local cultural and community values and the preservation of the colonial-built heritage of the surroundings (Croese, 2016).

The intention of the redevelopment of the Bay had three main objectives. Firstly there was an infrastructural need to intervene in the rainwater drainage conduits that flooded during the rainy season. Secondly, the existing infrastructure was obsolete and unable to cater to the current demands of sewage. Lastly, another infrastructural intervention was the road network's renewal and the waterfront area's amplification for leisure and gathering activities.

Before interventions, extensive traffic congestion occurred at the Bay, and the lack of parking facilities was a problem.

Besides infrastructural priorities, there were intentions to improve the image of the Bay in an attempt to rescue the city's 'postcard' image and capitalise on political legitimacy and stability for upcoming national elections (Croese, 2016b, 2018).

The project included an open-air shopping area, office blocks and residential units developed by the real estate and sold to an affluent clientele after completion (Croese, 2018). Such developments pose state-of-the-art architecture to the city while mimicking clear examples of gentrification. Furthermore, the site embodies a poetic symbiosis of built and social–historical memories of the city, where contemporary architecture and urban design interventions have the opportunity to capitalise on and aid the promotion of tourism and public life.

According to Luanda's Master Plan (PDGL) and the National Population Census from 2014, out of almost 7 million people living in the city, more than 60% live in informal settlements (GPL et al., 2015). Due to density challenges, POSs in informal settlements are rare. However, in the POSs in the formal urban fabric, not only the advantaged but also the less advantaged of Luanda can have the opportunity to 'breath', enjoy the city and socialise with better comfort (Fig. 5).

Fig. 5 A The divide between Luanda´s revitalised Bay of Luanda and the inner city

EXERCISE 1—Proposing a set of services and amenities according to the syntactic analyses properties of the space.

Choice—Betweenness Centrality

The street networks are primarily used for movement and serve as a medium for social encounters with economic and cultural meaning (Pont et al., 2021). However, determining when a given street will receive more movement than another depends on its centrality within the network (Ibid.). The concept of accessible density is relevant in this discussion because it refers to urban culture and the concentration of social practices and forms of behaviour," all of which interact based on spatial co-location, proximity or overlap", which underpins city functionality (Ibid.). Street networks' centrality and density factors are strong drivers of urbanity. These parameters go beyond population density and economic activities but encapsulate walkability, appropriate service provision and public transport (Ibid.).

Therefore, commercial activities such as Restaurants and Laundry shops are positioned based on high density and centrality values to promote encounters and livable streets. Coincidentally, streets with high centrality values already present a high concentration of offices, hotels, and government offices.

On the other hand, the elementary school is located in the middle of a residential area away from major traffic routes for children's safety reasons. However, the proximity of restaurants to residential areas is a good option because its use can prolong after office working hours.

Parking facilities are scarce in downtown Luanda; therefore, the hospital is close to a well-integrated route but away from denser important nodes to avoid traffic congestion and difficulty of access, especially by car (Fig. 6).

Integration

Evidence shows that locations with high integration values coincide with high renting costs (Pinelo & Heitor, 2007). Although this correlation may present exceptions (Ibid.), it is sensible to say that such a parameter supports the investigation of the success of businesses with the syntactic integration metrics of a specific site.

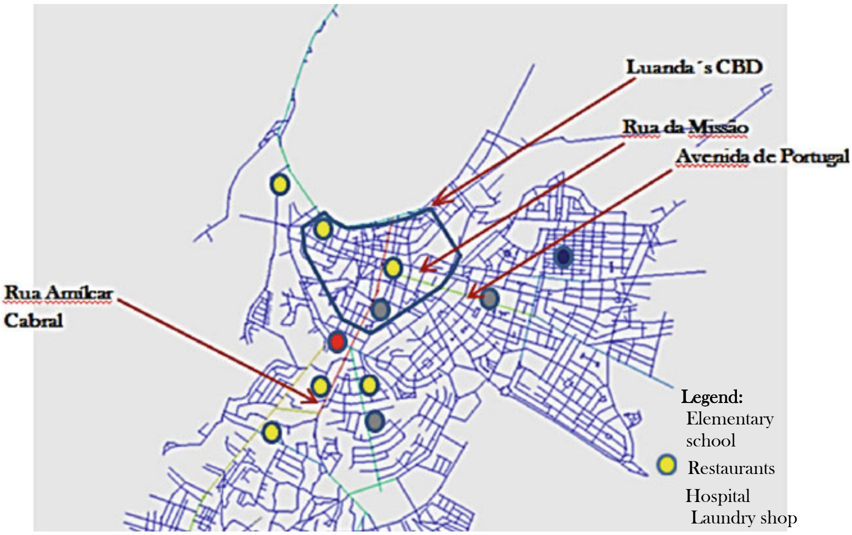

Fig. 6 Choice analysis in Luanda´s CBD DepthmapX 0.8.0

The criteria for identifying preferable locations considered road integration and the targeted public audience. Choices are consistent with those made for choice. High integration and visibility values support the probability of a given site´s spatial configuration attracting more significant social interaction and rich public vitality through co-presence and encounters in public spaces (Peponis et al., 2021). However, less integrated streets and access to open public spaces are essential for recreation and stress reduction (Pont et al., 2021) and children´s social equipment. All these considerations weighed on the exercise´s outcome.

The location of services and equipment does not alter significantly compared to the previous exercise. The location choices reinforced the integration analysis as a strategy to enhance livability along streets with high integration. In Luanda´s urban culture context, increasing the density of restaurants and commerce is advised (Fig. 7).

EXERCISE 2—Proposing an alteration on the network with a physical obstruction

In this second academic exercise, the axial map produced for Luanda's CBD displays the effects of creating a public space with a built structure/building that obstructs both visibility and motorised traffic introduced as a simulation.

The choice analysis results in alteration/interruption in the main connectivity axe that links the inner area of the CBD and the Bay of Luanda, which corresponds to the

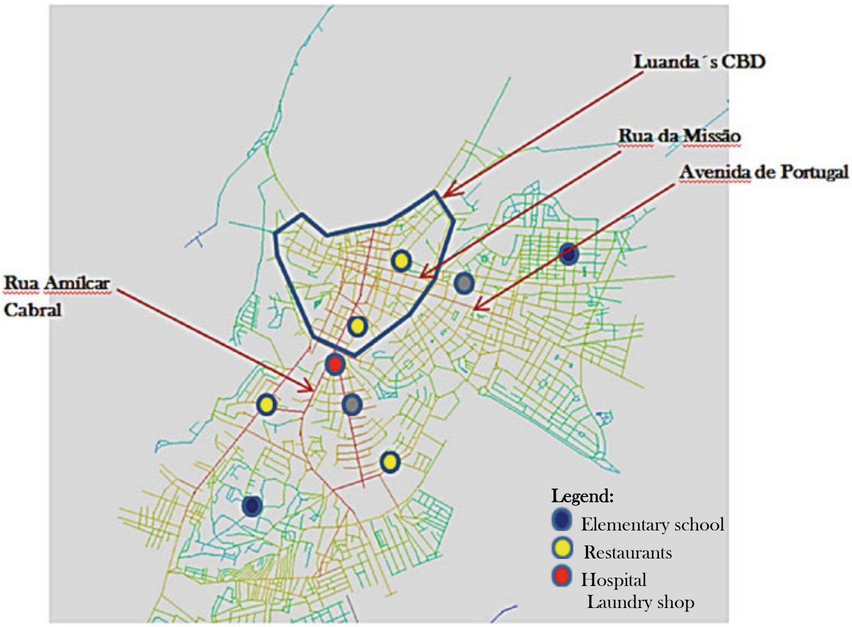

Fig. 7 Integration Distribution in Luanda´s CBD Axial map 2008, Depthmap 0.8.0

Fig. 8 Choice analysis on the altered road network Axial map 2008. DepthmapX 0.8.0

intersection of Rua Amílcar Cabral and the two perpendicular roads, namely, Rua da Missão and Avenida de Portugal. As a result, the city centre loses its use intensity comparatively to its initial character as a primary route of choice from any origin to any destination in the city (Fig. 8).

Similarly, as presented in the Choice analysis above, a second analysis was done on the axial map produced for Luanda's CBD from an integration perspective. Again, an alteration introduced simulates the creation of public space with a built structure that obstructs both visibility and motorised traffic. The result is alteration/obstruction in the central connectivity axis that links the inner area of the CBD and the Bay of Luanda from the intersections between Rua Amílcar Cabral and Rua da Missão. However, the integration values of Rua da Missão do not alter compared to prior to the introduction of the obstruction. Furthermore, in this case, the importance of the city centre has not been as severely affected, meaning that it did not lose its high integration values compared with the rest of the city.

After all, initial ideas from the 1960s modernist urban plans are valid and pedestrian civic centres a possibility left behind worthy of consideration. Mutamba was initially conceived as a pedestrian square and motorised connection to the Bay thought to be a tunnel (Fig. 9).

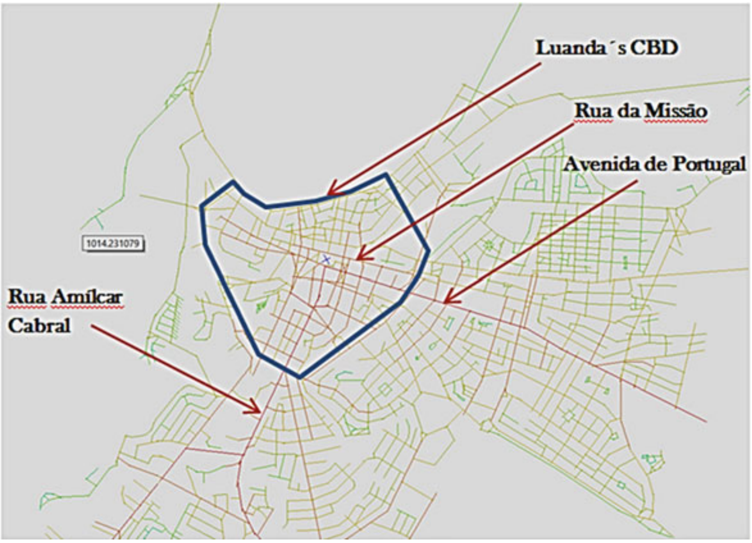

Fig. 9 Integration analysis on the altered road network Axial map 2008. DepthmapX 0.8.0

5 Results

Based on the literature review presented in the Theoretical Framework section of this paper, the attractiveness of public spaces depends on their accessibility, variety, legibility, robustness, visual appropriateness, richness and personalisation; the absence of these qualities might fail to create a responsive space (Khan, 2014).

The academic exercises aimed to investigate the strength in the connectivity between the inner city centre and the Bay in the event of creating a public built-up square or pedestrianising a square. We conducted an analytical simulation on both scenarios. Some preliminary conclusions from the exercises derive from the outcomes of these exercises.

Building a structure, such as a museum or a multiuse public building, in the city centre square affects mainly the integration and choice parameters and weakens the connection between the inner city and the Bay. As a result, the city loses its robust connectivity and integration with the Bay, and the northeast connection alters significantly. Considering that the Bay of Luanda is the city's most significant open public space, the connection between the newly created open space (in the simulation) and the Bay must be strengthened and not disrupted.

On the other hand, pedestrianising the square has no impact on the behaviour of the network since space syntax looks at lines of sight and pedestrian movement rather than motorised circulation. Therefore, creating a pedestrian open square presents a better opportunity to enhance walkability, trivial encounters and social interaction, as discussed above. These characteristics, combined with outdoor comfort, visual appeal and safety, are critical elements in promoting vibrant public spaces (Lamour et al., 2019), which is the paper's central argument. Furthermore, from the perspective of locating services around the Bay, the suggested square and surrounding areas, the analyses have aided in understanding the most integrated roads and those with high choice parameters. These parameters are essential to locate business and envisage financial gains, which makes the syntactic analysis valuable.

6 Discussion

This paper focuses on testing the ability of POS to be valuable catalytic tools in an urban revitalisation strategy. The strategy proposed aims to create a network of places where evidence-based interventions may improve public life. Additionally, the architectural, urban design, and social history embedded in the space add potential value to the use of the space. The natural beauty of the Bay, its urban design, and the intertwined architectural additions represent strong physical and imagery poetic icons of Luanda. Even though these characteristics are appealing, previous experiences show that improving safety, outdoor comfort and walkability is vital, as is promoting open-air activities and locating services that stimulate social interactions and trivial encounters.

Each city holds particular social, cultural, economic, political and environmental characteristics. These characteristics reflect on the project and the chosen approach; thus, interventions must combine architectural and urban design expertise with community participation to grasp residents' aspirations and socio-cultural paradigms of the place. The community's resistance to accepting the initial Dubai-like proposal for revitalising the Bay of Luanda reinforces this idea.

This paper contributes to the scantiness in the literature about urban revitalisation processes and peculiarities in the global south in general and the sub-Saharan context. Furthermore, the exercises shed light on understanding the study of POSs interventions in the Angolan context. Finally, the syntactic analysis is a valuable method of site analysis to improve and create better public open spaces and public life in Luanda's city centre.

These exercises open a research window on urban revitalisation projects using space syntax as a methodology and a tool. In addition, comparative studies across cities in the developing world are an opportunity to expand the knowledge and improve POSs interventions in these regions.

7 Summary and Preliminary Conclusions

The present article investigated the usefulness of POSs in promoting vibrant public life and social inclusion using space syntax.

The literature review demonstrates that POSs are essential to cities, such as promoting urban tourism, government hegemony, city branding and boosterism to attract foreign investment (Hoyle, 2000; Harvey, 2008; Amado, 2019) and promote the urban micro-economy. However, and most relevant to this paper, is the fact that POSs also offer opportunities for social interaction and cohesion through public manifestations, festive celebrations, entertainment events; enhanced walkability and human well-being (Hughes, 1999; Gehl & Svarre, 2013; Lamour et al., 2019). In addition, architecture and urban design aesthetics and functionality significantly influence the use, comfort, safety and attractiveness of POSs (Lamour et al., 2019). Furthermore, the variety of uses that POSs may offer is crucial for city centre vitality.

The simulations in the academic exercises have shown the possibility of pedestrianisation. Pedestrianising streets do not impact the pedestrian's perceived connectivity of the site. Additionally, evidence shows that pedestrianising streets and reducing motorised circulation have improved public life and social interactions (Montgomery, 2013; Aşilioğlu & Çay, 2020). The temporary closing of streets in London and New York to create safe environments for children to play are examples of tactical urbanism that promotes walkability and social interactions (Lydon & Garcia, 2015).

One of the challenges of urban revitalisation is the risk of failure upon heavy financial burdens for the state (Carmon, 1999; Kayanan, 2022), thus the rising neoliberalism and urban entrepreneurship in urban revitalisation projects (Kayanan, 2022). The evidence that Space Syntax helps to determine the investment returns through the correlation between high integration values and high office rents (Pinelo & Heitor, 2007) is another valuable aspect of this method. However, integrating community co-participation ensures the use and preservation of the spaces in the long run and can reduce perceptions of social exclusion.

Furthermore, from the Luanda's Bay revitalisation project, there is a visible improvement in the space but also a lack of a strategy to activate the space and promote trivial encounters through mixed-use services and activities accessible to every social extract. Therefore there is evidence that physical requalification does not spontaneously revitalise (from a social interaction perspective) and that urban revitalisation needs to be an intentional process to which Space Syntax is valid.

Finally, Space syntax analysis is a valuable tool for simulating alterations such as pedestrianising (Yamu et al., 2021; Heitor & Silva, 2015), encouraging social interactions and trivial encounters.

Further syntactic analysis of different districts of Luanda will strengthen the research and widen the understanding of human behaviour in public spaces within the city.

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Integrating Formal Methodologies in a Multi-Layered Analysis for Management Policies for the Pedestrian Use of Public Space

Catarina Ruivo, Franklim Morais, Joaquim Flores, and Jorge Vieira Vaz

1 Introduction

Taking advantage of the opportunity to carry out a project of analysis of municipal intervention in the public space of the city of Porto, it was possible to test and disseminate a set of formal and digital methodologies, comparing them with more traditional methodologies.

The central objective of the project concerns the pedestrian use of public space, especially its traffic component. The immediate motivation arose from the imposition of measures taken to counter the Covid-19 pandemic, which resulted in a large increase in the use of open public spaces at the expense of private spaces, which are much more closed. However, the project was intended to be more comprehensive than the single analysis of the implications for pedestrian traffic.

> Ensuring that walking is an attractive alternative and complement to motorised transport is a core response to the challenges of climate change, fossil fuel dependence, pollution, maintaining mobility for an ageing population, health … (ITF, 2012).

This paper will not deal with all the issues described in this OECD report. It will focus only on the physical occupation of space.

As the project included obtaining empirical data, as well as using theoretical models, it served to confront and test theoretical models and determine ways to improve them. Pedestrian mobility in the city of Porto had already been the subject

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of another study (Jabbari et al., 2018), although more limited in terms of objectives and methodologies used. The results of this study were also compared.

The paper will then summarize the theoretical and methodological advances obtained.

2 Empirical Data

Knowledge of the reality of public space required the collection of concrete information about its (a) spatial configuration (a1) material and (a2) functional, as well as about (b) the actual use of spaces by part of its various users.

2.1 Empirical Data on the Use of Spaces

Possible ways of collecting information on the uses of space are summarized in Table 1. Its characteristics are shown in Table 2. We are referring to systems for large scale and public spaces. Similar systems are also used in smaller spaces, both public and private.

Manual and automatic counts, surveys, and video camera images were used in the project.

A limitation arising from the legislation on the **protection of personal data** imposes that the following types of data are excluded from registration:

- Almost all of the designated special categories.
- All direct identifiers.
- Personal identification (except for some generic indicators, but only in surveys).

Table 1 Possible ways of collecting information on the uses of space

A	Manual counts
B	Surveys
C	Automatic counts—for example by IR or floor bands with different technologies. Those made by video images are in E
D	Social networks—using data that citizens make public—Facebook, Twitter, etc.
E	Video images—captured with video cameras spread throughout the city
F	GPS—using citizen devices with this capability (usually smartphones)
G	WiFi—using analytics from the public hotspot network (which includes public transport)
H	GSM/5G—using TSP (commercial Telecom Service Providers) analytics regarding mobile devices usage
I	Others—there are multiple other systems with tokens, cards, RFID, etc.

Table 2 Characteristics of the possible ways of collecting information on the uses of space

	A	B	C	D	E	F	G	H	I
Dissemination	No. sometimes they are eventually carried out	No. sometimes they are eventually carried out	Public transport service has a controlled system for validating transport tickets	Reasonable	Reasonable distribution in some areas of the city	Yes	Reasonable distribution in some areas of the city	Yes	No. some cities have systems like these
Equipment	Small equipment very affordable	Small equipment very affordable	If dedicated, they are expensive	Of the citizens. But they require the networks of the TSPs	If dedicated they are expensive	Of the citizens. But they require the networks of the TSPs	If dedicated they are expensive	Of the citizens. But they require the networks of the TSPs	If dedicated they are expensive
Less qualified human resources	Extensive if large surveys	Yes	No	No	No	No	No	No	No
More qualified human resources	For statistical analysis	For statistical analysis	Yes, specific HW and SW	Yes, specific SW	Yes, specific HW and SW	Yes, specific SW	Yes, specific HW and SW	Yes, specific SW	Yes, specific HW and SW
Objective/ subjective data	Objective	Subjective	Objective	Subjective	Objective	Subjective and/or objective	Objective	Objective	Objective
Static counts	Yes		Yes		Yes	Yes			Yes
Immediate path determination	No		No		Yes	No	No	No	Dependent on the case

(continued)

Table 2 (continued)

	A	B	C	D	E	F	G	H	I
Mediate determination of counts and paths	Inaccurate approximation		Reasonable approximation, or good if personal data usable		Automatic can be further improved	Good	Good	Good	Dependent on the case
Georeferencing accuracy	Very accurate but static	Very accurate but static	GPS accuracy	GPS accuracy	Very accurate	GPS accuracy	Typically GPS accuracy	GPS accuracy	Case dependent
Evolved semantics		From subjective assessments		From subjective assessments	Yes, based on advanced theoretical studies	Yes, based on advanced theoretical studies	Yes, based on advanced theoretical studies	Yes, based on advanced theoretical studies	Case dependent
Citizens' authorization and participation	No	Needs Authorization and participation	No	No, but there are many legal doubts	No	Authorization and participation, in some cases	No	No	Authorization and/or participation, depending on the cases
Allows protected personal data	No	Yes	Yes, some titles can be individualized	Yes, people are identifiable	Yes, people are identifiable	Yes, people are identifiable	Yes, users are identifiable	Yes, users are identifiable	Yes, users are identifiable
Contention of personal data		Administrative authorization of survey questions	No use of customizable data	there are many legal doubts	Do not carry out personal identifications	Do not use personal identifications	Do not use personal identifications	Do not use personal identifications	Do not use personal identifications

(continued)

Table 2 (continued)

	A	B	C	D	E	F	G	H	I
Observations			Needs coordination with other municipal services	In the EU, there are many legal limitations	Needs coordination with other municipal services		Needs coordination with other municipal services	Needs contracts with TSPs	

- Identification of contact/fixed locations (postal or electronic addresses, including social networks).
- Physical-physiological, health, and biometrics.
- Academics.
- Economic, professional, and patrimonial.
- Legal and criminal.

2.1.1 Counts

Counts performed by humans are still one of the most widespread methods to obtain the most basic data: cardinality of occupancy in given time periods. These figures then make it possible to obtain other information, semantically built upon these data. For example, together with information about the spatial configuration, occupancy densities can be deduced. There are even approximate methods (with several simultaneous counts in certain gates, and with the network of connections between those spaces) of making approximate deductions about the routes used.

In the case of this project, and as automatic methods are also used, manual counts were essentially used to compare and confirm other methods.

For example, agents in agent-based models were launched according to the data collected in these counts.

Instead of the usual manual notes, applications were developed for mobile devices, smartphones, and tablets, which made it possible to easily obtain not only the counts, but also:

- the immediate geolocation.
- the precise moment (up to the second) of the passage.
- the type of entity (pedestrians, motor vehicles, bicycles, and others).
- the direction of movement.

Figure 1 shows (a) version of the Android App, (b) CSV file with records, (c) database scheme, and (d) some initial statistical presentation of the recorded data.

Fig. 1 **a** Version of the Android App, **b** CSV file with records, **c** database scheme, and **d** some initial statistical presentation of the recorded data

2.1.2 Inquiries

Two field surveys were carried out.

One with a very short response time, aimed at most passive users of public spaces, particularly those in the pass through;

It essentially included multiple-choice questions.

- Usual location identification.
- Identification of the type of activity.
- Motivation for the specific use of space.
- Motivation for choosing the route.
- Specific identification of the route (total (and means of transport used) and last means of transport, in principle pedestrian).

A second survey (Fig. 2) was dedicated to the group of users of the space on a more permanent and continuous basis, such as owners, employees, inhabitants of adjacent buildings or frequent users of these spaces. It was a longer survey with a longer response time. It contained 68 questions with some character of subjectivity.

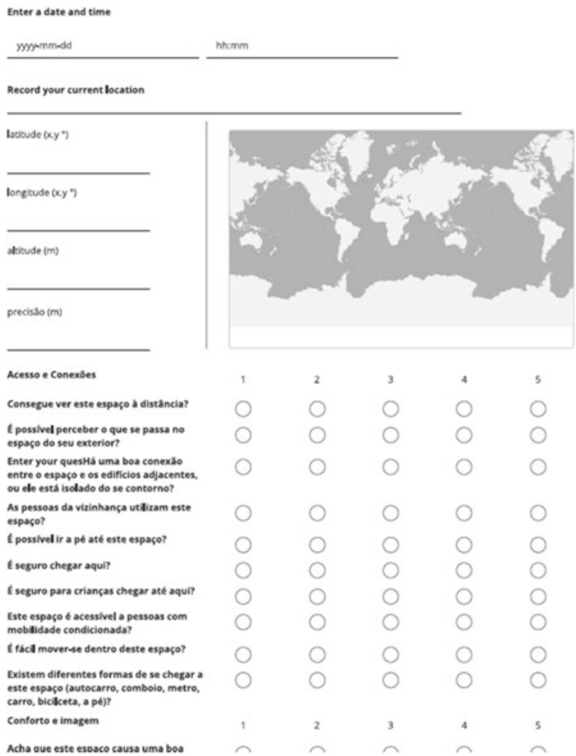

Fig. 2 Android App for pedestrian survey

- Objective questions: location and date, weather conditions, gender and age, residence, and functional relationship with the space.
- Subjective questions regarding: "access and connections", "comfort and image", "use and activities", "sociability", and "generic questions".

2.1.3 Andante Validations

Yet another counting system was used. The city's public transport service has an automatic registration of the validation of transport tickets (designated Andante), so it is a system without added costs and with a huge perfusion of data. Available data include station indication and precise validation moment. Other data would be technically possible, such as a (non-individualizable) reference of the title, but this was prevented by personal data protection reasons.

Although these validations only indicate the exit of pedestrians from the areas in which they are validated (and not the entry) to other means of transport, a less restrictive use of this system (for example, a unique reference of the ticket, even if not individualizable) would allow a very concrete framework of movements throughout the metropolitan area.

As the objective of the project was the study of pedestrian behavior in restricted areas and not urban travel, the data collected served (a) to study the impact of concentrations at modal interfaces on pedestrian traffic and (b) to have a general overview of pedestrian densities throughout the city so that a zoning can also be carried out using the density parameter.

Figure 3 shows the zones covered by Andante and the layout of the bus routes that arrive at one of the public space locations.

2.1.4 Video Images

One of the most relevant forms of empirical data collection for the study was the one that originates from the images obtained by video cameras disseminated in the city, and which, in the case under study, are publicly owned and managed by the municipality.

The reasons for this choice were essentially the following:

- The enormous possibilities in diversity and depth of the types of information that could be collected.
- The relative ease of technical implementation of the solution:
  - The equipment was already available, so there were no additional costs.
  - There were dozens of cameras scattered throughout the city, which made it possible to cover the areas under study.

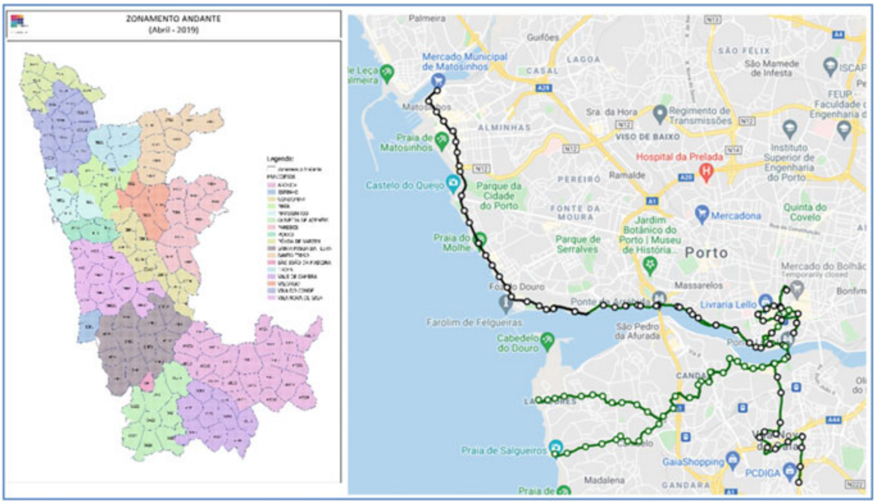

Fig. 3 Zones covered by Andante and the layout of the bus routes that arrive at one of the public space locations

– The image processing technologies (computer vision and machine learning) are well established, so there was no need for a great effort in basic research, but only in the development of applications adjusted to the project.

Although the management of images is public, multiple problems arise from the application of legislation on the protection of personal data, which is very restrictive with regard to the use of video images, as they offer immense possibilities for personal identification. Restrictions include, for example, the impossibility to record images, except by law and court order. In addition, technical limitations are derived from the need to use exclusively the computers of the municipal service dedicated to this function.

The **operational process** was carried out as follows:

- At first, which takes a few minutes, some operations are carried out for the particularization and tuning of the computer application for the camera used at the moment.
- The processing of video images is then carried out in real time.
- The output data is stored in a CSV and ASCII text format file, regularly downloaded via a 'USB pen'. This is the only information that leaves the system.

More important than the operational process is the **informational process**, how it is possible to obtain valuable information for the project, even with the limitations imposed.

The information processing (from the input video data), necessary to arrive at the output data, uses very abstract analyzes of current use in the technologies of 'computer video' and 'machine learning'. It is necessary to understand that video image processing applications do not have human mental processes, which make identifications of colors, textures, shapes, objects, and people, in an almost transparent way for human beings. All this identification has to be carried out explicitly, in computer algorithms. These processes use ‘frames’ of ‘pixels’ and analysis of comparison, patterns, contrasts, textures, etc., without any individualizable semantic value.

There are several different strategies for these applications.

The first, through intensive use of deep learning, identifies objects in each frame, that is, it is able to discriminate the various objects that appear in the image and identify each one of them. This identification can have a greater or lesser particularization, according to the knowledge bases used for these identifications. For example, you can identify whether it is a vehicle, a motor vehicle, a model M car in color C, the car with license plate X; if it is a person, a child, a child with clothes C, the child named N, etc.

This strategy may (or may not, depending on the objectives and means used) obtain ‘prohibited’ information, and they need the so-called supervised methods, which need to be crossed with non-allowed external knowledge bases. They also need computers with processing capabilities (e.g. in speed) that are difficult to achieve in sealed municipal equipment, for real-time image processing.

Fortunately, there is another strategy, which obtains much less information, but is much easier to implement, does not pose problems regarding the protection of personal data, is compatible with available computers, and, even so, obtains very relevant information. The technique is to analyze changes between successive frames (very similar to the compression techniques that everyone knows and are used in animated images—for example, MPEG). Changes between frames do not allow you to individualize objects, but allow you to reach very significant information, essentially paths of moving objects (time, position, dimension, and generic shape of the object), which allow fruitful analyzes in terms of the use of public space, but not any personal identification.

At this stage, the data is less abstract than the structures of the previous processing, but its information is already completely depersonalized, in relation to the input data.

The problems arising from this strategy are diverse, including:

- As it uses unsupervised machine learning, data only establish relationships with each other, not allowing any comparisons with similar reference data, which contain any individualizable information. It is not possible to establish an identification of these detected patterns, for example, a face, with any similar information in a database of faces. It was not in the interest of the project to obtain such details as to reach the personal identification of the subjects in the public space. But it should not be hidden that further differentiation could be beneficial—for example, by age, by personal space utilization goals, etc.
- For the same reasons, it is not possible to carry out learning processes.
- There is no re-verification of the information obtained by comparison with the recorded video images. All access to images is in real time. Any anomaly detected cannot be re-evaluated against recorded images.

- Object tracking is not perfect, for multiple reasons, for example:
  - In the case of compact groups, there is a great difficulty in individualization,
  - At path crossings,
  - With immobilization of objects along the paths,
  - If the object's path is lost on the periphery of space, it is not possible to reunite it with another path of the same reentering object, becoming two different objects.
- A given space can be followed by more than one video camera, meaning that the same object can have more than one reference.

The global solution for acquiring knowledge that was adopted consisted of carrying out **four distinct phases**.

The **first phase**, in real time, is the one already described, but in which different filters and parameters were placed to improve the quality of the information collected, for example:

- Tuning of brightness, color, contrasts, distances, depth of field.
- Generic dimensions and shapes of significant objects.
- Object immobilization times.
- Prediction of paths for path crossings between diverse pedestrians.

The **second phase** is dedicated to the geolocation of objects—projecting the location on the screen's frame to a three-dimensional geolocation in physical space.

The **third phase** consists of essentially heuristic AI processes to improve the identification of objects and paths. These heuristics are fundamentally well established—for example, the impenetrability of matter tells us that two referents at the same time and place refer to the same object. Some of the issues addressed are:

- Concatenation of paths with several referents, but which are assumed to belong to the same object. For example, if an object is lost in a position, it could be the same object that reappears in the same position but was immobile.
- Two identical paths from two cameras are the same path.
- Separation of compact groups.

The **fourth** uses generally unsupervised machine learning processes.

However, some learning processes were carried out with images recorded from other places and for free use. These processes make it possible to build new synthetic knowledge from the output data of the previous phases (which, remember, are paths of mobile objects with a generic dimension and shape).

Some results are a consequence of well-established heuristics or theories, for example:

- Travel speeds.
- Traffic Densities.
- Empirical formula relating speed and displacement, important to adjust calculations using traffic flow theory.
- Traffic light timing.

- Type of object (pedestrians, vehicles) from speeds, dimensions, and shapes.
- Improper uses (pedestrians on the street, mechanical traffic on sidewalks, illegal parking, disregard for traffic signs, etc.).
- Clearance of the paths from physical obstacles.

Others use machine learning methods (generally—classification through clustering (Witten et al., 2011)) to make an attempt at interpreting, classifying, and standardizing, for example:

- types of routes or paths (passing through, access to the periphery of space, usufruct, ambulatory/tourist routes) based on average speeds and their variability, distance from the distance actually covered in relation to the optimal distance.
- Changes in locomotion parameters introduced by the various types of physical objects existing in spaces.
- attraction (and repulsion) of certain locations, through proximity analysis of routes.
- types of distance between objects (approaching or distancing behaviors in relation to other objects).
- optimization of passing through paths in various traffic densities.

The problem with these investigations is that we start from heuristic principles (those we admit as valid, given our previous, often informal, experience) to formally demonstrate the validity of certain theories. Now the logical formalisms used always arrive at results that tautologically include the first axioms. This means that if we start with wrong heuristics, we can arrive at wrong results, without any formal way of detecting it.

For example, if we want to know the behavior of pedestrians who only make crossings in public spaces, we start from some basic idea of their behavior, which taints all subsequent conclusions with prejudice. That is why there is a need to invent tests that allow the theories to be contradicted by the studies, which is not always easy. Taking the previous example, and as already explained, it was not possible to ask the pedestrians if the objective of their crossing is just to pass through.

Much of this knowledge is then used as parameters in other types of theoretical analyses, described in the following points.

The image of Fig. 4 refers to the computer application, in real time, for processing the images of the video cameras. The image is not from a location in the city of Porto, as it is not possible to record it. (a) is the monitoring area of the results obtained, (b) is the monitoring area of the tuning of results of the filters for recognizing the movement of objects, which are updated in (g), (c) is the selection of the camera's area, (d) is the area of operation of images and recordings, (e) is the area of selection of automatic recording periods, and (f) is the area of identification of coordinates in the image with specific points in real space. As it is not possible to consult the a-posteriori images, it is necessary, in the recording preparation phase, to identify points necessary for the geo-referencing of the images (transformation of the coordinates on the screen into real coordinates).

Figure 5 shows a mapping of pedestrian paths in a given period of time.

Fig. 4 Computer application, in real time, for processing the images of the video cameras

2.2 Empirical Data—Physical, Geometric, and Functional Surveys

The analysis of pedestrian traffic reveals that there is extreme sensitivity to all the small volumetric 'accidents' of space. For this purpose, an exhaustive survey was carried out of all the existing equipment in the spaces under study, dimensions, and location. The various coverings of the entire ground floor of the space were also considered.

The functional aspects of the space are also extremely relevant, and both the uses of the space itself and the uses of the entire surroundings must be considered.

Table 3 refers to most of the objects and uses considered.

The formats of the information storage intended to make them available to the computer applications that would be used and those that are available in the municipal services. A multiplicity of formats and their compatibility had to be ensured.

Figures 6 and 7 show some 2D and 3D models of public space.

Fig. 5 Mapping of pedestrian paths in a given period of time

3 Pedestrian Dynamics Methodologies

There are three large groups of methodologies for the treatment of pedestrian traffic. First group, (A), is very closely linked to most theoretical engineering, which will seek its inspiration from the dynamics of fluids, and is essentially expressed in differential equations (Cristiani et al., 2014). Second group, (B), is also from engineering, but of a much more empirical character and with simple formulations to treat more current problems (Transportation Research Board, 2016). Third group, (C), comes from architecture and is based on the configurational analysis of spaces, using concepts of analytical and mass geometries, and graph theory.

Methodologies can be grouped as follows (Table 4) with the characteristics expressed in Table 5.

The available methodologies have points of contact, but also some obvious differences. For example (Cristiani et al., 2014) does not even consider that theoretical engineering methodologies can be addressed to architects.

Table 3 Types of objects and functional uses under detailed survey

Infrastructure		Other		Flooring	
Fire	Hydrant	Information	Advertising support	Mechanic	Automotive
Energy	Cabinets		Exhibitor		Ramps
Comms	Wifi		Billboard		Bus lanes
	Cabinets	Separators	Windshield		Parking
	Mailbox		Transit pins	Pedestrian	Walks
	Phone booth		Fences		Cross walking
Water	Fountains	Green	Flower pots	Other	Bike paths
	Drinking fountain		Tree		
Sanitation	WC		Bush	Periphery	
	Waste bin		Vegetation cover	Facades	Shop windows
	Glass bin	Others	Statue/public art		Advertising support
	Recycling point		Kiosk		Indentations
	Wastepaper bin		Chairs		Front porch
	Dog bags		Tables		Awning
Lighting	Lamp		Stalls		Shadow brim
Transport	Wastepaper bin		Exhibition	Access	Garage door
	Bike support		Terrace cafe		Door
	Traffic signals		street trade	TYPE	Housing
	Bus shelters		street artist		Business
	Bus stops		events		Restaurants
	Taxi station				Hotels
	Traffic light				Public parking
					Public services
					Private services
					Church
					Monument
					Museum

3.1 *Traffic Flow Methodologies—Mobility Analysis*

The first theoretical methods used in the project were those currently used in traffic engineering.

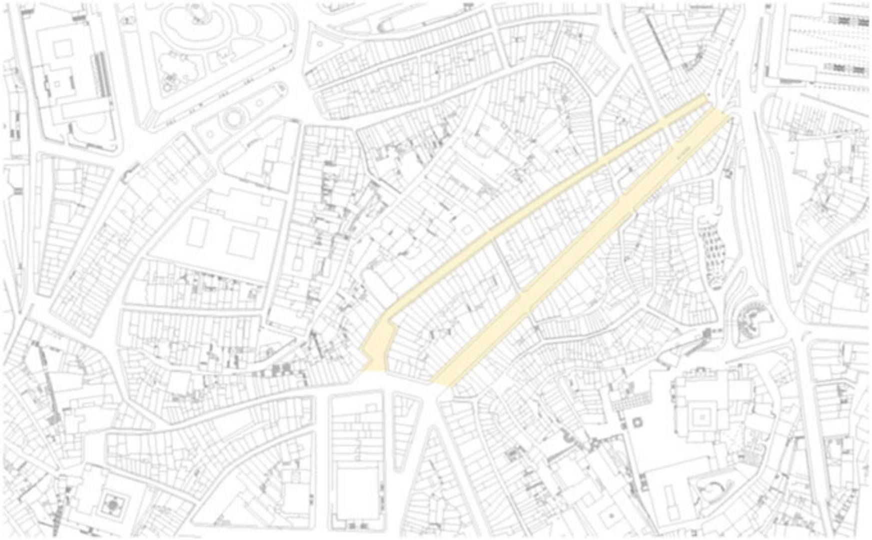

Fig. 6 2D model of a zone under study

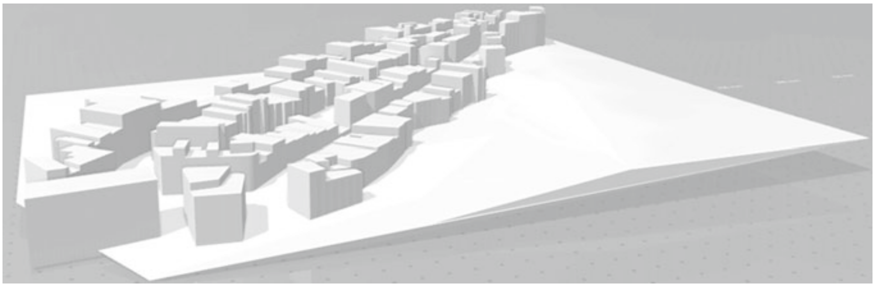

Fig. 7 3D model of a zone under study

Table 4 List of methodologies for studies of pedestrian dynamics

A1	Differential analytical models applied individually to pedestrians
A2	Cellular automata models
A3	Static differential analytical models applied to flows
A4	Dynamic differential analytical models applied to flows
A5	Multiscale analytical models
B	Multimodal mobility analysis
C1	Space syntax—segment analysis
C2	Space syntax—visability graph analysis
C3	Agent-based analysis

Table 5 Features of the methodologies for studies of pedestrian dynamics

	A1	A2	A3	A4	A5	B	C1	C2	C3
Dissemination among professionals	Small	Small	Small	Small	Small	Medium	Small	Small	Small
SW	Academic	Academic	Academic	Academic	Academic	Easy	Academic	Academic	Academic
HW resources needed	Big	Less big	Big	Big	Big	Small	Small	Less big	Less big
Pedestrian scale	Individual	Individual	Flow	Flow	All	All	N/A	N/A	individual
Practical Space scale	Small	Medium	Small	Small	Small	All, but condensed in one place case	City and bigger	Medium	Medium
Math model	Analytical differential	Discrete algorithmic	Analytical differential	Analytical differential	Analytical differential	Analytical algebraic	Discrete graph	Discrete graph	Discrete algorithmic
Time consideration	Dynamic	Dynamic	Dynamic	Static	Dynamic	Static	Static	Static	Dynamic
Empirical parameters needed	Yes	Yes	Yes	Yes	Yes	Few	No	No	Yes
Interpretation for urban planners	Hard, needs additional calculations	Medium, needs additional calculations	Hard, needs additional calculations	Medium, needs additional calculations	Hard, needs additional calculations	Easy	Medium, needs additional calculations	Medium, needs additional calculations	Medium, needs additional calculations

They are more applied in mechanical traffic, but they are also already developed for other forms of locomotion, such as the bicycle and especially in the case that interests us—the pedestrian.

These methods are aimed at meeting only one of the desideratum of the occupation of public space by the population—accessibility, i.e., they only study what is relevant for one of the human activities within the public space—the displacement of people and goods, possibly the most relevant but not the only one.

Briefly, evaluations of pedestrian traffic flow methodologies calculate a Level of Service (LoS) based on semi-theoretical empirical formulas. This semi-theoretical character is revealed in two aspects: (a) they are based on basic theories of dynamics in flow channels (relationships between velocities, densities, and channel geometry), but in which many parameters are obtained empirically (for example, pedestrian base speed) and (b) the calculation formulas are not very generic, with different formulas for many different cases (shared roads, mixed roads, parallel roads, intersections, stairs, squares, signposted intersections, traffic lights, roundabouts, etc.). The more 'theoretical' theories are more abstract and generalist, depend less on empirical parameters, and tend to be generalizable to a more general and diverse universe of situations.

The classification by LoS makes evaluations based essentially on speed, but also considers comfort (the available space per pedestrian or the number and types of crossings between pedestrians and vehicles).

Then there is a formula, in each typical case, to determine the LoS, whose validity is ensured by a base speed and a formula for the relationship between speed and traffic density. This formula applies to each specific case, in which the geometry (the width of the channels) and the flows (number of pedestrians per unit of time, but also flows of other types of transport) are known and the LoS is determined. The management policies possible in this way are reduced to finding solutions to increase or decrease the calculation width (which is not exactly the geometric width) of the pedestrian channel and reduce 'frictions' with other means of transport and with the periphery of spaces.

There are generic values accepted by the scientific community for these empirical parameters based on years of observations. However, the project made possible the measurement applied to the case of Porto, through the treatment of video images. It was possible to establish an average base velocity, an empirical formula relating velocities and densities, and also the consequences on the effective widths of the channels introduced by the physical objects existing there.

Figure 8 shows, for a given street, the LoS obtained for the traffic flows measured during the day.

In the traffic flow methodology, the dominant geometric data is the channel width, although affected by all the objects that populate it. But they all converge to that width. Next, we describe other methodologies that allow us to know the situation with much greater accuracy, in which the geometry is much more detailed, and in which the intended objectives are not limited to the speed of movement.

Fig. 8 Level of services obtained for the traffic flows measured during the day in a given street

3.2 Agent-Based Methodologies

Agent-based methodologies allow studying the relationship between space and the objects (agents) that move within it. The space can be extensively detailed and the agents obey sets of programmable and parameterizable rules (Batty et al., 2012; Burstedde et al., 2001).

There are several computer applications for implementing these theories. However, as some of the rules of the agents that we intend to use space syntax theories, the obvious option was to use DepthMapX. However, although there is a lot of bibliography on the subject, DepthMapX does not provide some of the considerations that were intended to be carried out, and which appear in the text below. As the team of this project is the author of the DepthSpace3D (Morais, 2018), it became easier to develop add-ons for this application, which will be integrated into future releases.

The application is used in two distinct phases. In the first learning process, it tries to adjust the parameters of the agents' behavior rules in such a way that the virtual model, treated by the application, resembles the real case. In the second phase, the already set parameters will be used.

Regarding space, it is possible to define attributes for each zone. The main thing is their characterization as (a) entry/exit points to/from another public space (b) entry/exit points in/from the built periphery or (c) points of the space itself under consideration. This will allow defining one of the first rules of agents—their origin and destination. Other qualities can also be attributed to the various areas of the space, for example, bus stop, monument, shop, and terrace cafe.

Then the application launches agents into that space. Launching agents will obey two types of application usage. In the first learning phase, it is done according to the empirical data collected either in the counts (being the counting gates, the agents' virtual launch gates), or in the information collected from the video cameras. The launch timing can actually be empirically gathered. In the next phase, there are already defined statistical parameters for the place and time of the successive launches of the agents.

The agents have starting rules, such as the destination and the type of usufruct they want to have from the public space. There is a certain percentage of agents of each type.

In addition to the starting point, agents make movement decisions from time to time. This is because there are changes (a) in the perception (for example, the view) of space with movement and (b) there are changes in the space itself, due to the presence of other agents. The standard solution is to consider steps of 0.7 m and reassessments every 3 steps. There are other more complex criteria. The one used was reassessment whenever there is a significant change in the assessment parameters (obviously the most important is that the intended path is blocked).

The evaluation criteria are diverse, with each type of agent having its own values for them. The weights of each criterion also vary with the type of agent. We can cite some of the parameters that can regulate decisions:

- if it has a destination, or the displacement is peripatetic.
- the target for those who have a destination.
- the type of peripatetic interests (types of places to visit).
- base velocity (velocity people would keep if they were alone in the domain).
- repulsion levels (avoid collisions, avoid crowds, stay clear of walls and obstacles).
- attraction levels (social groups).
- previous knowledge of the space (agents have a mental plan of space) or not (agents that are only guided by what they can visualize at any given moment).
- right/left preference.
- perception distances of the agents to novelty.
- keeping direction level.
- shortest path criterium.
- least time criterium.
- shortest leg first criterium.
- straighter leg first criterium.
- more or less turns criterium.
- total angular distance criterium.
- more visibility of the space criterium.
- sensibility level to space syntax quantities beside visibility (occlusiveness, integration, etc.)
- 'appetite' for the use of prohibited spaces (for example, the mechanical traffic lanes by pedestrians).

This methodology makes it possible to study the changes to the uses of space introduced by variations in geometries, in a more precise way.

The following figures show results for several different situations:

In Fig. 9, agents prefer the shortest path (in the actual case of the space with channels for pedestrians and for mechanical traffic, and consequences of the pedestrianization of the entire space).

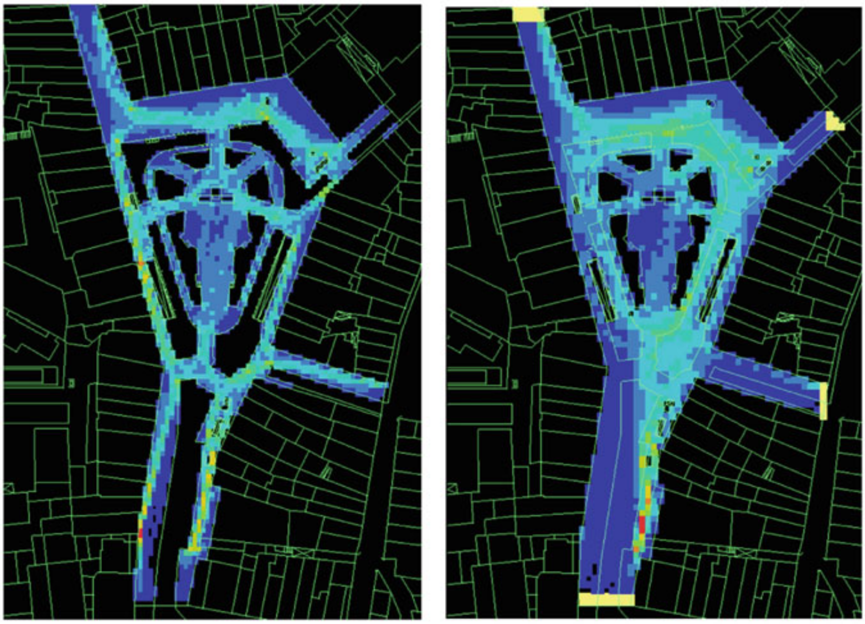

Fig. 9 Comparison of agent analysis for square with and without mechanical traffic. The pedestrian agents prefer the shortest path

In Fig. 10, the agents' rules favor much more visual aspects such as occlusiveness, which brings them closer to the centers of spaces.

In Fig. 11, the introduction of (a) a compact terrace café and (b) the same but more dispersed is studied.

3.3 Space Syntax—Segments

Space syntax (SSM) methodologies are much more popular, so we will only mention a few more relevant aspects (Al_Sayed et al., 2014).

As already mentioned, the large scale is much less relevant to the project, so the so-called segment analyses are not fundamental. But a known weakness of SSM is not being a distributive 'operation' (with A and B spaces under analysis, SSM(A) + SSM(B) <> SSM(A + B)).

Segment analyses were then carried out to be able to integrate the analysis of small areas of public space (square, street, garden) within the overall configuration of the city, without ignoring the relationships that are established between this area and the entire city.

Figure 12 shows the integration (space syntax quantity) of the entire city and also an area bordering the metropolitan area.

Fig. 10 Comparison of agent analysis for square with and without mechanical traffic. The pedestrian agents prefer visual aspects

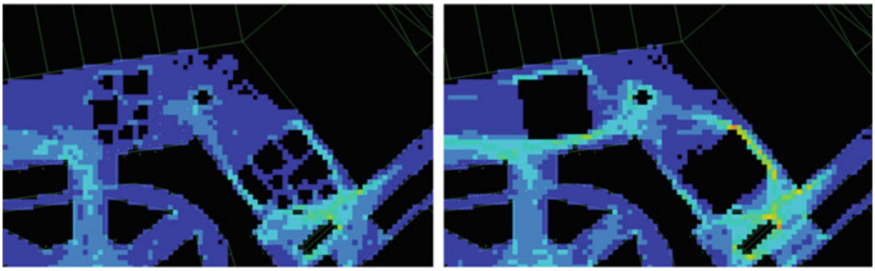

Fig. 11 Agent analysis for two different layouts of a terrace cafe in a square

Table 6 shows the space syntax configurational properties of the public space zones under study.

For the purpose of zoning the city, the functional aspects of the use of space were also introduced.

Figure 13 shows the map of the city's points of interest and Fig. 14 shows the density maps of points of use for (a) services and (b) tourism in the city.

Fig. 12 Integration (space syntax quantity) of the entire city and also an area bordering the metropolitan area

Table 6 Configurational properties of the zones under study

Zone	NaIn r5000m (integration global scale)			NaIn r800m (integration proximity scale)			NaCh r5000m (choice global scale)			NaCh r800m (choice proximityscale)		
	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min
Ribeira	0.82	0.89	0.70	1.17	1.35	0.89	1.01	1.21	0.71	1.05	1.20	0.65
São Bento	0.96	1.03	0.83	1.34	1.57	1.06	1.17	1.36	0.84	1.15	1.32	0.88
Santa Catarina	1.01	1.07	0.93	1.45	1.66	1.21	1.12	1.27	0.86	1.03	1.16	0.72
Poveiros / São Lázaro	0.98	1.07	0.85	1.43	1.80	1.01	1.11	1.32	0.56	1.11	1.34	0.51
Mouzinho	0.90	0.95	0.79	1.25	1.50	0.98	1.09	1.24	0.56	1.13	1.33	0.67
Rua das Flores	0.91	0.96	0.86	1.24	1.39	1.11	1.10	1.24	0.89	1.16	1.32	1.05
Rua Costa cabral	1.11	1.19	0.97	1.25	1.49	1.02	1.11	1.25	0.68	1.15	1.34	0.57
Carvalhido	1.24	1.40	1.00	1.42	1.66	1.11	1.21	1.37	0.79	1.12	1.31	0.88
Carlos Alberto	0.93	1.06	0.83	1.31	1.83	0.96	1.06	1.29	0.51	1.08	1.30	0.67
Campo 24 de Agosto	0.99	1.09	0.85	1.58	2.11	0.80	1.04	1.30	0.40	1.10	1.45	0.54

Fig. 13 Map of the city's points of interest

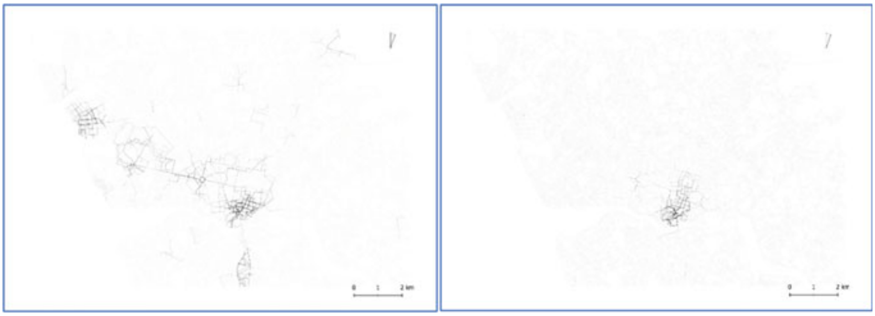

Fig. 14 Density maps of points of use for **a** services and **b** tourism in the city

3.4 Visibility Graph Analysis

Another methodology associated with space syntax is the VGA (visibility graph analysis), perfectly adjusted to the scale of the cases under study.

As they are also current methodologies, we will not detail the studies developed by the project. VGA makes it possible to carry out studies similar to those performed by agent-based methodologies, which has been proven by several decades of scientific studies.

For example, in Fig. 15, the integration map (VGA) of the same zone shown in previous figures is presented (a) for the current space (pedestrians and cars) and (b) with its proposal for total pedestrianization.

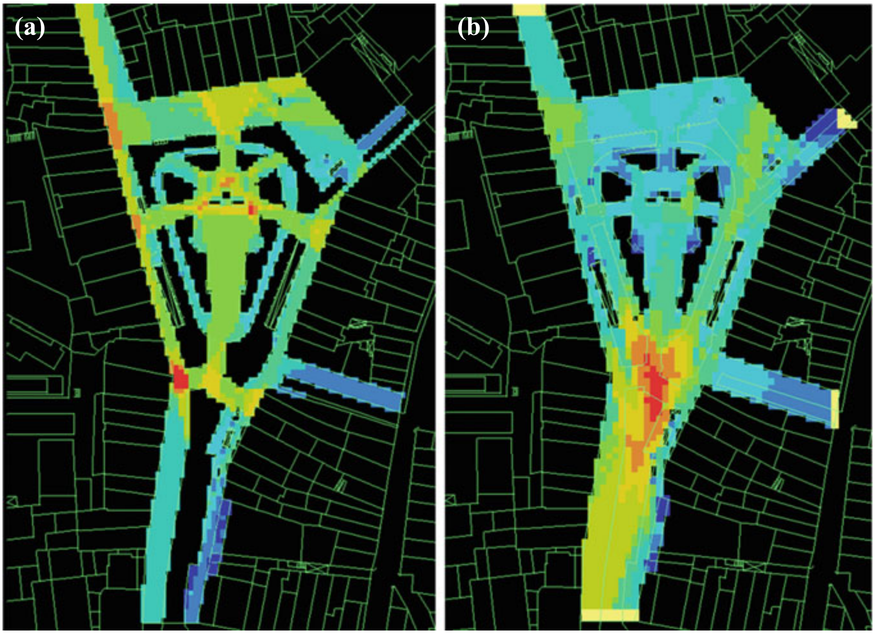

Fig. 15 Integration map (VGA) of a square (**a**) for the current space (pedestrians and cars) and with its proposal for total pedestrianization

3.5 3D Space Syntax

The project also used the space syntax methodology in three-dimensional models. These models do not bring any substantial advantage to the analysis of traffic, but they seem to bring something new to the analysis of other aspects of the use of public spaces by citizens. This also allows you to introduce space syntax quantities into agent-based analysis parameters (Morais, 2018).

Among these aspects are:

- Visibility in 3D spaces is much more intensively analyzed. For example, to determine the best locations of specific observation points of monuments.
- Skyline protection.
- Protection of privileged views.
- Sky visibility levels.
- Consequences on the visibility of the (de)forestation of public spaces.

Figure 16 shows the visual integration in a 3D model of public space in the city.

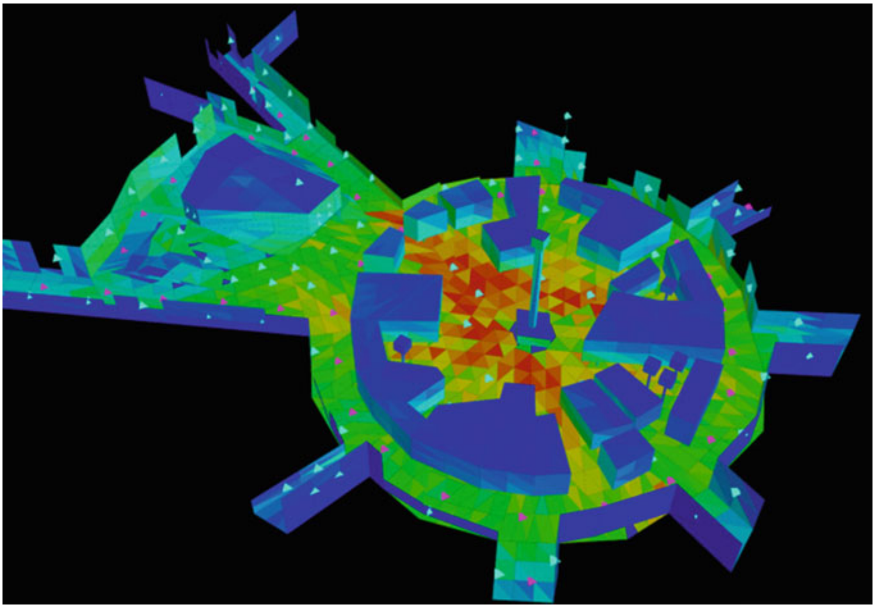

Fig. 16 Visual integration in a 3D model of public space in the city

4 Conclusions

The **first observation** about the project refers to the demonstration of the potential of using diversified formal and digital methodologies, supplementary in some cases, which allowed confirmations and validations, and complementary as a whole, allowing some integration of results. There is still no single methodology for dealing with the problems covered by the project, but an attempt has been made to take advantage of the best potential of each of them.

Different methodologies (and their digital applications) were used: (a) Android Apps (APK) for counting, (b) Web apps (browser) for surveys, (c) Specific Windows applications (MS-Access VBA source, Windows) for statistical treatment of counts and surveys, (d) Space Syntax applications (DepthMapX, Space Syntax Add-on for QGIS (Gil et al., 2017), DepthSpace3D) and very specially the specifically developed by the project,

(e) Set of applications for processing images from video cameras (Windows) with Computer Vision and Machine Learning techniques,

(f) Traffic Flow Theory calculation and analysis automation application (MS-Access VBA source, Windows), and

(g) Add-ons for agent-based analysis in DepthSpace3D.

The **second aspect** is the importance of using methodologies for obtaining empirical data to develop the theories themselves.

If the problems to be dealt with can be solved with scientifically highly developed and tested theories, the empirical data only serve to acknowledge the concrete case to which the theory is going to be applied. Otherwise (and it's our case), empirical data also serve to confront and test theoretical models and determine ways to improve them.

The **third aspect** to be highlighted refers to the integration of methodologies to obtain meaningful information from one to the other.

The following Table 7 is a chart showing the combined uses of methodologies.

There is another great conclusion: the need to make the use of new methodologies much more widespread in the professional practice of architecture and urban planning and to be available at the most diverse levels. It is not just a matter of applying it to specific cases of public utility, through studies carried out by highly specialized professionals.

The project placed in the hands of the technicians of the city administration is a set of work tools that included not only the computer applications already mentioned, but also training actions in these applications, in their theoretical foundations, and in their practical potential.

Also, the entire large set of relevant information was made available for future uses, in various formats to allow its use by a vast set of digital tools more or less disseminated.

Data from empirical studies, such as counts, surveys, and video cameras were made available in SQL DBMS, CSV, XLS, and geo-referenced for GIS.

Physical survey data and 2D and 3D analysis results were provided, as appropriate, in DXF, PDF, and Shapefiles for GIS, STL, OBJ, DWG, and DepthMapX.

It is intended that the results of the project are also accessible to political urban managers, as well as citizens in general, so all forms of transmitting information in an accessible way to non-experts are welcome.

Figure 17 shows precisely the same map of results from a space syntax analysis, in the original format and in Google Maps from QGIS (Gil et al., 2017).

Table 7 Integrated uses of several methodologies

	Counts	Video	Traffic Flow	Agent-based
Counts		Confirmation	Densities	Launching Agents
Surveys				Rules of behavior, user type percentages
Andante		Confirmation	Mass traffic	
Video	Confirmation		Densities, speeds, effective width	Comparison and confirmation, behavior rules
Agent-based		Comparison and confirmation		
Space syntax				Rules of behavior

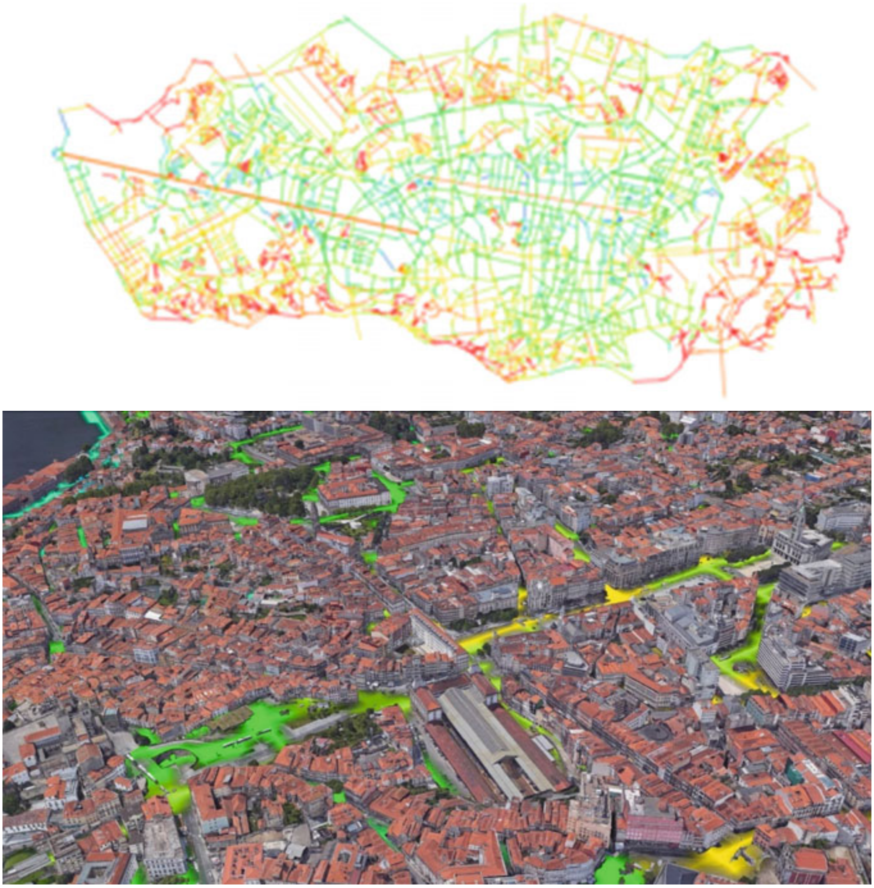

Fig. 17. Map of results from a space syntax analysis in the original format and in Google Maps

5 Future Work

This project fell far short of exploring all the possibilities that formal technologies offer. Examples of in-depth studies, for example:

The video analysis showed many possibilities, but it is necessary to deepen the capacity of the learning phase, which will only be possible with a relaxation of the personal data protection rules, which is possible by studying less restrictive solutions, but without losing their fundamentals of protection.

The influence of environmental conditions has hardly been studied, for example, climatic conditions or the influence of floor covering types.

Another way seems to be the active participation of citizens who actively accept to personalize their experiences, for example, with smartphone apps dedicated to these studies. These solutions have already been tested by the design team, albeit in much smaller-scale studies. An example already mentioned was that of groups of tourists voluntarily using an app that helps to understand the attractiveness of the various locations of the city.

VGA analysis is spatially detailed but does not pay attention to uses or traffic quantification. In traffic flow theories, the fundamental parameters of speed, flow rate, and density are studied for very simple spaces and only consider one use of public space, which is mobility. The agent-based methodology seems more versatile, but it relies heavily on very broad subjective considerations about human behavior.

It will certainly not be possible to fit human traffic into the elegant and perfect theory of fluid dynamics. It is difficult, but is it possible to move toward the integration into a single theory of all the contributions taken into account? History teaches us that there is never a perfect theory, but that we are permanently on the way to its formulation.

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Space Syntax as a Distributed Artificial Intelligence System: A Framework for a Multi-Agent System Development

Ana Cocho Bermejo

1 Introduction

Thomas Schelling developed the first social agent-based simulation in 1978 (Schelling, 1978). The study was focussed on housing segregation using agents as people and interactions representing any socially relevant process. He studied the residential choices in a red–blue environment demonstrating that having people with 'mild in-group preference towards their own group' could still lead to a highly segregated society via de facto segregation.

As so, he stated that patterns can emerge not necessarily being consistent, or implied, with the objective of individual agents. With a simulation implementing a 60% tolerance he demonstrated agents will move at each step until the fraction of neighbours that are from their own group is greater than or equal to a value that finally leads to the groups segregating themselves (Fig. 1).

Societal behaviour models can be found since then. What is complicated to find are human behavioural models linked to real physical environments implementing Gibson's proposed natural movement rules. That is precisely where Space Syntax's existing agent-based simulation model can be used as the basis for research for tackling the no existence of that bridge.

Multi-agent systems provide strong models for representing complex and dynamic real-world environments. A multi-agent system is one that consists of a number of agents, which *interact* with one another. In the most general case, agents will be acting on behalf of users with different goals and motivations.

From now on DAI.

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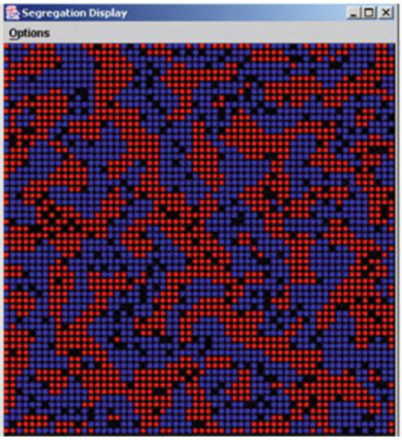

Fig. 1 T. Schilling NetLogo implementation

Agent-based models provide an excellent tool for the analysis of walking behaviour and allow cost-effective experiments under a rigorous statistical framework.

Manenti et al. (2012) defended in 2012 within the framework of *MABS 2011: Multi-Agent-Based Simulation XII* that generally, in literature so far, two aspects were treated in a simplistic way,

- the impact of cultural heterogeneity among individuals;
- the effects of the presence of groups and particular relationships among pedestrians.

focussing as so their work on some fundamental anthropological considerations on which most pedestrian models are based, and, in particular, on proxemics.[1]

Mainly two approaches can be defined nowadays, apart from the classical observation one, when speaking about pedestrian behaviour research (according to Wozniak and Dziecielski (2022)) both based on agents' systems: the one focussing on microscopic models (more focussed on the characteristics of the individual) and the other focussing on macro- and mesoscopic models (that describes pedestrian in fluid terms). Obviously, this research will be focussed on the first approach as it is an empowerment proposal for agent-based Space Syntax analysis (Fig. 2).

Nevertheless, multi-agent systems are distributed systems, one of the most complex classes of computer systems to design and implement as interconnections need to be designed too. A typical multi-agent system will be more complex than a typical distributed system as it is composed of autonomous entities being able then to exist conflicts between them.

Also, cooperation forms are dynamic and as so fulfilling human cooperation manners as well as a possible emergent human group behaviour. Agent simulation

[1] The branch of knowledge that deals with the amount of space that people feel it necessary to set between themselves and others.

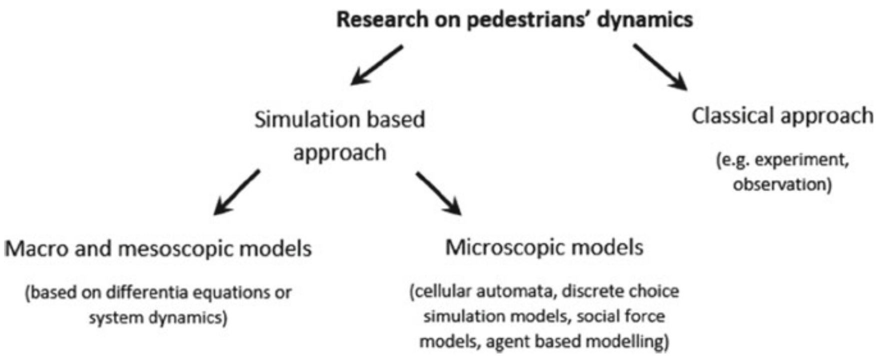

Fig. 2 Research on pedestrian dynamics classification according to Wozniak and Dziecielski (2022)

is based on 'Local' interaction among agents within an environment with no central authority or controller for system operation.

Designing agents' rule-based system for decision-making will depend very much on the agents' final goal and also on the type of agent architecture implemented.

This text develops an introduction on how to tackle the two key aspects for developing space syntax agent-based analysis as a proper multi-agent-based system:

- First, the way in which pedestrian choose their routes and take their decisions.
- Secondly, agent technologies and framework customization for the implementation.

2 Pedestrian Route Election and Allocation

Turner et al. (2002) proposed a methodology for the analysis for the architectural space based on isovist and visibility graphs. They proposed the use of the mean shortest path basing their approach on Gibson's ecological theory of perception while defending it has not been proposed yet as the basis of an approach to design agent-based models of human movement.

Most examples nowadays of human behaviour inside buildings have been developed for the purpose of analysing emergency evacuation. In fact, most of cellular automata pedestrian decision-making improved behavioural models have been developed in the context of human evacuation studies (Longzhen & Feng, 2022).

As mentioned previously models are divided into macro- and micro-models. The macro-model considers the movement of pedestrians as flow.

The most common micro-models include *the social force model* (Helbing & Molnar, 1995), *cellular automata* (Burstedde et al., 2001), *multi-agent model* (Pan et al., 2007), *lattice gas model* (Muramatsu et al., 1999) and *RVO model* (Zhou et al., 2010).

High number researchers until nowadays used the cellular automata space discretised model, with an average cell size of 0.45×0.45 m $\times$ m as it is based on a grid dynamics and allows obstacles avoidance, panic, following, helping and inertial behaviour. Also, as Zhong et al. (2022) implemented in their earthquake simulations the idea of static attractors (i.e. exit doors) and also dynamic ones (herd behaviour).

Agent-based modelling for evacuation of building models have fundamentally implemented BDI (belief-desire-intention) architectures due to the following reasoning as stated by Kaur et al. (2022):

- BDI paradigm is based on the concept of folk or commonsense technology which can naturally predict the behaviour and mental states of individuals.
- BDI paradigm offers a crisper description making agent-based models simpler and easier to understand for modellers and end-users.
- BDI paradigm can be implemented using a wide variety of multi-agent programming platforms like PRS (Procedure Reasoning System, Agent Speak (L), JASON, JAM, dMARS, JACK etc.).

Modelling agents with as perfect as possible human behaviour is a complicated task. Every agent has its own attributes, physical and psychological. Some researchers have included in their agent-based simulations for emergency evacuation purposes genetic algorithms and also fuzzy logic making their agents learning agents able to adapt (Şahin et al., 2019).

How to model agents for space syntax analysis and what of their attributes are relevant is a fundamental question. They not only have to be defined but also might be able to be customised question that deserves proper deeper research.

Some trajectory prediction approaches use more complicated algorithm combinations. Papathanasopoulou et al. (2022) proposed a data-driven model based on a database of pedestrian observations (i.e. position, speed, acceleration, etc.). An LSTM (long short-term memory) approach was implemented via a classification and a regression algorithm.

Ma et al. (2022) have just proposed in 2022 an approach to route choice based on a combination of cellular automata and game theory.

Approaches on how to implement the best methodology for simulation human decision-making process on route choice or even on collaborating/communication with others are infinite. Tong et al. (2022) developed in 2021 a literature analysis to demonstrate how often that topic is covered in the scientific literature (Fig. 3).

After analysing the results, they proposed four principles for pedestrian route choice:

1. Information perception (highly individual dependant).
2. Information integration (humans do that subjectively by mental representations of the environment). In the case of space syntax three different representations can be developed: isovist, convex, and axial map as well as the network representation. Other approaches are based on the development of cognitive maps.
3. Responding to information.

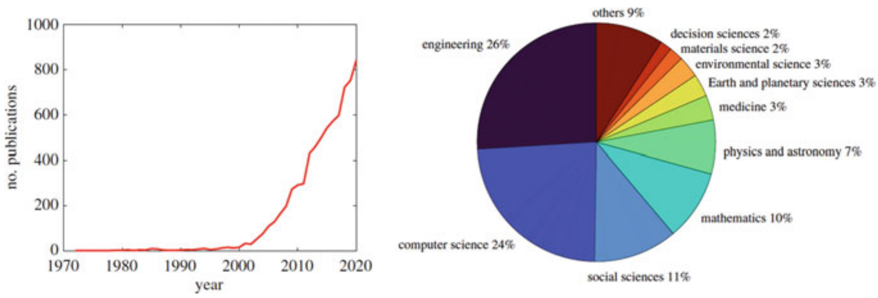

Fig. 3 Analysis of research on pedestrian route choice

4. Decision-making mechanisms, being Utility theory of special importance as it will allow the future implemented agent-based system to have implemented a cost function that user will be able to vary depending on the goals of every agent (i.e. visit the maximum amount of works if in a museum, shortest path to an exit in an evacuation…)

It is important to point out that there exists a lot of literature about pathfinding that is based on research for gaming improvement. Despite not being segregated in the graphic above, some relevant theories like Reynolds, which will be mentioned afterwards, have been developed within that framework.

One of the main advantages of implementing space syntax analysis and an agent-based system will be that it will be opening the possibilities of the rules for the agent-decision-making processes. As so, for every particular scenario agent behavioural flowcharts will be able to be customised further than just following Gibson's natural movement theory.

Each agent will also be able to have its own set of attributes that consist of physical and mental parameters, such as gender, mobility, age, and weight and it will be possible to establish the basis for the relationships between the agents not existing currently in the space syntax existing model.

3 Agent Technologies and Existing Frameworks Implementations

Several agent-based technologies have been developed from the 1990s but none of them have so far been able to simulate real human pedestrian behaviour. Within them, GIS systems were linked to them to map real physical built environments as late as 2014.

Agent technologies can generally be grouped into three categories as follows:

- *Agent-level (micro-level) technologies* concerned only with individual agents
- (i.e. procedures for agent reasoning and learning).

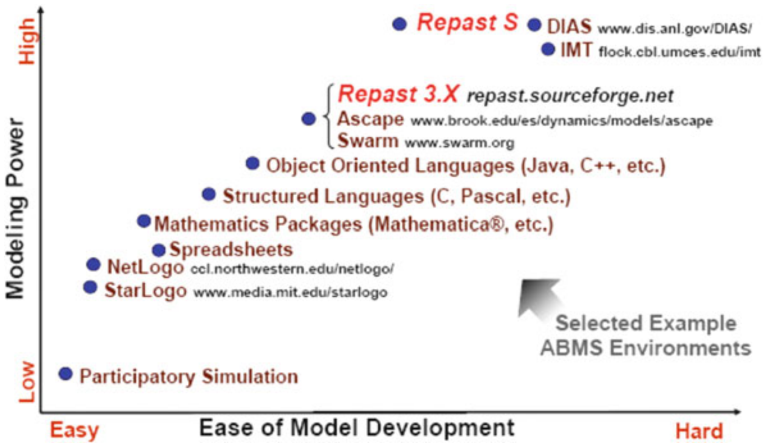

Fig. 4 Existing agent-based modelling tools (1990–2019)

- *Interaction-level technologies* that concern the communication between agents' communication languages, interaction protocols and resource allocation mechanisms.
- *Organisation-level (macro-level) technologies* related to agent societies as a whole (i.e. structure, trust, norms, obligations, etc.).

Speaking about microscopic models, some focus on cellular automata like space syntax, and others on social force models, for example, creating more complex descriptions of pedestrian behaviours with a more accurate movement of individuals.

Nomad, for example, developed by Hoogendoorn and Bovy in 2002, (Hoogendoorn & Bovy, 2004) proposes a pedestrian walking theory that couples the development of the model and assumptions on walking behaviour derived from a minimal effort principle (Fig. 4).

Some agent-based modelling simulation existing toolkits that should be mentioned and taken into account as shown in the previous figure might be:

Swarm (1996)

It is considered to be the original ABM tool. Swarm is a free and open-source toolkit with both Objective-C and Java bindings (Minar et al., 1996). It was originally developed as a software toolkit for the creation of simulation models in the field of Artificial Life (A-Life) (Macal & North, 2009).

NetLogo (1999)

Created by Wilenski (Wilensky, 1999) is open source and uses a modified version of the Logo programming language. The program directly supports reactive architectures and for belief-desire-intention and hybrid ones need to use some external libraries.

Repast 3 (2000)

The free and open-source *REcursive Porous Agent Simulation Toolkit (Repast)* was originally developed by Collier et al. (2003) at the University of Chicago. It was expanded by Argonne National Laboratory as a reusable software infrastructure (Mallach & Macal, 2001). It is a family of three Java-based free and open-source libraries (North & Macal, 2007). The three libraries are Java-based Repast J, C#-based Repast.NET, and NQP (Not Quite Python)-based Repast Py. Repast 3 uses a 'new BSD' (Berkeley Software Distribution)-style licence and includes third-party libraries with compatible licences.

Ascape (2001)

Ascape (Parker, 2001) is free and open source and it is a library that represents models as a complex series of nested 'scapes' populated by agents whose behaviours are implemented with abstracted rules.

StarLogo (2001)

StarLogo is a library and environment that uses Java. StarLogo is an educational system using the Logo language (Harvey, 1997) to make it easier to learn the library and to use it to develop agent models.

Mason (2005)

It is free and open source and provides core services that can be mixed easily with other libraries (Luke et al., 2005).

EcoLab (2008)

*It is a general-purpose C++ and TCL/Tk agent-based modelling library (*Standish, 2008*). Users write models in C++ and then invoke the models using TCL. Tk can be used as needed to develop user interfaces.*

Repast Simphony (2013–21) (North et al., 2013).

The Repast Suite is a family of advanced, free and open-source agent-based modelling and simulation platforms that have been under continuous development for over 20 years. All components are java plain objects easily accessible and modifiable and it uses eclipse as its main development environment. It maintains a strict differentiation between: model specification, model execution, data storage and visualisation (Fig. 5).

3.1 Built Environment Existing Representations: NETLogo and Repast GIS Extensions

NETLogo's GIS extension was made available in 2014 by Eric Russell and several relevant improvements have been included since then (Broday Walker & Johnson,

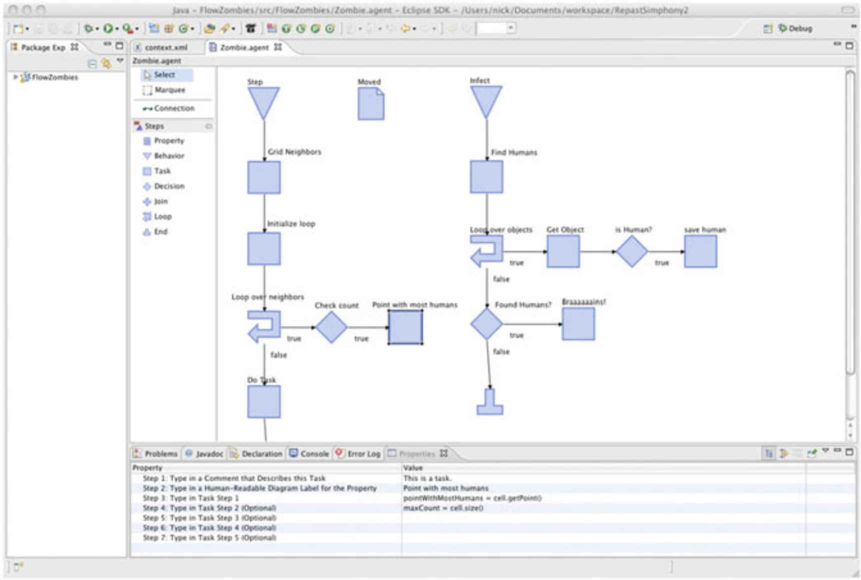

Fig. 5 Repast agent flowchart sample

2019). It introduced the possibility of importing map and its association GIS for running the simulation.

Wozniak et al. proposed in 2022 the following flowchart regarding a presented analysis on a cityscape where they were using NETLogo and its GIS extension for implementing the cities map (Fig. 6).

In this particular example, the authors analysed three different main scenarios: first, the agents just have to find the path between given coordinates, then an obstacle is placed in the way and finally 50 extra agents with random paths.

They modelled human walking behaviour based on the normative pedestrian framework settled by Hoogendoorn et al. (2014).

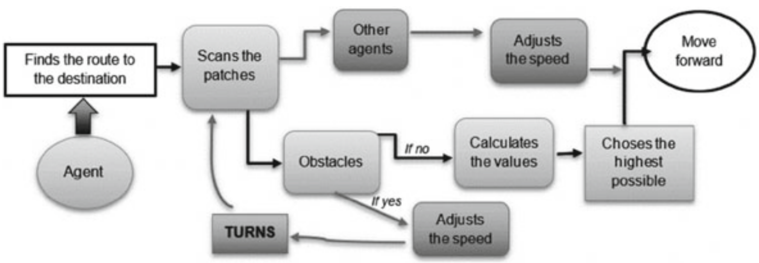

Fig. 6 Agents behavioural flowchart (Wozniak & Dziecielski, 2022)

Pedestrians optimise their decision-making utility function that relates a performed activity and the utility gained. As so all actions of the pedestrians are supposed to provide a utility to him that can be simulated (Fig. 7).

NETLogo allows reactive and hybrid architectures to be implemented and it is easy to design certain 'allowed Paths' assigning them to navigable patches (Sakellariou et al., 2009). Nevertheless, that is not enough detail for the purpose of analysing the human movement inside of a building.

Repast Simphony provides GIS through geography projections that can correlate agents in space. A priori its possibilities regarding building's interior environments looks promising.

Using *GeoTools* (Java tool kit) the geography projection is associated with coordinate referencing system (CRS) which is based on *Open Geospatial Consortium* (OGP) standards and can be used to execute geographical queries on the topology (Collier & North, 2003).

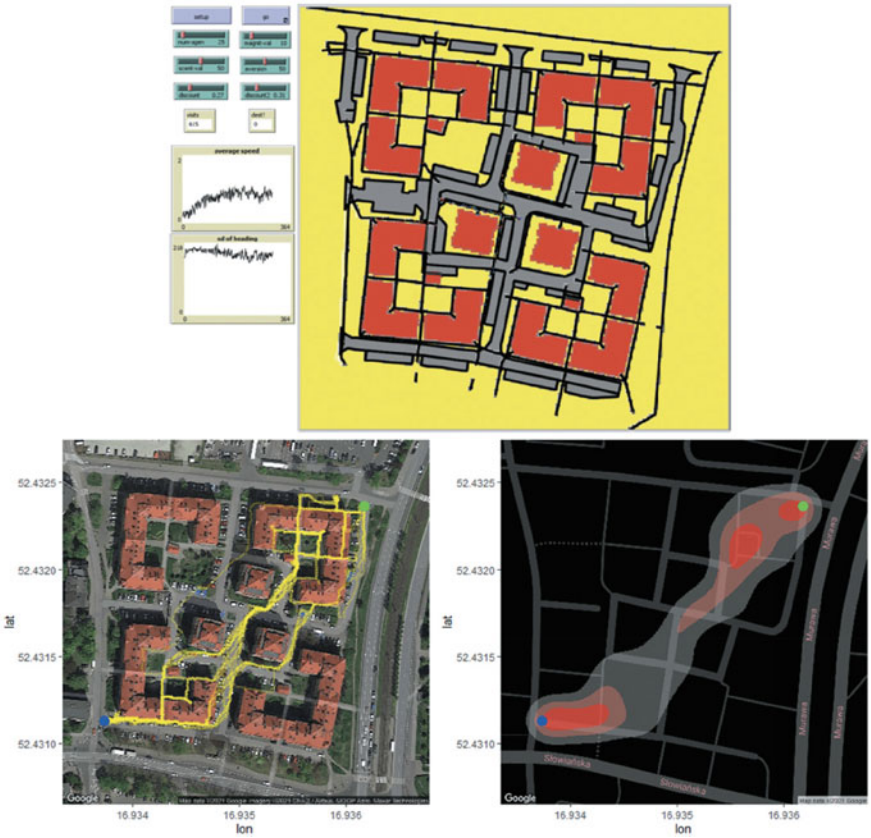

Fig. 7 Left, NetLogo plus GIS implementation by Wozniak and Dziecielski (2022). Right, agents' paths and initial simulation

As such agents can make queries to the geography and doing so determine their status regarding other agents, borders… Also, elements of the geography can be static (road, buildings…) or have dynamic positions. It allows a 3D implementation in which an agent can be represented simultaneously in a series of different topologies (networks, grids…). Agent's location can be tracked and updated continuously regarding the topology within which it resides and also location of it in 2D or 3D. That might be a very relevant quality when in the future trying to implement space syntax graph analysis connection.

Opposite to what happens with public space simulations (Uno & Kashiyama, 2008) most complex building plans or building 3D internal simulations that you can find in the literature these days are not based on highly defined plans or drawings. Simplifications of the spaces are mainly developed in NetLogo or Repast for testing several hypotheses or newly improved decision-making protocols implemented for the agents (Fig. 8).

It is true nevertheless that simulations taking into account more than one room or floor can be found when analysing evacuation (Ha & Lykotrafitis, 2012), but their spatial configurations have normally been simplified too. The way in which DepthMap inputs and maps the building plans has not yet been implemented in such a similarly detailed way when using evacuation purposes' agent-based simulation. In fact, in some cases, as the mapping process has not been automated yet, walls are coded 'by hand' just as non-accessible patches (Fig. 9).

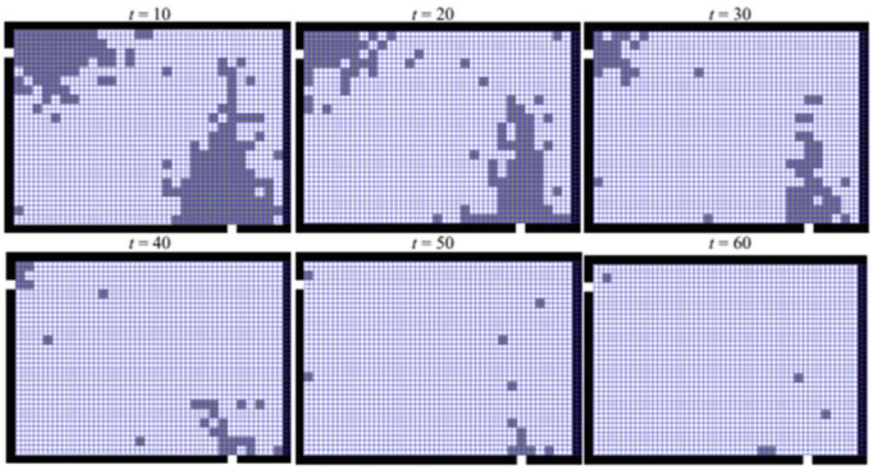

Fig. 8 Left. Simulation of evacuation behaviour in the same room with different exits (Uno & Kashiyama, 2008)

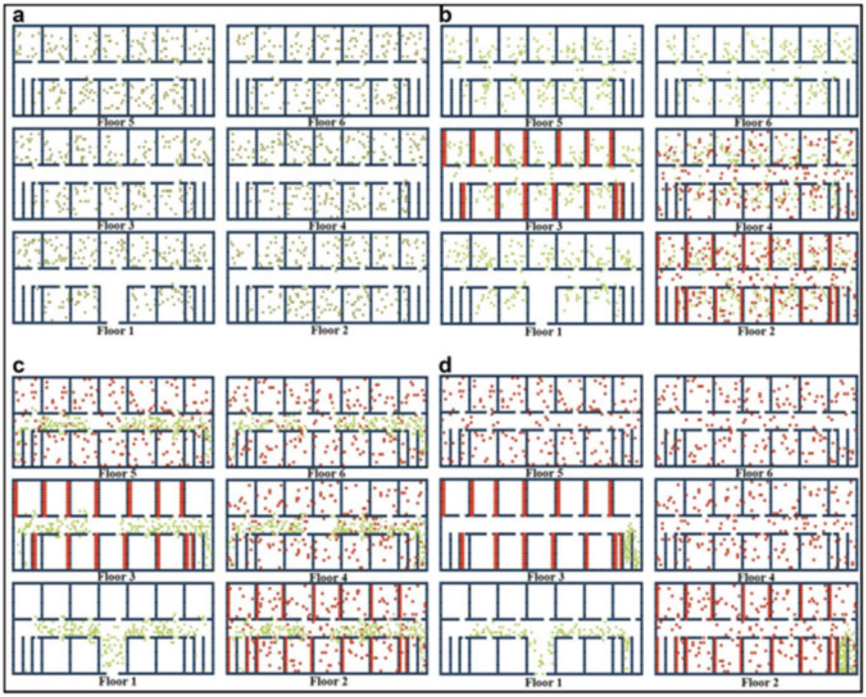

Fig. 9 Simulation of evacuation on simplified plans of a building obtained from an earthquake scenario simulation software. Above left, pedestrian distributions after 0.92 s. Above right, 2.88 s Below left, 17.28 s. Below right, 389 s (Ha & Lykotrafitis, 2012)

3.2 Built Environment Existing Representations for Evacuation Simulations

Most advanced methods on implementing architectural plans in simulation and already existing softwares available nowadays for agent simulation within buildings are as mentioned the ones focussed on emergency evacuation.

Evacuation simulation methods appeared in the 1990s and are as old as the SIMULEX software that appeared in 1995 (Thompson & Marchant, 1995) or EXIT89 (Fahy, 1994) presented in 1994. By then most of the methods were based on flow simulations and their development represented the first attempt to model agents individually. In Simulex, for example, each person was randomly assigned an initial angle of orientation and a normal walking speed between 0.8 and 1.7 m/s. Angle deviation was calculated when a person was obstructing the path as well as contact between two people was calculated also via a formula based on two rotated ellipses (Fig. 10).

Korhonen et al. proposed *FDS* + *Evac* in 2010 (Korhonen & Hostikka, 2010) combining an agent-based model and a Computational Fluid Dynamics (CFDs)

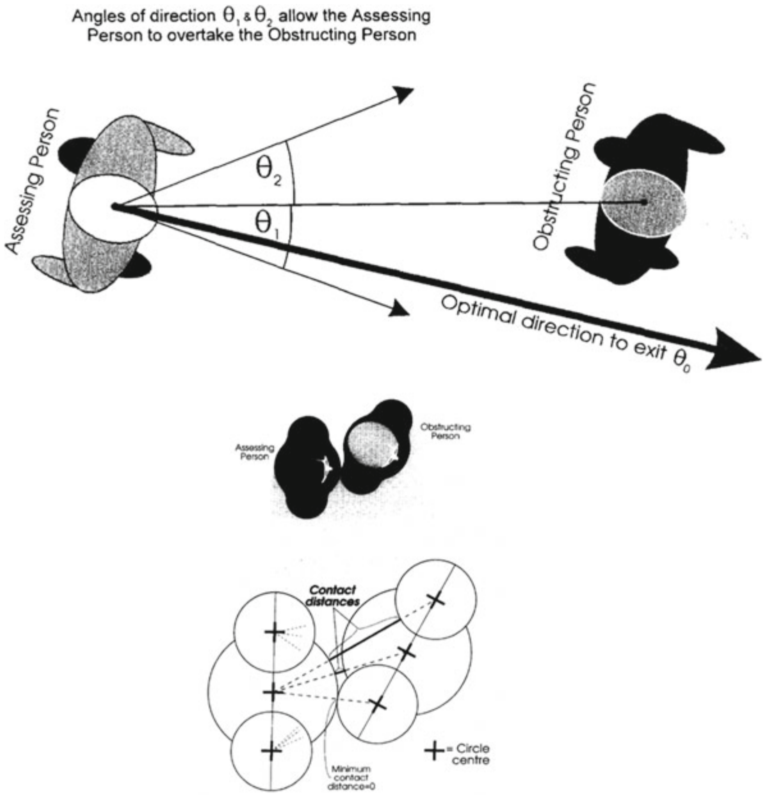

Fig. 10 Left, angle deviation calculation. Right, contact mathematically described

model. Each agent used stochastic properties for assigning their main characteristics: walking speed and response times.

Simulation of Transient Evacuation and Pedestrian Movement (STEPS) proposed in 2010 (Mott MacDonald Simulation Group, 2010) was an agent-based model in which the path to the exit is calculated through a grid (CA). The movement towards the exits is calculated through a potential map that allows the user to implement certain random parameters about pre-evacuation times and travel speeds (Fig. 11).

Pathfinder was presented in 2009 as an agent-based model using Reynolds steering behaviour model redefined by Amor (Engineering, 2009). Agents move inside a continuous 2D surface represented by adjacent triangles. Passengers move along paths and each occupant to interact with the environment and the other occupants. As the purpose of these existing models is evacuation, modelling parameters like speed-density, that implements the relationship walking speed/people density, can be included.

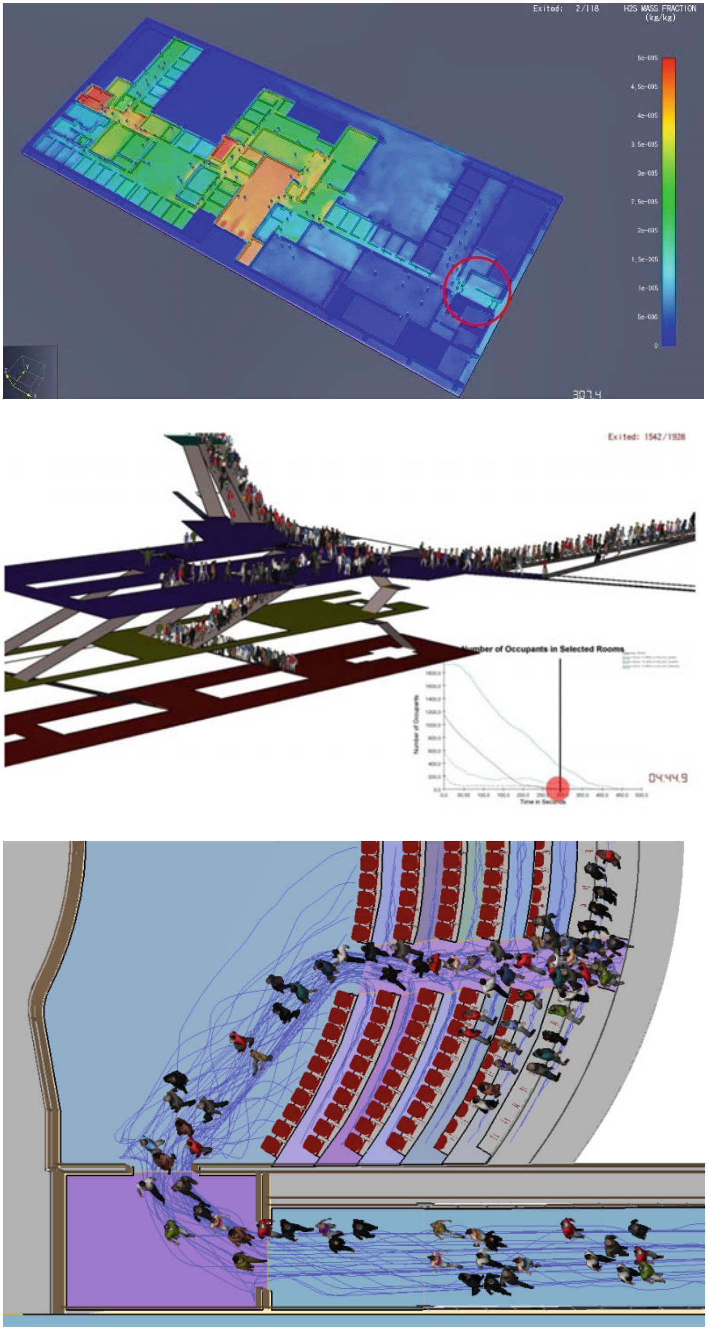

Fig. 11 Pathfinder simulation layout as in Argyropoulos et al. (2017)

3.3 Steering Behaviours Implementation: Relevant Gaming Technologies

Steering behaviours were proposed by Reynolds in 2002 as a response to the navigation mesh algorithms used so far (Reynolds, 1999). Steering behaviours are used for AI agents in a 3D environment, normally a gaming environment, being the agents able to react to changes in their environment. Autonomous characters are agents used in computer animation, games and virtual reality.

The navigation mesh algorithm was a collection of two-dimensional polygon mesh that defined which areas of an environment were traversable by agents. Adjacent polygons are connected to each other in a graph making the algorithm work well for planning a path from one point to another but not for dealing with dynamic objects such as other agents.

Reynolds, on the contrary, introduced the physics of the simple vehicle model where, each simulation step, behaviourally determined steering forces are applied to the vehicle's point mass. An agent is considered to have several behaviours like *Seek* for a static target, adjusting the character so that its velocity is radially aligned towards the target; *Pursuit; Evasion; Obstacle avoidance; Arrival…* (Fig. 12).

They are in fact some gaming technologies nowadays, like *Unity* (Rahouti et al., 2019), that will allow the designer to develop pretty realistic simulations. Some authors already are using some existing components in Unity 3D, like navigation mesh agents and added some more coded by themselves attaching them to each Unity agent (Fig. 13).

Dividing the agents in ambulant/non-ambulant (as research in Rahouti et al. (2019) was developed for a hospital evacuation), the behaviour of an ambulant agent was modelled by reducing its speed and assigning her/him a place of safety or multiple places of safety as known targets. Then, the agent can decide either randomly or using the shortest path as a criteria of target selection through an embedded C# script (Fig. 14).

In fact, Lochhead et al. (2019) have recently developed a comparative analysis of building emergency evacuation scenarios comparing 2D/3D GIS systems and Unity-based environments developed for the same purpose.

Beyond simply visualising data in new ways, these technologies offer a workflow for incorporating the spatial and dynamic complexities that are problematic for GIS

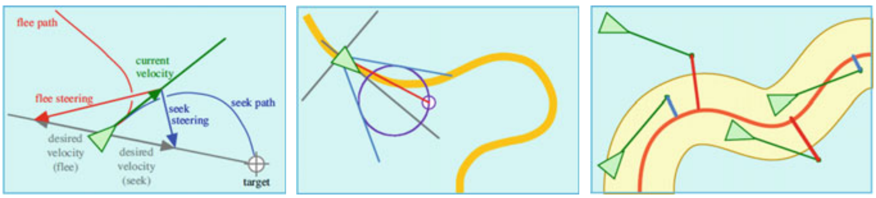

Fig. 12 Reynolds steering behaviour diagram. Left, Seek & Flee behaviours. Centre, Wander behaviour. Right, Path following (Reynolds, 1999)

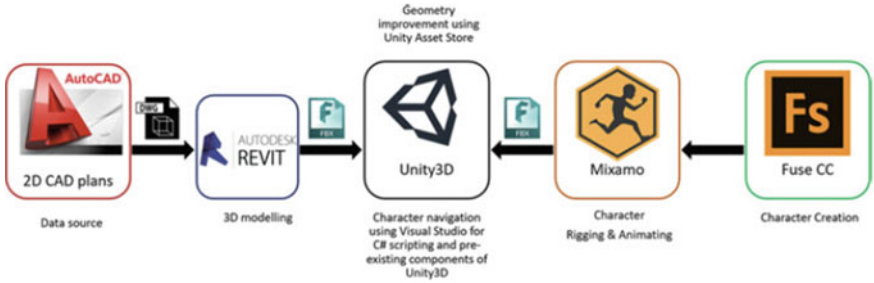

Fig. 13 Software implemented connections and workflow (Rahouti et al., 2019)

software. Using Unity VE they, as GIScientists, draw upon non-traditional software for geospatial applications demonstrating it can serve a valuable purpose as such pointing out that AI-based agents, navigation networks and visualisation modalities are useful functions not found in common GIS applications.

4 Multi-agent Systems Models (MAS) Foundational Basis

An agent-based model consists basically of

1. A set of agents.
2. A set of agent relationships.
3. A framework for simulating agent behaviours, interactions/communication protocols.

As so fundamental question when trying to develop a space syntax-based agent system the main questions we address will be

- What kinds of languages can agents use to communicate?
- How should agents communicate?
- How can cooperation emerge in societies of self-interested agents?

Also, to successfully interact, they will require the ability to *cooperate*, *coordinate* and *negotiate* with each other.

Let's approach these concepts now within a possible space syntax agent-based improved simulation framework.

4.1 FIPA and Agent Communication Protocols

F.I.P.A., Foundation for Intelligent Physical Agents, was founded in 1996 as an institution for developing and setting computer software standards for heterogeneous and interacting agents and agent-based systems.

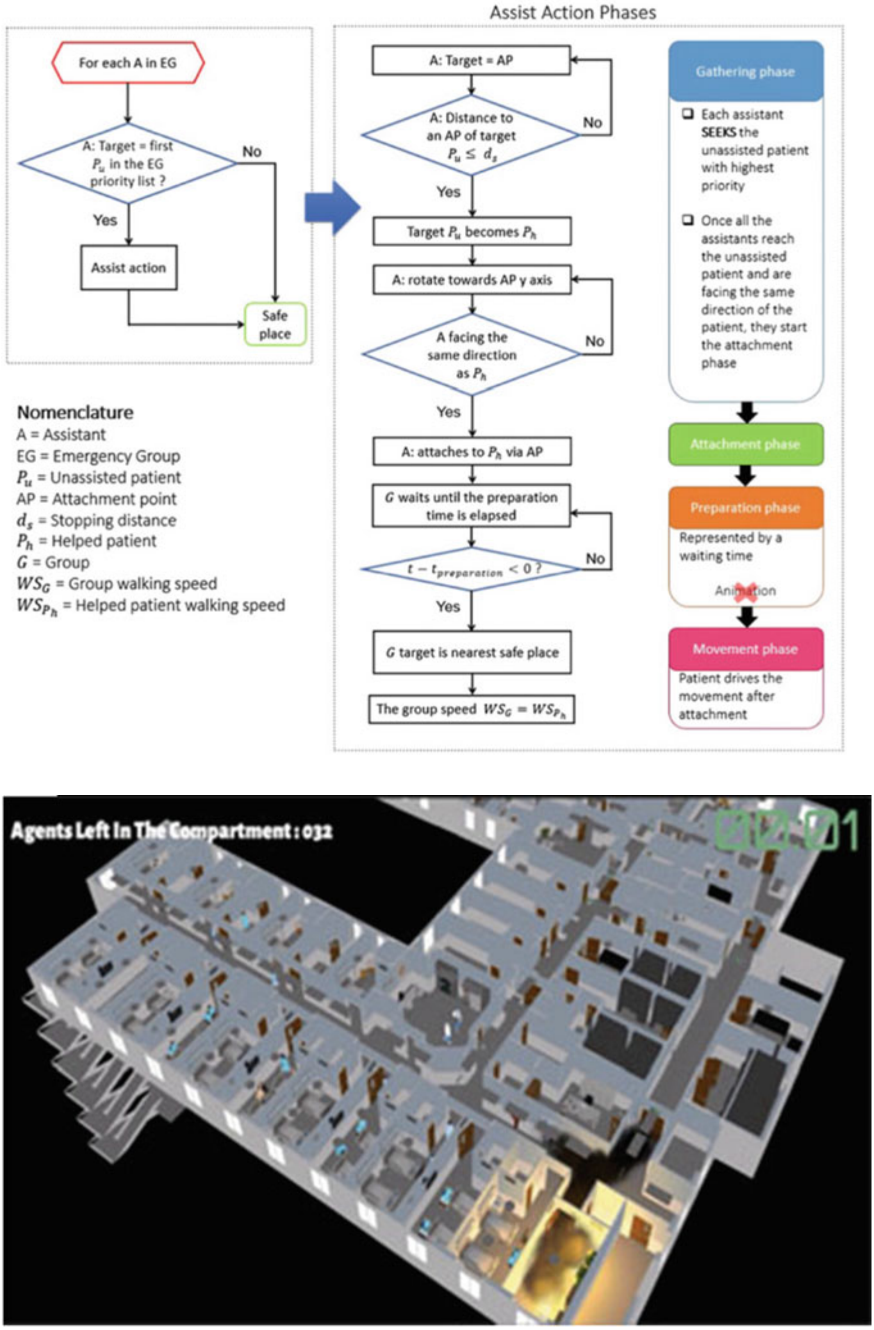

Fig. 14 Flowchart proposed. Simulation process image

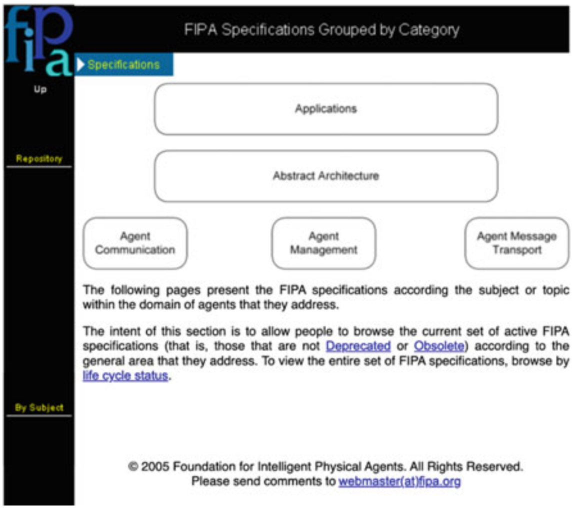

Fig. 15 FIPA specifications grouped by categories (Lochhead & Hedley, 2019)

Their main goal was by then not only to establish a set of standards[2] for both implementing agent systems but also how agents themselves should communicate and interoperate in a standard way. As so some agent communication protocols were proposed as well as an agent communication language, FIPA-ACL.

That will be in fact the main point of criticism introduced along this research.

The definition of an agent includes per se several characteristics without which an agent cannot be considered an agent being one of them communication between the agents (Fig. 15).

In fact, if we have a look at the still operative FIPA website, we can see how the specifications were settled by the three main group properties and behaviours inherent to agents: communication, message transportation and societal management.

There are really not established standards per se but it can be said that there are some de facto ones:

- FIPA agent architecture.
- FIPA-ACL agent communication language.
- OWL ontology language.
- CORBA communication middleware.

As so there will be used some agent communication protocols for the message types, message attributes and shared ontologies between the agents (Fig. 16).

It will be therefore decision-making needed regarding agents' communication according to:

1. Agent communication Blackboard systems.
2. Message passing FIPA standards.

[2] The Foundation of Intelligent Physical Agents (FIPA) is now the eleventh Standards Committee of the IEEE Computer Society as FIPA dissolved in 2005.

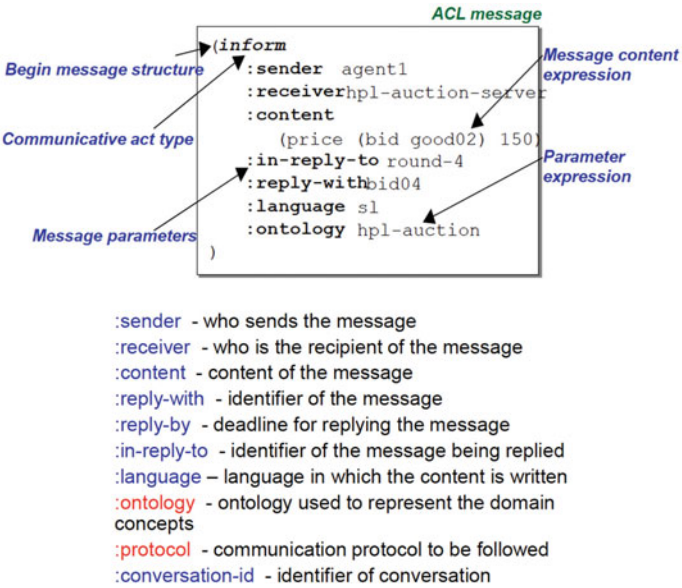

Fig. 16 FIPA-ACL message. Left, components. Right, parameters

3. Basic communication protocols Contract Net.
4. Ontologies design.

As so, it should be understood that communication is the first step towards the sophisticated activities mentioned:

- *Coordination* on how to divide a task between a group of agents (distributed planning).
- *Cooperation* to share intermediate results and resources.
- *Negotiation* (i.e. e-commerce) to agree conditions in an economic transaction or to find the agent that can provide a service with the best conditions.

Being the focus of the research basically on local and occasional cooperation not implementing any negotiation of task suballocations.

4.2 Agent's Coordination

Coordination is fundamental as it is the process through which it decides for each agent in the context of a multi-agent system what activities it should do and when it should do them (planning, scheduling) and also what it should communicate, when it should communicate and to whom (cooperation).

Let's consider, for deciding what type of MAS will be the most adequate to implement for space syntax agent-based analysis, Franklin's cooperation hierarchy diagram.

It is not possible to assume in advance the principle of benevolence of by default cooperative behaviour when referring to human pedestrian behaviour.

As so it will make sense to focus on the idea of independent and self-interested agents (Fig. 17).

In a discrete MAS independent agents will pursue their own agenda with no cooperation at all.

In an emergent behaviour MAS agents can cooperate with no intention of doing so. The system can exhibit high-level, complex, intelligent, coordinated behaviour without any designed coordination mechanisms, just as a side effect of the interactions among agents (Wooldridge, 2009).

Developing and designing an agent-based system must follow, according to Macal and North (Anthony et al., 2014), an organised process:

1. Agent identification and theory of behaviour proposal.
2. Agent relationships and theory of interaction proposal.
3. Get the requisite agent-related data.
4. Validate the agent behaviour models in addition of the model as a whole.
5. Run the model and analyse the input, linking the micro-scale behaviours of the agents with the macro-scale behaviours of the system.

Let's then start with the different elements of the system definition prior to the environment definition as the environment development is directly linked to UCL DepthMap analysis.

So, we will proceed as follows:

- Identifying agent types.
- Define internal agent methods.
- Define agent interaction.

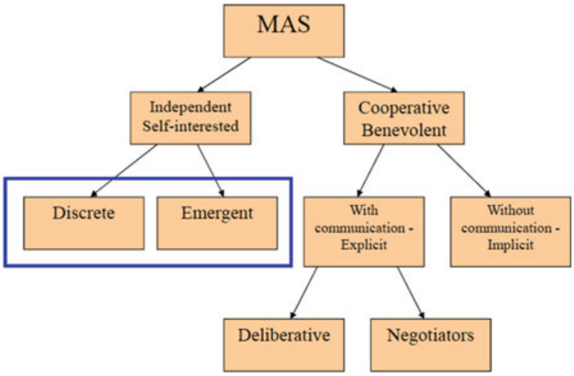

Fig. 17 Franklin MAS hierarchy diagram as in Franklin and Graesser (1997)

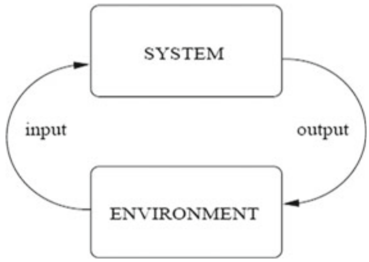

Fig. 18 Basic agent system working schema

5 Agents Properties, Architectures and Multi-Agent System MAS[3] Definition.

An agent can be defined as a computer system that is located in a dynamic environment and is capable of *independent action*, on behalf of its user or owner, and *Intelligent action,* probably using Artificial Intelligence tools and techniques.

It can be understood as an element perceiving the environment and receiving information from it and then acting through the environments via actuators (Fig. 18).

Nevertheless, an agent should satisfy a certain number of properties to be correctly defined as an agent.

An agent should be reactive towards changes in the environment, proactive aiming to fulfil a goal and social being able to interact with others.

As so most basic properties are

1. Autonomy.
2. Reactiveness.
3. Reasoning and learning.
4. Communication.

Obviously, there are more properties agents have but, as no agent requires to have all of them to be considered, just the main basic ones have been considered for the purpose of this research. Others properties can be Benevolence, Veracity, Emotion, Mobility, Character, Temporality, etc.

As so we can describe the fundamental characteristics of the agents to implement as

- *Autonomy*: Ability to pursue goals in an autonomous way, without direct continuous interaction/commands from the user.
- *Rationality*: An agent will act in order to achieve its goals and it will not act in such a way as to prevent its goals from being achieved.
- *Reasoning capabilities* upon a knowledge base with beliefs on the world and the ability to infer and extrapolate based on current knowledge and experiences and, by doing so, the capacity to make plans.

[3] From now on MAS.

- *Learning*: It can be considered as the (automatic) improvement of the performance of the agent over time.
- Must be capable of *flexible action* in some dynamic complex environment and for doing so an agent must be.
  - A *reactive* system able to maintain an ongoing interaction with its dynamic environment.
  - Agents should be *proactive* hence they must exhibit goal-directed behaviour.
  - Agents must have *social ability* so they interact with other agents via some kind of agent communication language, and perhaps cooperate with others.

Regarding the ways in which agents will be able to achieve reactivity what will be considered will be the idea of a reactive architecture with a situation-action protocol not including a priori any hybrid or layered architectures for doing so.

5.1 Agent Architectures, Foundations of Agent's Reasoning

The foundation of the agent's reasoning mechanism lies in the agent's architecture. An architecture proposes a particular methodology for building an autonomous agent. It can be understood as the software architecture for an agent's decision-making process.

As so it is of fundamental relevance the type of architecture that is decided to be implemented for the space syntax agent-human-based analysis system. It determines how information is represented and the action to be taken by the agent.

How the construction of the agent can be decomposed into the construction of a set of component modules and how these modules should be made to interact are the two aspects that define it (Duch et al., 2008).

Relevant architecture can be classified into three main categories:

- Classical architecture (reactive, belief-desire-intention, logic-based architecture/ deliberative or layered/hybrid).
- Cognitive architecture.
- Semantic agent architecture.

5.2 Classical Architecture: Reactive Versus Deliberative

Deliberative, logic symbolic-based architecture was one of the oldest one resting on the physical-symbol resting hypothesis (Fig. 19).

Deliberative architecture will be needed to have an explicit representation of the environment (map) so planning can take place.

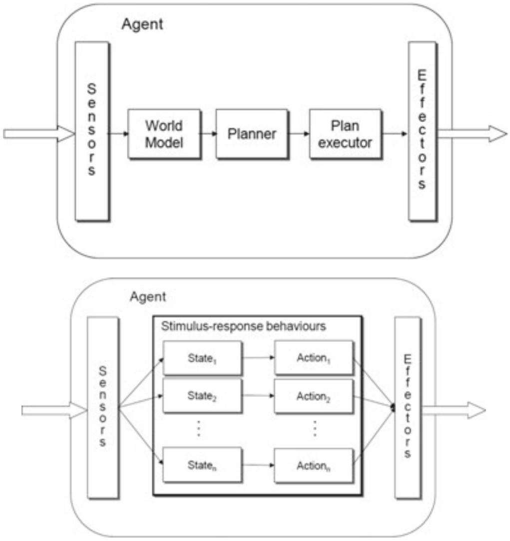

Fig. 19 Left, Basic deliberative architecture. Right, basic reactive architecture

The computational cost of these types of architectures used to be high as it developed a planning procedure that finds the minimal route between the current position and the destination.

Optimal route will be found if the environment is static but it would need to be re-planned if the environment changes. This type of architecture lies in the translation of modelling into symbolic representation that is not always easy. Information needs to be represented in a symbolic way that is suitable for the agents to reason. It is very complicated to put down all rules of a situation within a complex environment.

On the other hand, purely reactive agents do not have an internal state and agents have at most a very simple internal representation of the world. There isn't any global world model.

Also, the perception and action are linked tightly being the intelligence the product of the interaction of the agent and its environment. Complex behaviour patterns appear as a result of the dynamic interactions that are simple interactions.

They have a minimal, low-level communication between modules and there isn't any planning/controller/coordinator agent.

A reactive architecture will imply then a simple design for the agents and also good adaptability in very dynamic and unpredictable environments.

Low computational cost will be achieved as it will avoid complex planning/reasoning procedures. The system will also be quite robust against failure as there will be no central planning component.

Nevertheless, if we are deciding for this architecture for the agents, we must take into consideration certain relevant issues:

- Agents without environment models must have sufficient information available from local environment.

- Decisions are based on the local environment, so if needed, how can it be taken into account *non-local* information?
- There are no long-term planning capabilities.
- It is hard to engineer agents with large numbers of behaviours (as dynamics of interactions become too complex).

5.3 *Classical Architecture: Belief-Desire-Intention (BDI) Model*

Having discarded deliberative architecture we now consider this architecture that is based on the theory of practical reasoning. Originally developed by Michael E. Bratman in his book '*Intentions, Plans, and Practical Reason*' in 1987, it concentrates on the roles of the intentions in practical reasoning.

Human practical reasoning consists of two activities:

- *Deliberation,* deciding *which* state of affairs we want to achieve.
- *Means-ends reasoning,* deciding *how* to achieve these states of affairs.

Outputs of deliberation are considered to be *intentions* and the outputs of means-ends reasoning the *plans.*

As so, intention is choice with commitment and intentions enable the agent to be goal-driven rather than event-driven. By committing to intentions the agent can pursue long-term goals (Fig. 20).

An autonomous agent should act on its intentions, not in spite of them, adopt intentions that are feasible, drop the ones that are not feasible and commit to intentions, but not forever.

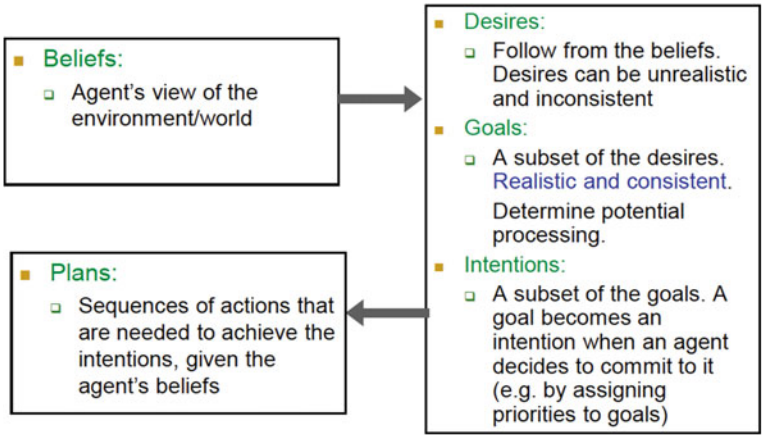

Fig. 20 Belief-desire-intention flowchart

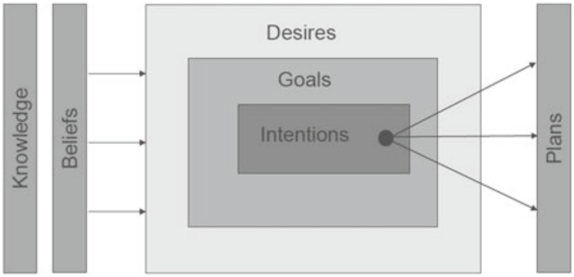

Fig. 21 Belief-desire-intention basic architecture

It has to discharge those intentions believed to have been satisfied being able to alter intentions when relevant beliefs change (Fig. 21).

5.4 Classical Architecture: Hybrid/Layered Architecture

As deliberative architecture has already been discarded it makes no sense to consider this type or architecture that is characterised for allowing both reactive and deliberative agent behaviours.

5.5 Cognitive Architecture

This type of architecture is based on cognition science and on the way it understands human cognition and psychology.

Main two characteristics of cognitive architectures are memory and learning and it is precisely according to that we can classify the types of these architectures as follows (Fig. 22):

ACT is one of the earliest cognitive architectures to model human behaviour coined by Anderson in 1976 (Heise & Westermann, 1989).

As it is based on human behaviour it proposes two main differences:

- A programming formalism to encode knowledge and associate it with its interpreter.
- Strong assumptions on the representation of knowledge.
- Assumes a modular representation of knowledge.
- It provides a unified approach with a common set of representations and mechanisms which reduces programming cost.

They are used commonly to produce intelligence systems that model human performance and according to Langley et al. (2022) must possess the following characteristics:

- Short- and long-term memories for storing agents' beliefs, goals and knowledge.

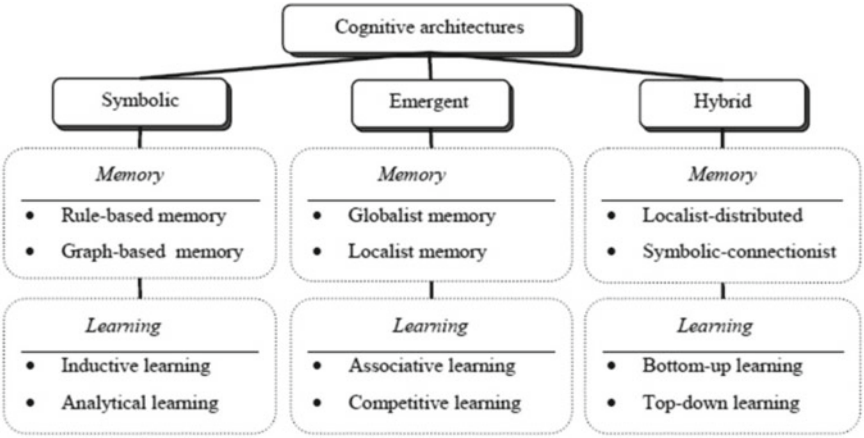

Fig. 22 Cognitive architectures classification (Langley et al., 2009)

- Representation of memories and their organisation.
- Functional processes that operate on these structures.

As Langley et al. pointed out in his conclusion in Langley et al. (2009), these architectures solve some limitations of reactive architectures combining them with deliberative problem-solving but they still rarely confront the interactions between body and mind that arise with real embodiment.

As so for the purpose of a space syntax-based implementation they do not really mean a real advantage over reactive or BDI architectures as they do not examine the manner in which physical embodiment impacts thinking that would be the basic fundamental reason for implementing this type of agent architecture.

6 Conclusions

Along this text it has been introduced some of the elements and topics that must be considered for the implementation of a distributed artificial intelligence approach to the agent-based analysis that UCL DepthMap proposes.

6.1 Goal and Decision-Making Process Customization: Cost Function

One of the main advantages of implementing space syntax analysis and an agent-based system is that it might be possible to customise some agent goals and decision-making processes depending on the type of building and situation pedestrians are in.

As so, it has been mentioned that it will be really helpful to implement a cost function for the purpose of goal customisation further that just following Turner's implemented goals. Utility theory will be of special importance as it will allow the cost function implementation and definition depending on the required goals.

Also, it will be possible then to customise some variables that highly influence the decision-making process of the agents for moving, further than the already implemented Gibson's natural movement and shortest path-based decision-making. As so, for every particular scenario agent behavioural flowcharts will be able to be customised.

There have been several decision-making studies present in the literature being considered the more adequate the four points one from Tong et al. (2022) altogether with Gibson's.

6.2 Adequate Existing Technological Approaches

On the other hand, existing technologies for agent-based analysis have been analysed. From within the set of ABS analyses, NETLogo and Repast have been pointed out as the most adequate ones. Also, evacuation simulation softwares and gaming technology approaches to 2D mapping and human-based agents decision-making have been analysed.

NETLogo is robust and powerful and it is easy to learn, allowing reactive and BDI architectures to be implemented pretty easily. On the other hand, *Repast* allows that agent's location is tracked and updated continuously regarding the topology within which it resides and also location of it in 2D or 3D. That might be a very relevant quality when in the future trying to implement space syntax graph analysis connection.

Some of the most recent human behavioural walking implementations analysis linked to build environments via GIS have been analysed and compared to Unity gaming environment as both compensate for what are considered to be each other's failures. As so, despite not being shown rigorously mapping real physical environment through GIS Unity allows the upgrade of some of the built-in agents via direct coding property that can be really helpful.

6.3 Agents' Architectures, Languages and Attributes

As mentioned along the research, the most adequate architectures to be implemented are considered to be a reactive architecture and a BDI architecture.

The first one will be adequate for simple scenarios with almost nonexistent cooperation while the second one will be the one used when certain levels of learning and cooperation are required by the analysed scenario.

Each agent will also be able to have its own set of attributes that consist of physical and mental parameters, such as gender, mobility, age, and weight, and it will be possible to establish the basis for the relationships between the agents not existing currently in the space syntax existing model.

The framework proposed will be the one with FIPA-based communication protocols and standards.

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Examination of the Diffusion of COVID-19 Cases in Viçosa, Minas Gerais (Brazil): A Configurational Approach

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1 Introduction

In March 2020, the World Health Organisation (WHO) declared a world pandemic called Coronavirus or, currently, the SARS-CoV 2. The first signs of this pandemic refer to cases of pneumonia evidenced by the new RNA virus as the responsible pathogen identified in Wuhan, the capital of Hubei Province (China), in December 2019.

The main means of contamination and proliferation of SARS-CoV 2 is the contact between contaminated and non-contaminated. The urban space has been recognised worldwide as one of the main factors affecting the spread of infectious diseases. The severe acute respiratory syndrome of Coronavirus, which causes COVID-19, is much more transmissible than the respiratory viruses already experienced in previous

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pandemics. Therefore, the role the urban space configuration plays in the dissemination of COVID-19 are highlighted, knowing that it is in the urban space that social dynamics are developed, as well as physical contacts between individuals.

To understand the configurational influence in the infection propagation process, it was used, in the research methods, morphological analysis techniques derived from Space Syntax—which is a set of theories and approaches to understand how the space configuration correlates itself with social dynamics. Within this framework, it was relevant to investigate the sort of role the urban space played regarding the spatial spread of COVID-19 cases in Viçosa-MG (Brazil).

This study collected a set of 12,715 confirmed cases of SARS-CoV-2 and their respective contamination sites between April 1, 2020, and February 14, 2022, in the city of Viçosa-MG. Considering Space Syntax, Choice and Integration measures were selected as quantitative indicators for the urban space configuration. In addition, it was developed an overlapping process of syntactic analyses with the Kernel Density Estimator (also called Kernel Map), to estimate the density and concentration of confirmed cases of COVID-19 in the urban space. In this method, observations are weighted by distance from a central value. The result of a Kernel Map is an overview of the intensity of a certain phenomenon, or process—in this case, the spread of the infection.

The option for the study in Viçosa-MG is justified by its characteristics as a hub city for its educational needs. Such characteristics enhance the attraction of other people from other cities and even from other states. The migratory flow enhances the movement and agglomeration of people daily in the city, a fact that contributes to the spread of infectious diseases such as COVID-19.

The option for the use of morphological analysis techniques derived from Space Syntax in the set of methods applied in the research is due to the contact process of the spread of the disease, since the virus spreads from person to person through droplets from the nose or mouth that are spread when the patient coughs or sneezes. In addition, spreading situations also occurred from surfaces and nearby objects. As such, close contact favours infection.

Through this study, it was possible to reveal a strong relationship between the urban space configuration and the spread of COVID-19 cases. Highlighting the role of topology, but also of the network accessibility and of the centrality of the urban space, the effectiveness of the type of analysis proposed in this paper has been demonstrated for the interpretation and prediction of the spread of COVID-19. In general terms, this study seeks to contribute to the current literature by investigating the spread of COVID-19 cases at a local scale, from a configurational approach.

2 Contextualization of the Study Territory

Viçosa is a municipality located in the state of Minas Gerais (Brazil) (Fig. 1) and, according to the 2010 census, the municipality has about 72,220 inhabitants, of which about 20,000 people correspond to the floating population (IBGE, 2010). The population estimate in July 2021 was 79,910 inhabitants (IBGE, 2021).

The city has had an essential university vocation, since 1922, it has an institution of higher education of national prominence. First, as the Higher School of Agriculture and Veterinary Medicine, the institution would become the Rural University of the State of Minas Gerais in 1948, and later, in 1969, the Federal University of Viçosa (UFV). It also has other private higher education institutions, further enhancing its educational character. It is a city of national and international attractive potential due to scientific-academic events that take place around the universities.

The population of Viçosa-MG has grown significantly in the last fifty years, always following the growth of its university activity. Its population is mostly made up of young people, which gives the city its own dynamics.

With regard to COVID-19 data in the municipality, from April 2020 to February 2022, 12,715 cases were recorded, of which 149 were deaths. These data include records from the urban perimeter, rural area, and from other municipalities notified in Viçosa-MG.

Since the first pandemic records, aiming at mitigating the contagion and the spread of the virus, the municipal management instituted a series of social distancing measures, among them the creation of sanitary barriers and the stoppage of face-to-face educational activities that only had their gradual return to from March 2022.

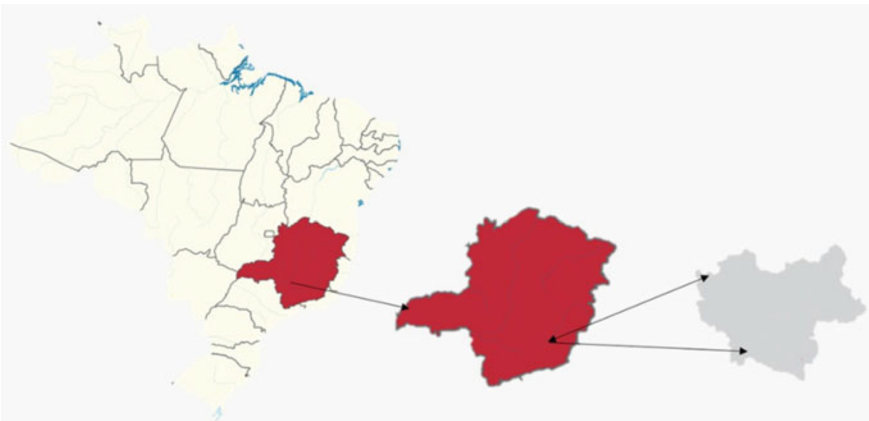


Fig. 1 Location of Viçosa, Minas Gerais, Brazil

As Viçosa-MG is characterised as a university city, during the period of remote educational activity, about 27% of its population, students, professors, and administrative technicians from other locations, returned, for the most part, to their cities of origin, a fact that may be considered relevant in the spread of the disease.

3 Theoretical Methodological Bases

3.1 Space Syntax

Space Syntax, as a theory, emerged in the 1970s, with the aim of analysing relationships between a space configuration and its respective patterns of use and occupation, based precisely on this premise of the existence of relationships between the social dynamics that occur in certain spaces and their settings. In the works *The Social Logic of Space* (Hillier & Hanson, 1989), *Space is the Machine* (Hillier, 1996), and *Decoding Homes and Houses* (Hanson, 1998), the authors, together with other collaborators from UCL/University College London, proposes a new theory and methods for investigating the relationship between social dynamics and the configuration of space, understood from its physicality. The theory proposes a model for describing the relationship between the space configuration and its social dynamics, assuming that the physical structure of a space is inseparable from social structures, acting and interfering with them. The contribution to the understanding of the role of the space configuration in social dynamics is based on procedures that have the triple possibility of first, representing it; second, quantifying it, involving mathematical methods and techniques; and third, analysing it from certain standards (Hillier & Hanson, 1989).

Hillier (1996) defines Space Syntax as a type of analytical theory, or a theory and method, in which analytical components advance together with design components. In this sense, Space Syntax understands the space configuration as a system of barriers and permeabilities of different types, related to the movement, and the co-presence, of people; the social structure is understood as a system of encounters and avoidances, contacts and interpersonal interactions between different categories of users (Holanda, 2010). In this way, the theory seeks to interpret space through the possibilities of displacement that it offers.

Movement is an important attribute for Hillier and Hanson (1989) in understanding the space configuration, as they understand that spatiality is intrinsically linked to this phenomenon. It is through movement that it becomes possible to know and learn space. This understanding is directly related to the idea of co-presence: in order to interact with different users, it is necessary to find them, and these encounters take place in the space plane, whether in the city or the building.

The theory's techniques operate from three main space units that apply to spatially distinct objects, from the identification and quantification of physical attributes, and from analytical decomposition. These spacious units are convex polygons, axial lines, and isovists. Such units aim to reveal the intrinsic space properties of the system of barriers and permeabilities that configure the space. Each unit is applied according to the way in which human experiences develop in space: thus, maps, or diagrams, of axial lines seek to represent linear movements, and those of convex polygons represent spaces intended for the grouping and permanence of people, usually related to the development of functional activities.

For the developed research that this paper refers to it was developed an axial map of Viçosa-MG, focussing the representation of the movement, given that the spread and contagion of COVID-19 occur from the physical contact provided by the social dynamics in the spaces (expressed by the axial lines and its relations).

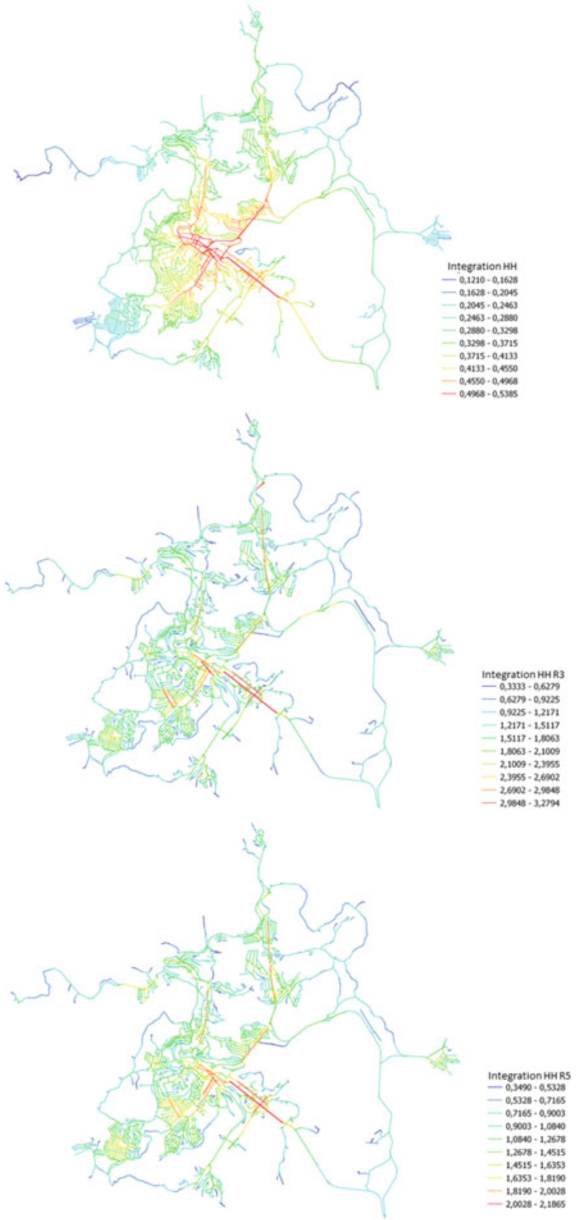
Axial spaces, or axial lines, are represented by straight lines capable of covering all open spaces of a given urban outline or building plan. These lines simulate movement, considering that people tend to move in a straight line and through the smallest geometric distances between points in a given space. For each road, a line is built that, when connected to the others, establishes relations of accessibility or permeability (visual or physical). This linear representation is the basis for the construction of the axial map (Hillier & Hanson, 1989).

The representations, maps and/or diagrams, derived from the analyses performed mathematically in the configurational analysis, are constructed from the usual representations of architectural and urban objects, such as floor plans of buildings or urban areas, and maps of cities, or any other representation architectural or urban foundation that favours geometric measures. However, from these representations, other representations are derived, which express the results resulting from the mathematical analytical operations, of a topological nature. Topological measures quantify the qualities of each represented space, considering the relationship system.

There are several measurements used for the analysis of axial and segment maps. As mentioned by Heitor and Pinelo (2015), of all the measures developed and tested, two stand out for their ability to analyse urban settings: Choice and Integration.

Integration: It is the most important measure for syntactic analysis. It is a measure of the degree of centrality. It quantifies the topological accessibility of each space in relation to all the others that make up the space system that contains it; mathematically expresses the syntactic distance from a space to all other spaces in the system (Hillier & Hanson, 1989). Measures to what extent, on each line of the map, fewer changes of direction to and from all other lines are present on the simplest routes. Integration tends to emphasise spaces in the city that individuals would call main streets, often associated with the concept of an urban centre. The Integration value calculation results in a numeric attribute for each space or each row. It can be analysed at several levels, for the scope of this paper two levels will be studied: radius N which measures how deep or superficial a line is in relation to all other lines in the system; and radii 3 and 5 (local radii) which measure how deep or shallow a line is relative to other lines that are 3 and 5 changes of direction away, respectively (Fig. 2). The first is considered a global analysis of Integration and the second a local analysis. Local Integration is a better indicator for smaller-scale movement, or pedestrian movements (Hillier, 1996).

Fig. 2 Axial Map of Viçosa-MG—integration HH RN, R3 and R5



Choice: concerns the flow potential, the probability of a route being used more than all the others due to economy of movement, that is, of a space being used because it is part of the smallest routes among all the routes of a space. In other words, it is related to the probability of passing a certain road when taking the shortest route when moving from one point to another on the map. For this measurement, it was used the same radius indicators as the aforementioned measurement (Fig. 3).

The configurational maps were correlated with COVID-19 data, aiming from the topology, network accessibility and centrality of an urban space to verify this type of analysis for use in interpreting the spread of the virus.

3.2 Kernel Maps

The Kernel Density Estimator is an interpolator (Bailey & Gatrell, 1995), which makes it possible to estimate the intensity of an event in the entire chosen area, even in regions where the process has not generated any real occurrence. It is a non-parametric probabilistic estimator (does not use mean and standard deviation as a parameter). Its only basic premise is that when evaluating the occurrence of events in space, one has to consider the location of events to be random. In a simplified way, it can be said that the Kernel Density Estimator (Kernel Map) consists of estimating the expected number of events per unit area.

Kernel Maps are widely used in the interpretation of a phenomenon represented by a map of points, they are an alternative to the geographical analysis of the behaviour of patterns. In this method, observations are weighted by distance from a central value. In this way, the result of a Kernel Map is an overview of the intensity of the process in all regions of the map. As a consolidated methodology in the analysis of the spread of diseases, it was decided to choose it in the research to the interpretation of COVID-19 cases in Viçosa-MG.

The database of confirmed COVID-19 cases, provided by the epidemiological surveillance of the municipality of Viçosa-MG, was georeferenced using "Google My Maps", generating a point in the urban network for each confirmed case. The data from the mapping were subdivided into months and later processed by the Kernel interpolator.

For the interpolation of the points in the kernel estimator, a radius of 500 m was estimated, because, with a larger radius, a satisfactory cartographic product was not obtained for the purposes of this work. For the developed research, the Kernel Map highlights with the warmest colour (red) the regions where there is a higher concentration of COVID-19 cases, where there is a lower concentration of cases, the colour is cooler (blue) (Fig. 4).

Kernel Maps were used as a correlation unit with configurational analyses in order to verify the relationship between the spatial configuration of the municipality and its relationship with the spread of COVID-19 in the urban space.

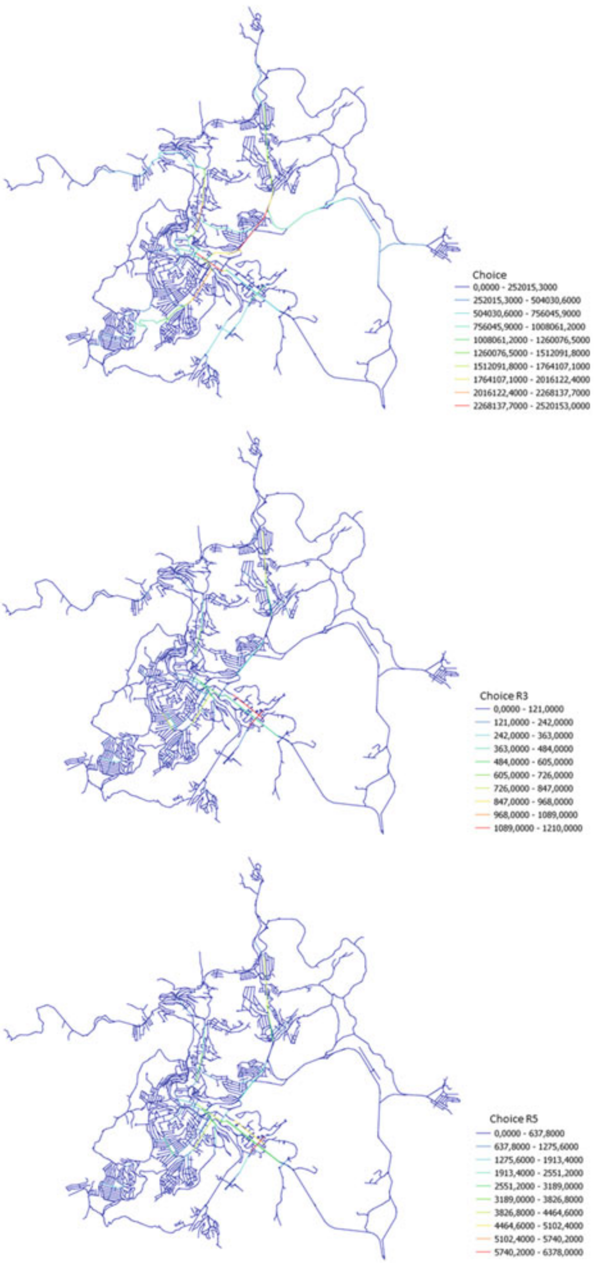


Fig. 3 Axial Map of Viçosa-MG—choice RN, R3 and R5

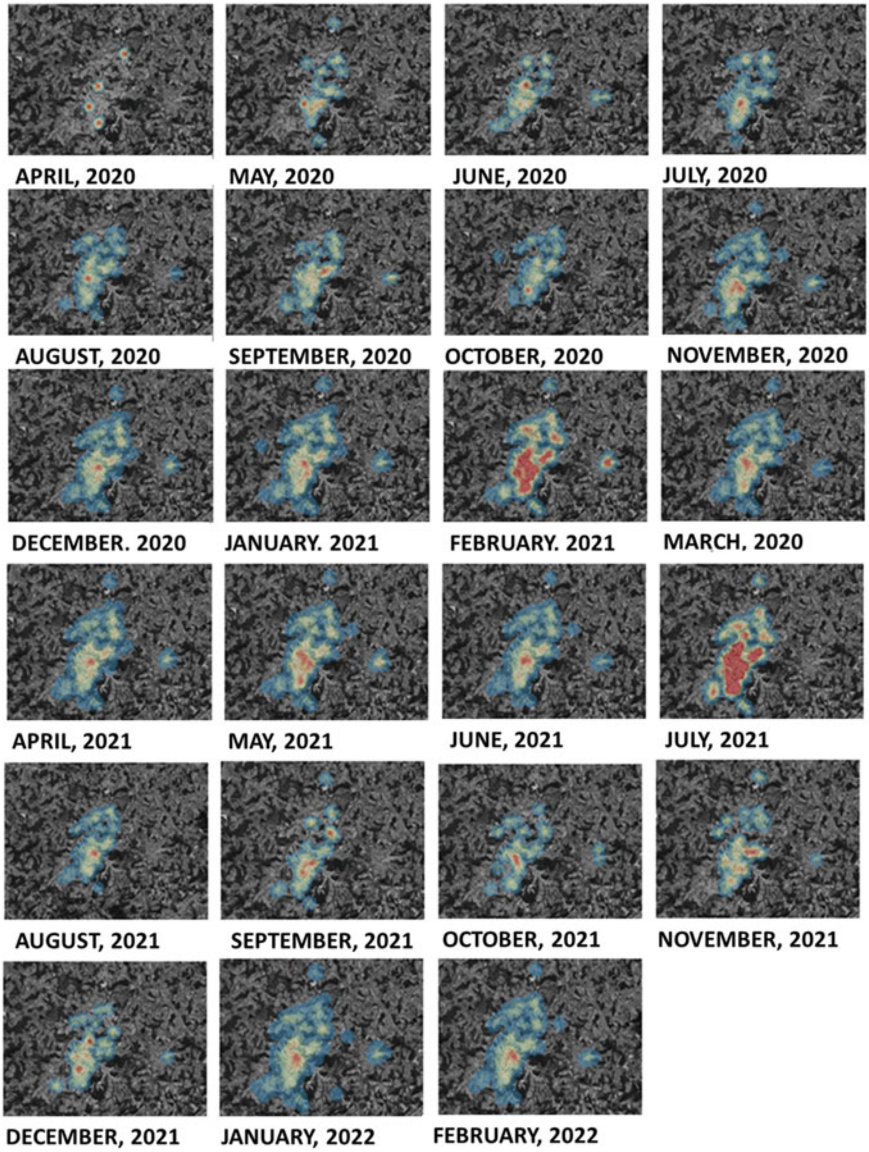


Fig. 4 Kernel Maps—COVID-19 confirmed cases by month in Viçosa-MG

4 Correlation Between Configurational Analysis and Density Maps

From the files provided by the municipal management, the quantitative data of confirmed cases of COVID-19 in Viçosa-MG were tabulated. Such data were subdivided into months in order to try to understand the logic of disease proliferation in the time window from April 2020 to February 2022 (Fig. 5).

In addition to the systematisation of the total months recorded (23 months), the moving averages of two and three months (Fig. 6) were also performed in the same time interval (April 2020 to February 2022), in an attempt to smooth out the large variety of registered cases, for example, from December 2021 (56 cases) to January 2022 (1,515 cases).

From the analysis of the graphs, it is possible to trace some relationships with the increase in cases registered in some specific months of the year. The periods with the highest incidence are related, for example, to festive periods such as Christmas and New Year's Eve and summer and winter school holidays, which take place, respectively, from December to February and July.

Other variables can be taken into account when comparing and analysing the growing data of COVID-19 in Viçosa-MG, among them the lack of national public awareness policies, the low adherence of the federal government to the WHO (World Health Organisation) recommendations, socioeconomic, cultural, environmental and climatic factors that will not be considered in this article but that are of paramount importance for the macro understanding of the spread of the virus in the country, states and Brazilian cities.

For the analysis where configurational measurements and density maps were correlated, the months that represent peaks (August 2020, January 2021, March 2021

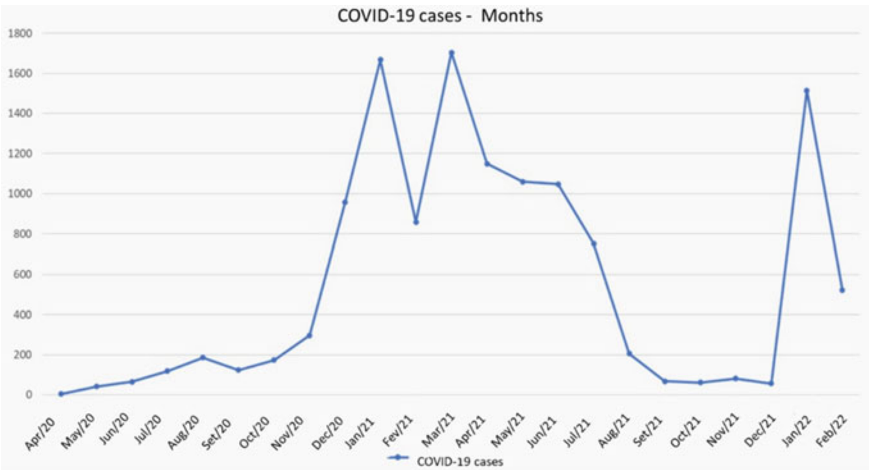


Fig. 5 Cases of COVID-19 in Viçosa-MG from April 2020 to February 2022

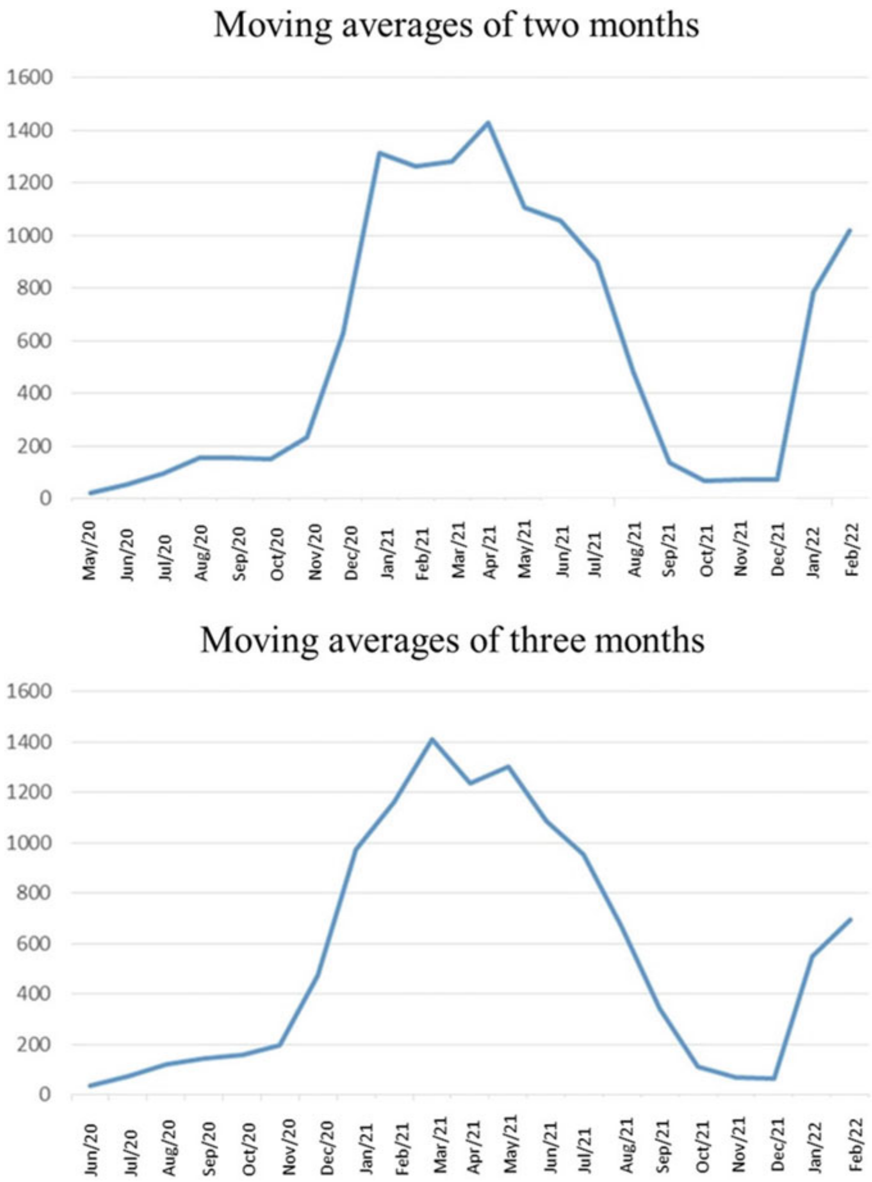


Fig. 6 Moving averages of two and three months of COVID-19 in Viçosa-MG

and January 2022) of cases in the recorded time period were selected, in addition to the months between these peaks that represent the lowest numbers of registered cases (September 2020, February 2021, December 2021 and February 2022), in order to obtain a general understanding of the spread of the disease in the municipality and its correlations with the urban space configuration.

4.1 Reading and Interpretation of Correlations

Here will be analysed Integration data HH, RN, R3, and R5 and data of Choice, both obtained through the methodology and tools of Space Syntax.

As for the measures of Integration, which are based on the centrality of proximity, referring to the ease of going from one point to another in the city, through this metric it is possible to understand various social processes as the cause of some places to present more flows of people than others, issues of socio-spatial segregation, land use and occupation, among others. Thinking about the logic of contamination of COVID-19 that occurs through physical contact made possible by social dynamics, lead to assume that there is a relationship between this measure and the proliferation of the disease in Viçosa-MG.

By superimposing the N-radius HH Integration maps (Global Integration) to the Kernel Maps, a strong relationship of proximity can be scored between the roads with the highest Integration values and the areas with the highest incidence of COVID-19 cases.

Already correlating with the ray 3 and ray 5 Integration maps (local rays), this relationship is even more evident, since such maps show this centrality potential on a neighbourhood scale, for example, the centrality on Rua Padre Serafim, which connects to the city centre and constitutes an old centrality that gives access to Rosário Square, Rosário Church; this street is perpendicular to Av. Santa Rita, to Rua Gomes Barbosa, both essential roads in the conformation of the city of Viçosa-MG. It is also possible to notice a centrality in the district of Fátima, with high values of Integration in the Av. Father Geraldo Martins Paiva and on Av. Bruno Martinho, which are the main roads that integrate the Fátima neighbourhood into the urban space and where the main attractions are concentrated.

In addition to the aforementioned centralities, significant Integration values can also be observed in sections of Av. Castelo Branco and Rua dos Passos, the latter constituting an embryonic road and consequently part of the first centrality of Viçosa. It is worth noting that these local centralities coincide with trade and service locations, that is, areas with greater potential for concentration and movement of people (Figs. 7, 8, 9, 10, 11, 12, 13 and 14).

The Choice measure, based on crossing centrality, calculates the probability of crossing a given road from all other points of origin and destination within a system. Taking into account the logic of the spread of COVID-19 in Viçosa-MG, the correlation of this measure with the Kernel Maps also reveals relevant insights, since

Fig. 7 August, 2020. Correlation between configurational maps and Kernel Maps—integration HH RN, R3, R5

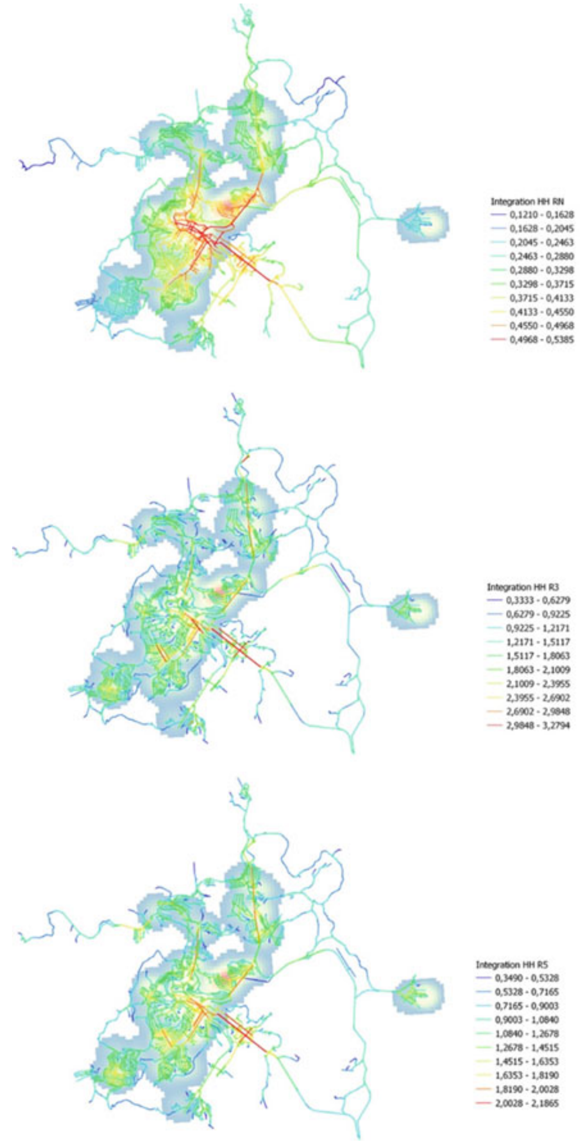


Fig. 8 September, 2020. Correlation between configurational maps and kernel Maps—integration HH RN, R3, R5

this measure shows how the space configuration controls and mediates the movement through a network of space connections. As with the Integration measures, the Choice maps show a correspondence with the urban space configuration.

The global pick map, radius N, shows the prominence of Avenue P. H. Rolfs, having one of its sections, along with some sections of Av. Castelo Branco, as those with the highest Choice value, followed by Rua Gomes Barbosa and Rua dos Passos. P. H. Ave. Rolfs, directly connects the UFV to the city centre and is also accessible to

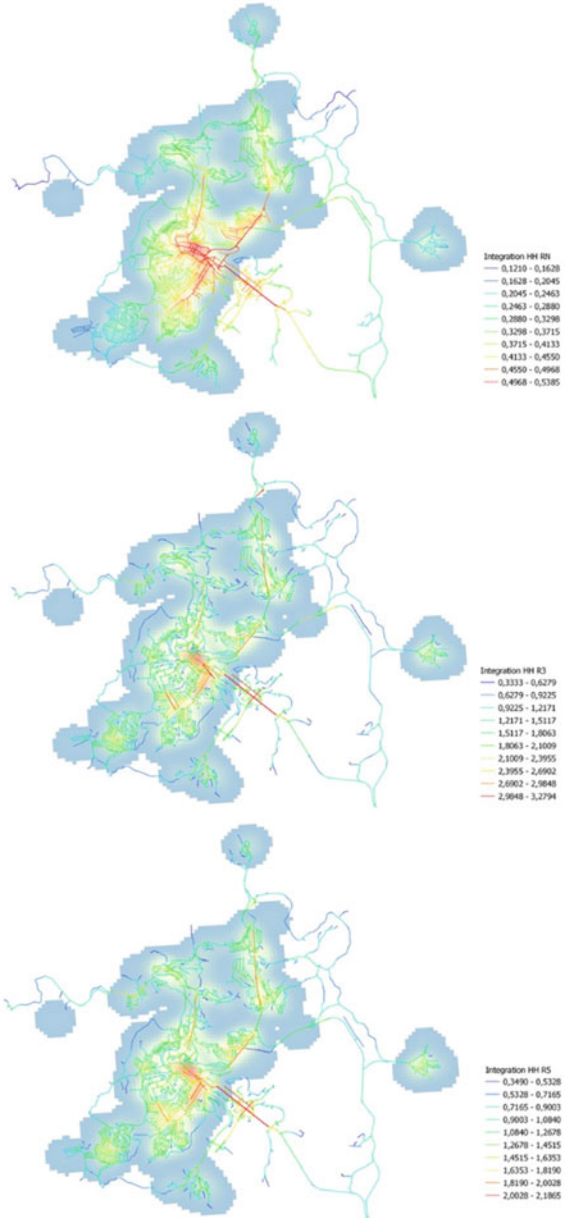


Fig. 9 January, 2021. Correlation between configurational maps and Kernel Maps—integration HH RN, R3, R5

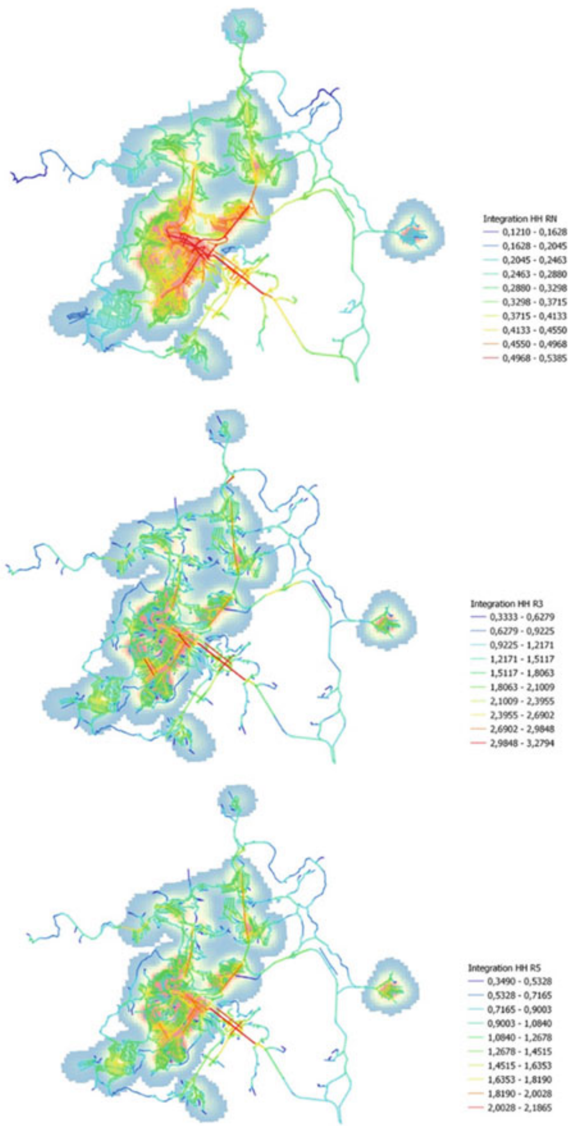


Fig. 10 February, 2021. Correlation between configurational maps and Kernel Maps—integration HH RN, R3, R5

the city, through the university, the MG-356 highway, as well as Av. Castelo Branco, which is access to the university and the city centre from the BR-120 highway, and Rua dos Passos, which connects with the MG-482 highway. Rua Gomes Barbosa is an important access road to the city centre from Bairro Nova Viçosa, connecting directly to Rua da Conceição/Estrada Nova Viçosa (Figs. 15, 16, 17, 18, 19, 20, 21, 22 and 23).

Fig. 11 March, 2021. Correlation between configurational maps and Kernel Maps—integration HH RN, R3, R5

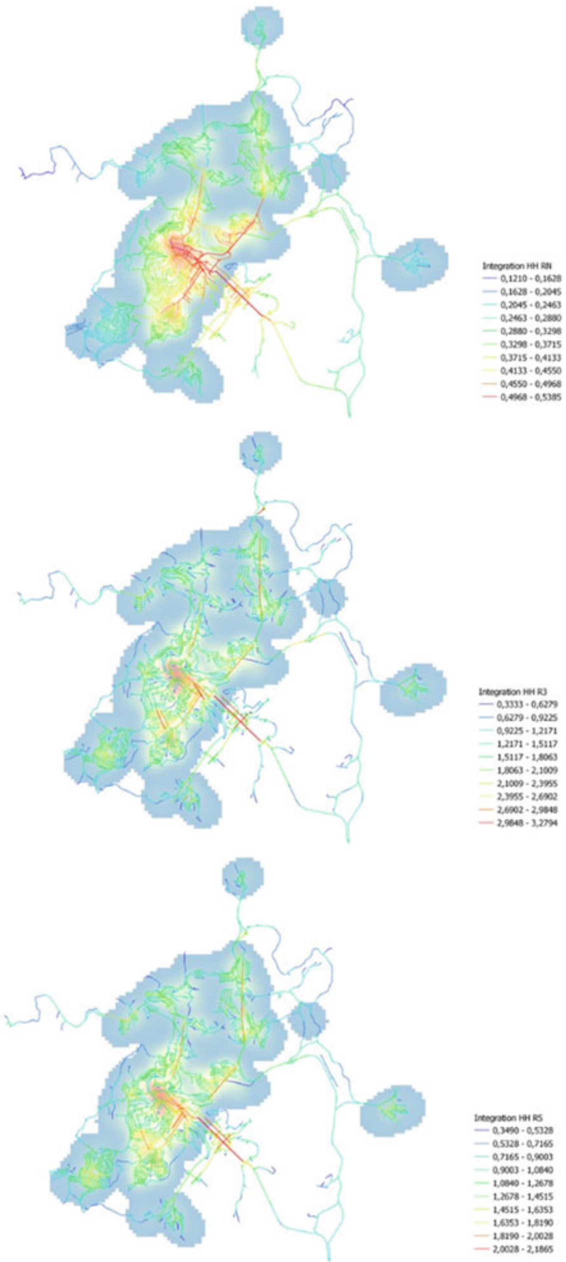


Fig. 12 December, 2021. Correlation between configurational maps and Kernel Maps—integration HH RN, R3, R5

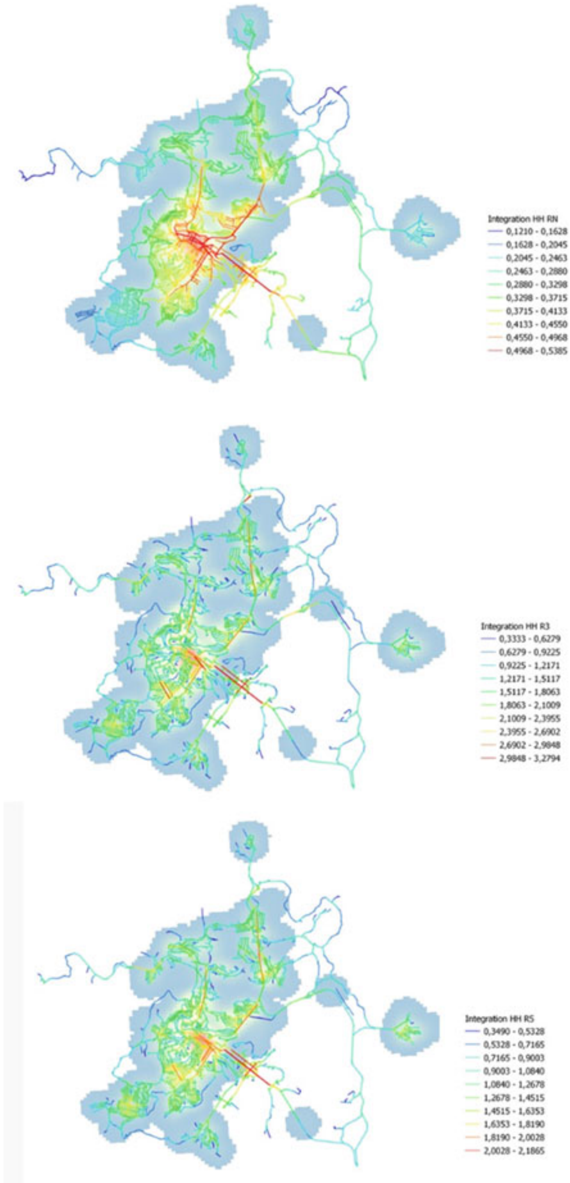
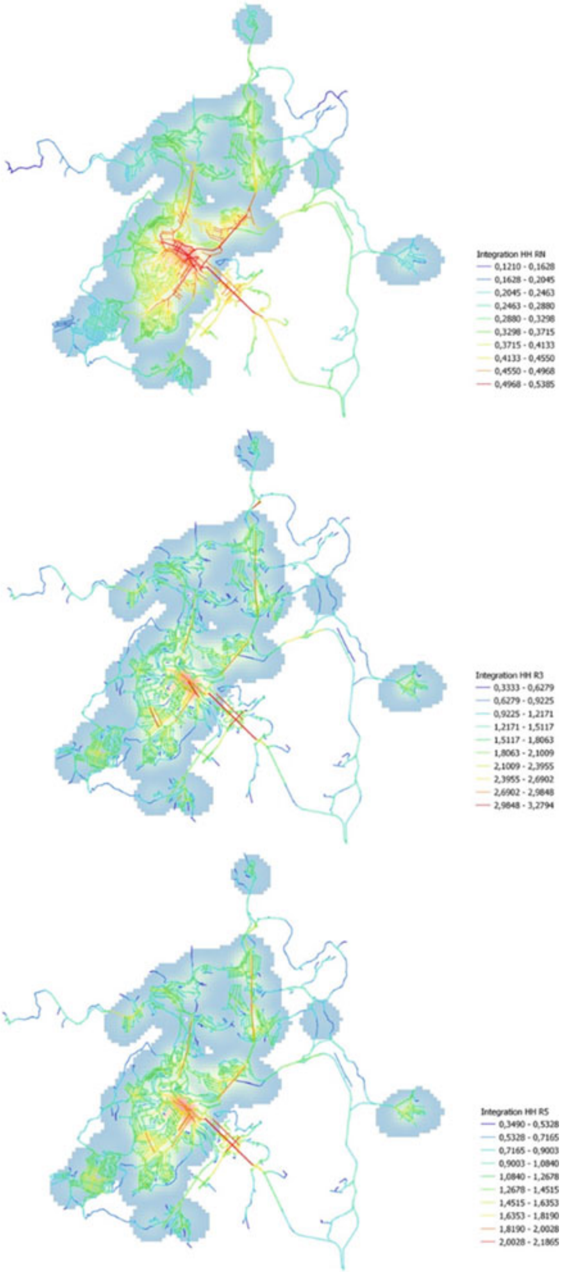


Fig. 13 January, 2022. Correlation between configurational maps and Kernel Maps—integration HH RN, R3, R5

The lines with higher Choice values coincide with the arterial roads of the city, which represent those roads that people would possibly have to travel to get to any other point in the urban space.

Fig. 14 February, 2022. Correlation between configurational maps and Kernel Maps—integration HH RN, R3, R5



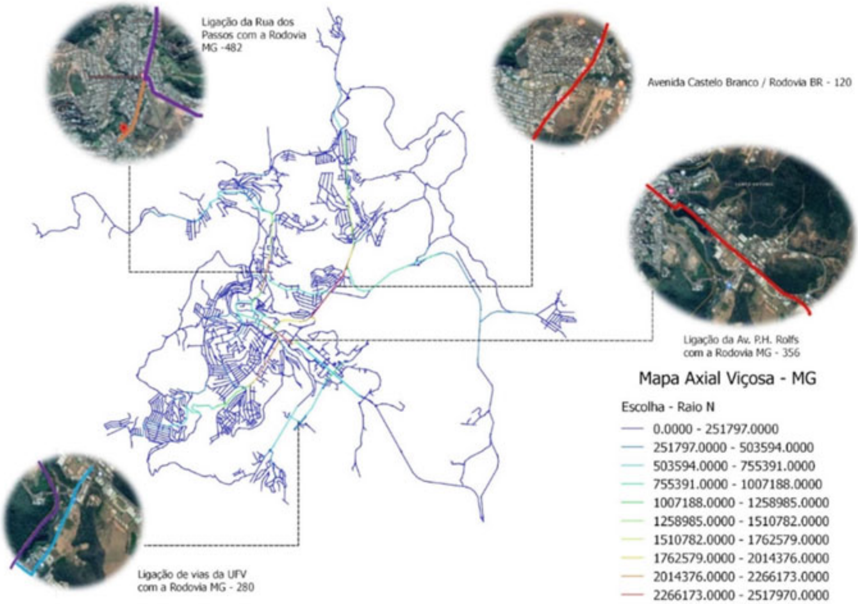


Fig. 15 Axial Map of Viçosa-MG—choice

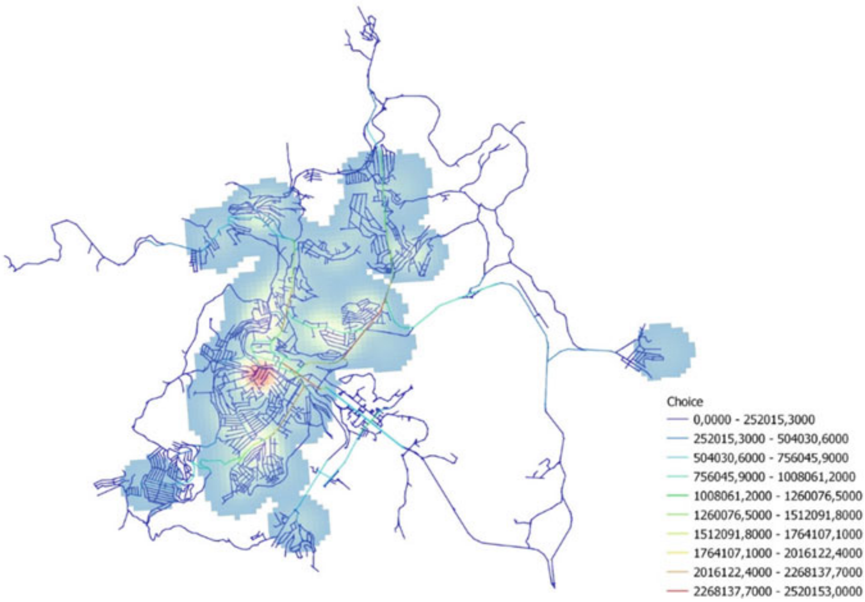


Fig. 16 August, 2020. Correlation between configurational maps and Kernel Maps—choice

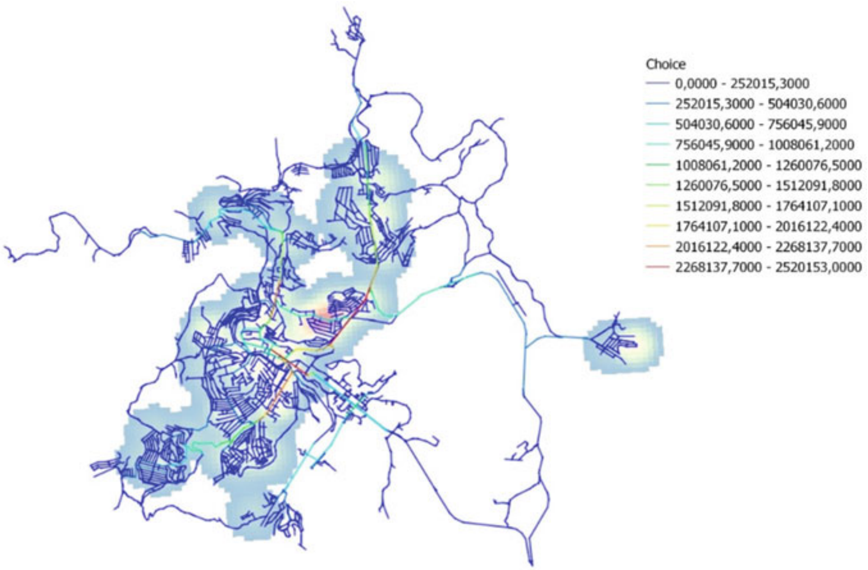


Fig. 17 September, 2020. Correlation between configurational maps and Kernel Maps—choice

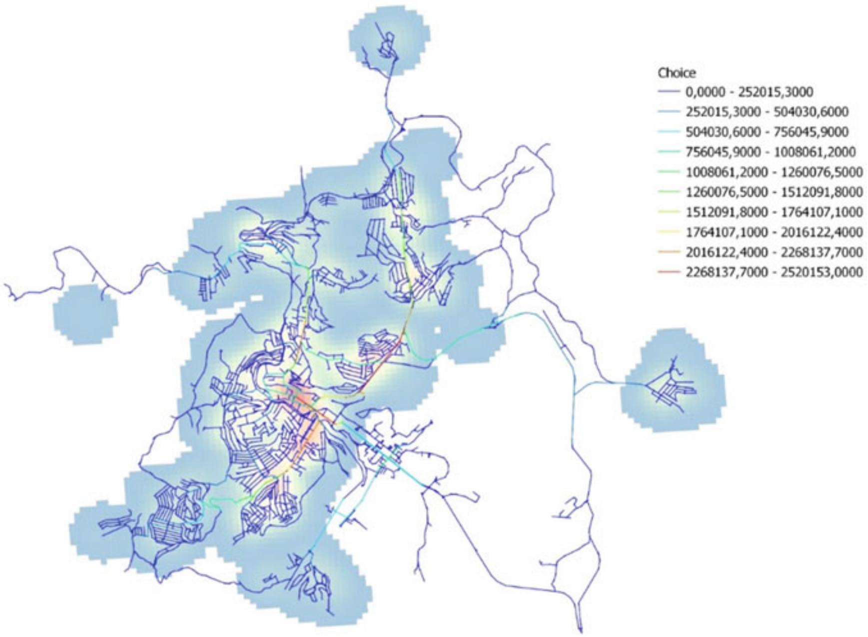


Fig. 18 January, 2021. Correlation between configurational maps and Kernel Maps—choice

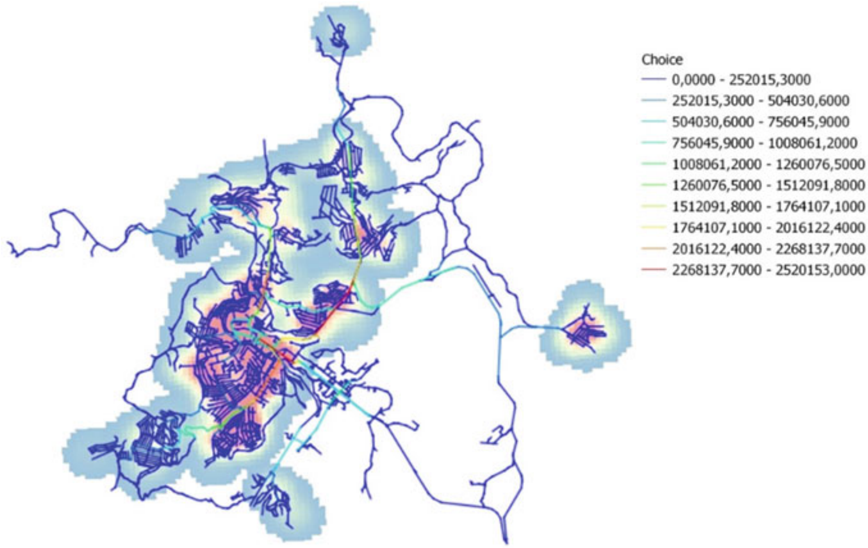


Fig. 19 February, 2021. Correlation between configurational maps and Kernel Maps—choice

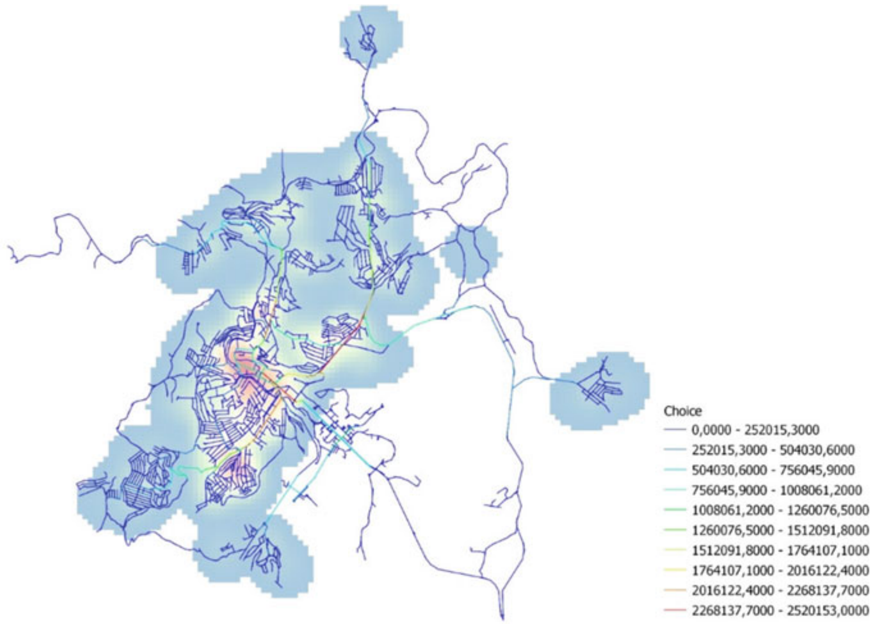


Fig. 20 March, 2021. Correlation between configurational maps and Kernel Maps—choice

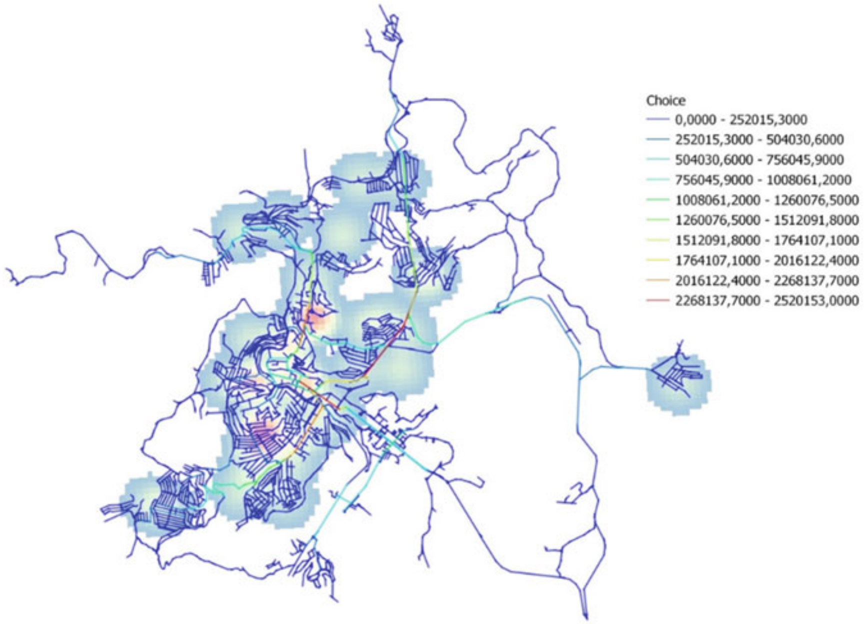


Fig. 21 December, 2021. Correlation between configurational maps and Kernel Maps—choice

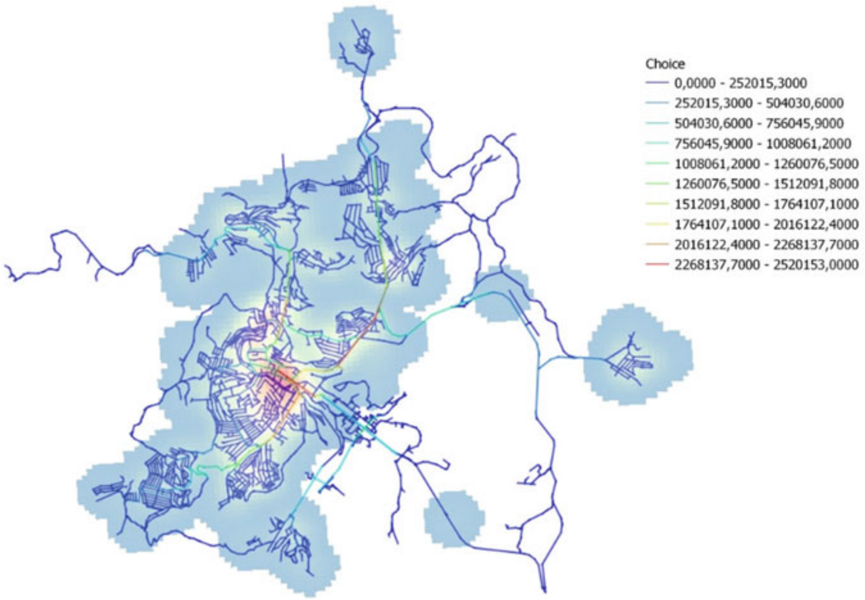


Fig. 22 January, 2022. Correlation between configurational maps and Kernel Maps—choice

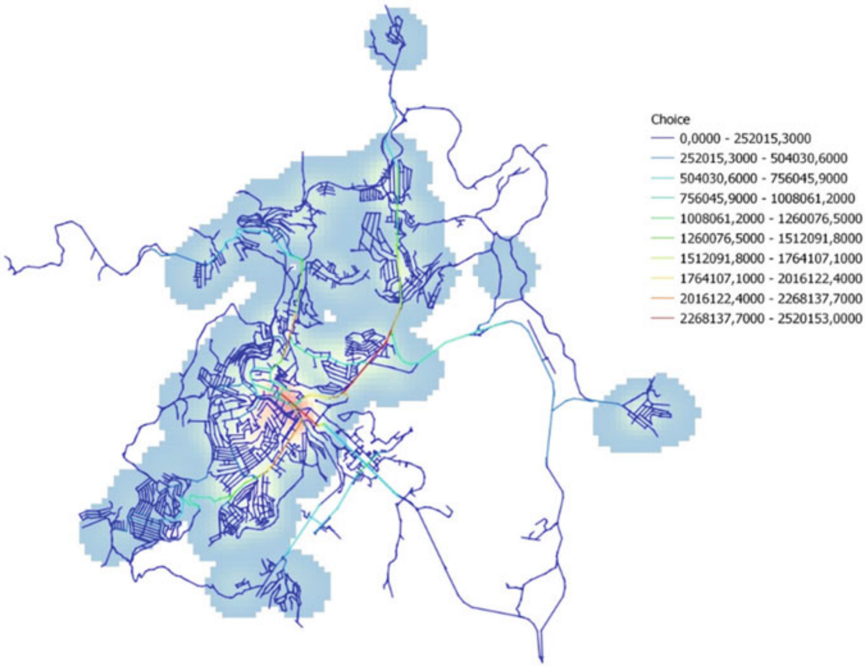


Fig. 23 February, 2022. Correlation between configurational maps and Kernel Maps—choice

5 Conclusions

In view of the analyses developed in this work, it is possible to conclude that there is a strong relationship between the urban configuration and the spread of COVID-19 cases in the municipality of Viçosa-MG.

The overall results indicated that places with greater accessibility and centrality tend to have more confirmed cases of COVID-19. This is due to the fact that these places are characterised as areas with greater risk of exposure and infection since the logic of contamination of COVID-19 is through social contact.

The analyses presented in this article were restricted purely to configurational analyses. But as stated earlier, for a thorough understanding of the COVID-19 phenomenon and its spread in the urban space, numerous other analysis variables must be taken into account, such as socioeconomic, cultural, political, urban infrastructure, and environmental analyses, among others.

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Applying a Morphological Approach into Istanbul's Urban Landscape

Muzaffer Ali Arat and Vitor Oliveira

1 Introduction

Barke (2018) argues that the relevance of urban morphology is threefold: philosophical, cultural, and practical. While the importance of urban morphology is demonstrated in many morphological approaches in philosophical terms, the practical aspect was not sufficiently explored to attract practitioners. The concept of morphological region, identified within the approach by M.R.G. Conzen, stands out as the climax exploration of the urban landscape (Conzen, 1960, 1975, 1988). The concept and the method of morphological regionalization play a crucial role in understanding the physical change and preservation of built heritage, and in the urban landscape management more widely (Oliveira & Yaygin, 2020; Whitehand, 2021). Despite the number of studies based on the concept, much remains to be done to clarify the basic constituents of the object of investigation (Oliveira & Yaygin, 2020; Whitehand, 2009). The main purpose of this paper is applying an historico-geographical approach to urban form, particularly the concept of morphological region, into Istanbul's urban landscape. This application aims at making the method more explicit and robust.

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2 Characterizing the Urban Landscape Through the Method of Morphological Regionalization

The urban landscape is the product of the combination of many social, economic, and environmental forces. The geographical units that have been recognized in articulating the historico-geographical character and the process of formation of this product have been described by the identification of morphological regions (Whitehand, 2009). The concept of morphological region and the method of morphological regionalization were identified within the historico-geographical approach, and on the basis of the seminal work of Conzen (1960), Oliveira (2019), Whitehand (1981). A morphological region is an area that has unity in respect of its form that distinguishes it from surrounding areas, based on a combination of town-plan, building fabric, and land and building utilization (Conzen, 2004; Larkham & Jones, 1991). The relevance of the concept of morphological region and the method of morphological regionalization stands out as one of the most important in recognizing the historico-geographical structure of the urban landscape (Conzen, 1960; Oliveira, 2019; Oliveira & Yaygin, 2020). The utility of the concept and of the method is demonstrated in several applications characterizing different urban landscapes worldwide (Oliveira & Yaygin, 2020; Whitehand, 2009). The method makes an important contribution to the provision of sound bases for planning practice (Whitehand, 2009, 2021).

In the first application of the concept, carried out in the English market town of Alnwick, Conzen characterized the townscape based on historical periods by identifying town-plan units (Conzen, 1960). In the Ludlow applications, he mapped the historicity of the urban landscape based on three form complexes for conservation purposes (Conzen, 1975, 1988). In 1989, Whitehand implemented the method to Amersham employing three elements of urban form for the purpose of townscape management and conservation. The characterization of the urban landscape is demonstrated in many other applications of the concept with the purpose of townscape management and conservation (see Barke, 2003; Barret, 1996; Bienstman, 2007; Birkhamshaw & Whitehand, 2012; Gu, 2010; Whitehand, 2009; Whitehand & Gu, 2007a; Whitehand et al., 2011). Following the Conzenian line, a considerable number of townscapes have been characterized based on morphological regionalization with different purposes (see Alsadaty, 2021; Baker & Slater, 1992; Chen, 2018; Jones, 1991; Kropf, 1996; Larkham & Morton, 2011; Oliveira et al., 2015; Whitehand, 2009; Whitehand & Gu, 2007b; Zhang, 2003, 2015). The historico-geographical approach, in general, and the concept of morphological region and the method of morphological regionalization, in particular, provide a framework for characterizing the urban landscape. The acknowledgement of that framework will contribute to the future management of the urban landscape and planning practice. Despite many applications worldwide, the method still lacks systematization and clarity. Thus, the method needs to be more systematic, rigorous, and robust. To overcome these issues, a criteria-based methodology is developed in this paper. This methodology aims at providing a more objective and systematic basis to practitioners and the

Table 1 The main procedural aspects of the methodology

Form complexes	Persistence	Morphological constituents	Criteria
Town-plan	Maximal	Streets	Age of streets
			Streets geometry
		Plots	Plot layout (area, width, depth)
			Building coverage
Building fabric	Considerable	Buildings	Architectural style
			Building material
			Building height
Land and building utilization	Minimal	Utilization	Utilization—general and detailed

local authority who are responsible for the management and shaping of the physical form of the city. This approach would contribute to a clearer and more rigorous understanding of the historical urban landscape. The methodology is based on the tripartite division of the urban landscape, including the town-plan, building fabric, and land and building utilization. The main procedural aspects of the methodology are identified in Table 1. It considers the form complexes, the persistence of each form complexes, the morphological constituents, and the criteria adopted for the implementation of the methodology. Eight criteria, which are based on the three form complexes, and then based on the morphological constituents, are used. These are the age of streets, streets geometry, plot layout, and building coverage on the basis of town-plan; architectural style, building material, and building height on the basis of building fabric; and finally the land and building utilization (general and detailed).

3 The Urban History of Istanbul

Istanbul has a unique urban landscape, with its historical and natural values. It was the cradle of three great empires, Roman, Byzantine, and Ottoman. Over this long-time period the city had different names. Byzantion was the name of the first settlement. After the occupation of the city by Romans, it was called Constantinople. In the Ottomans period, its name changed to Istanbul. The establishment and the expansion of the city are presented in Fig. 1. While the expansion of the city was around the city walls until 1960s, an extraordinary explosion has been carried out after this period.

The city of Byzantion was established in the promontory of the Historical Peninsula (Fatih District) in 659 BC by Byzas from Megara (an ancient and historic town in West Attica, Greece) (Müller-Wiener, 2001). It roughly corresponds to today's Topkapı Palace (Kuban, 2010). After the reign of Septimius Severus, the Roman

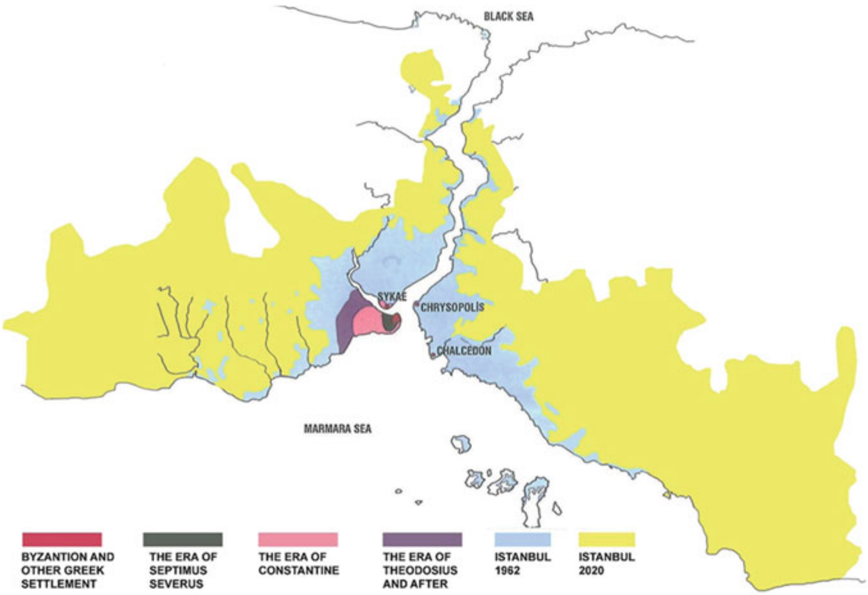

Fig. 1 The expansion phases of Istanbul from its foundation to 2020

emperor, the city's walls and the major part of buildings of the Greek period have been destroyed (Janin, 1950). After the occupation of the city by Romans, the capital of the Empire was transferred to the city of Byzantion in 324. In this period, the city was reconstructed by Constantine I. The Theodosian walls, which are the greatest legacy of Romans, were constructed in this period as a protection against the Huns (Kuban, 2010; Magdalino, 2007). Attracting many people, mostly from the Balkans, the city has grown and many projects (such as palaces, churches, and walls) and building activities were promoted. The symbols of the Roman and Byzantine cities are still alive: Rome still exists in the walls and Byzantine in the Churches and Monasteries (Kuban, 2010). Except for city walls, churches, palaces of the Roman and Byzantine empires, the built heritage of the city only lives in the pages of history. In the fifteenth century, the city was invaded by the Ottomans. In this period, the common characteristics of Islamic cities were partly implemented in Istanbul. The urban life in this new city was organized around the elements of family and mosque. Cul-de-sacs were included in the street system of the city for keeping family privacy. Commercial facilities were organized around the mosque (Çelik, 1993; Yılmaz, 2015). In the eighteenth century, the architectural character of the city started to change by the influence of French architects, engineers, and artists as a result of modernization and the westernization process.

With the fall of the Ottoman Empire, and moving the new capital to Ankara in 1923, Istanbul lost its historic and almost eternal status. The destruction of historical quarters in the city has been started by the bulldozer and car-based approaches in the 1950s. This led to the unplanned growth of modern residential and commercial buildings, and the destruction of the historical center (Kuban, 2010). The following years brought the profound transformation of Istanbul's urban forms, from the loss of Ottoman residential architecture and the destruction of Roman and Byzantine heritage, to the establishment of the *gecekondu*, the squatter settlements (Kuban, 2010; Müller-Wiener, 2001).

4 The Turkish Planning System and Built Heritage

There are two crucial aspects in the Turkish planning system and built heritage. The first is the lack of a systematic understanding of the urban landscape. Here, the issue of zoning is prominent. The second is the weaknesses in the preparation of legislation and regulations. While new plans and design proposals are prepared for cities, they still lack an historical framework and a clear description and explanation of the townscape. Mainstream planning practice does not have a consistent approach to assure the preservation of built heritage. Somehow, a number of urban regeneration projects contribute to the destruction of unique built heritage. Figures 2 and 3 support that the historical urban landscape is not considered while the new interventions were carried out. In Fig. 2, street patterns from 1875 and 2020 are presented to demonstrate how the town-plan is not considered. In Fig. 3, the extent of change in the urban landscape is shown. While the traditional urban fabric was conserved in 1900s (except of those destroyed by fires), it was completely changed into more contemporary fabric after preparing new plans.

The conservation legislation in the Turkish planning system is produced by the central administration, which does not consider the characteristics of different localities. The delimitation of conservation areas and their management are not based on a

Fig. 2 Street patterns from Ali Kuşcu Neighborhood (the left one from 1875 and the right one from 2020) (Ayverdi, 1958; IBB, 2020)

Fig. 3 Urban landscape from Aksaray Neighborhood (the upper is from 1900s and the bottom one is from 2022. 1-Hagia Sophia Mosque (previously church) and 2-Blue Mosque) (source for upper photograph Cezar, 2009 and for bottom photograph Posta.com.tr, 2022)

scientific basis. Generally, the process takes into consideration individual buildings without sufficient knowledge on the historico-geographical structure of the urban landscape. This gives rise to the loss of important built heritage, day after day.

The concept of morphological region and the method of morphological regionalization have a strong potential to deal with these challenges and reverse these trends. The systematic identification and understanding of the townscape on the basis of morphological regionalization of townscape character can support the definition of morphologically based planning zones.

5 The Application into Istanbul

The concept and method are applied into a part of the Fatih District, the historical core of Istanbul (Fig. 4). This area has a variety of forms and a strong historicity. After the identification of first-order regions, one area (Pantokrator-Porta Puteae) is selected to develop lower level regions, namely, second-, third-, and fourth-order regions.

Fig. 4 The case study, in different levels (Google Earth, 2022a, 2022b)

5.1 First-Order Regions

The identification of first-order regions is based on the historicity of the urban landscape and its geographical structure. The first two criteria of the methodology are the age of streets and the streets geometry.

The analysis of the age of streets is based on a set of historical maps and aerial photos. The first scientific map is that produced by Kauffer in 1776. The other historical records that contributed to the determination of the age of streets are Muhendishane map (1845), Ekrem Hakkı Ayverdi map (1875–1882), Goad's map (1904), German map (1913–1914), Necip Bey map (1914–1918), Wofrang Müller-Wiener map (1922), Pervititch map (1922–1945), and an aerial photo (1946). This cartographic set has been provided by the Metropolitan Municipality of Istanbul. Firstly, each of these maps supports the preparation of the age of streets' map. Secondly, the historico-geographical structure of the study area is identified, dividing the area into distinct regions. Thirdly, streets geometry is mapped based on their arrangement. Three types of street patterns are identified: gridiron, loose grid, and dead-ends. The composite map, of first-order morphological regions, is produced through the combination of the last map of the age of streets and streets' geometry. Ten first-order morphological regions are revealed: Constantine-Valens Aqueduct, Ayia Theodosia, Pantokrator-Porta Puteae, Yavuz Sultan Selim Road, Balat-Ahrida Temple, Ebu Zerr el-Gifari, Palatium Constantini (Constantine Palace), Draman Road, The Ecumenical Patriarchate Pammakaristos-Panagia Vlaherna, and some fringe belt features (Figs. 5 and 6). The names of these regions are related to their historical importance and authenticity.

Constantine-Valens Aqueduct and Ayia Theodosia regions share some common characteristics in terms of streets' age and geometry. The Constantin-Valens Aqueduct is a composition of contemporary buildings. The residential and commercial uses constitute its main utilization. This region could be divided into two sub-areas based on its characteristics. Ayia Theodosia is remarkably a small region. It is a consolidated area with traditional and contemporary buildings. It contains residential and commercial uses. The region of Pantokrator-Porta Puteae is a unique region in terms of the strong diversity of building fabric. The east and the north of the region are mainly residential with commercial uses. It includes some inner plots and empty spaces for new urban actions. Additionally, the buildings in bad condition are open to new interventions. Yavuz Sultan Selim Road is a region that distinguishes itself due to its loose grid street pattern. This region is a consolidated area with strong commercial uses and local services in addition to some empty spaces. Apartment blocks are dominant in the region. Balat-Ahrida Temple is a region with a very regular street pattern. It includes commercial uses and local services. The colorful houses and narrow stone-paved streets make the region more exclusive. Popular cafes and modern galleries are located on the same streets as the old grocers. Ebu Zerr el-Gifari is a small region with a regular street pattern. It is a consolidated area including residential and commercial uses. Palatium Constantini (Constantine Palace) region, next to the Theodosian walls, is a consolidated area with some empty plots that present

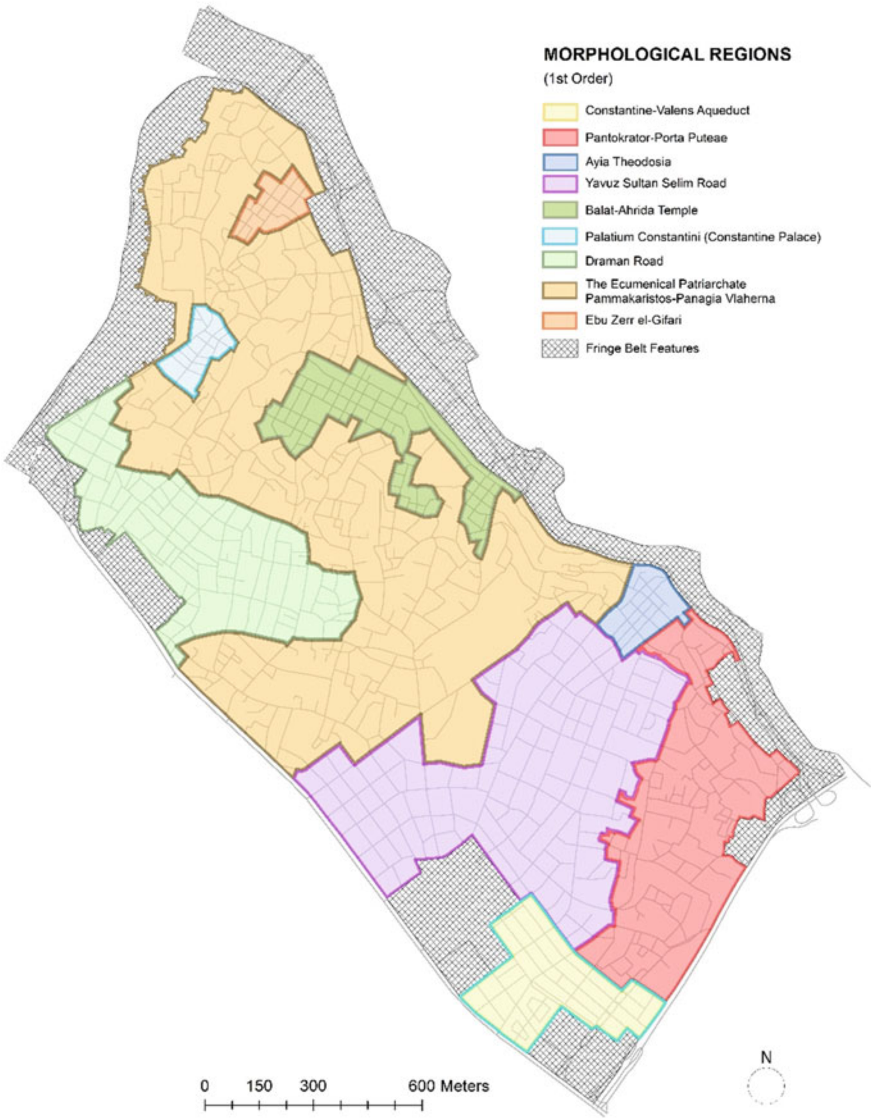

Fig. 5 First-order morphological regions

the potential for new actions. Draman Road region provides a consolidated structure with residential, commercial uses, and local services. The Ecumenical Patriarchate—Pammakaristos-Panagia Vlaherna is the largest region identified within first-order morphological regions. It provides a lively space for urban life having distinctive utilization in addition to residential uses. The region is also surrounded by different fringe belt features. In addition to those regions identified in the urban landscape,

Fig. 6 First-order morphological regions: top left—Pantokrator-Porta Puteae; top right—Yavuz Sultan Selim Road; bottom left—Balat-Ahrida Temple; bottom right—Ayia Theodosia (photographs by the authors)

some fringe belt features, which are representing community spaces and facilities, are mapped. The characteristics of first-order regions are identified in Table 2, taking into consideration the streets' age and geometry. It is argued that the map of first-order regions (Fig. 5) can offer the basis to produce a map of planning zones—a key tool to guide urban landscape management.

5.2 Second-, Third-, and Fourth-Order Regions

Second- and further order morphological regions are identified in Pantokrator-Porta Puteae region. The specific name of the region comes from Pantokrator Monastery, which is a religious building from the Eastern Roman period. Plot layout and land and building utilization are the two criteria that support the identification of second-order regions. Plot layout analysis is based on three morphological constituents: plot area, width, and depth. Three intervals, based on natural breaks, are identified for mapping

Table 2 The characteristics of first-order morphological regions

First-order morphological regions	Age of streets (based on the date range of the maps)	Streets' geometry
Constantine-Valens Aqueduct	1913–1922	Dense loose grid
Ayia Theodosia		
Pantokrator-Porta Puteae	1845–1904	Dead-ends
Yavuz Sultan Selim Road	1929	Loose grid
Balat-Ahrida Temple	1845–1904	Gridiron
Ebu Zerr el-Gifari		
Palatium Constantini	1845–1904	Loose grid
Draman Road	1845–1904	Loose grid-Dead-ends(few)
The Ecumenical Patriarchate Pammakaristos-Panagia Vlaherna	1776 and 1845–1904	Dead-ends

the three morphological constituents. The plot area is classified as small, medium, and large. Small and medium plots correspond mainly to residential and commercial uses. Large plots correspond to fringe belt utilizations. Plot width is categorized as narrow, medium, and large. Residential uses have narrow and medium frontages. Large frontages are characteristic of fringe belt uses. Plot depth has three ranges: short, medium, and long. The long plots are mainly characteristic of residential and commercial utilizations. On the contrary, medium depth corresponds to fringe belt uses. There is a wide range of land and building utilizations, including commercial, housing, educational, institutional, religious, and warehouses. The lively streets mainly have commercial uses. The fringe belt uses, such as educational, institutional, and religious, are in the southern part of the region. Residential uses are distributed over the whole area. Some residential buildings have commercial uses on the ground floor. Three maps on the plot layout and the map on land and building utilization are used to produce the composite map of second-order regions.

Nineteen second-order regions are identified: three commercial, nine residential, and seven fringe belt features and warehouses (second-order regions are represented by Roman numbers in Fig. 7). The contribution of plot area and width, and land and building utilization to the hierarchy of morphological regions is high. On the contrary, the contribution of plot depth is low.

The identification of third-order regions is based on plot layout, building coverage, architectural style, and land and building utilization—the three form complexes are taken together. The map of building coverage includes three intervals: low, medium, and high. With the exception of a few plots, there is a high building coverage.

The characterization of architectural styles is based on typological features of buildings, the characteristics of the façade of buildings, and the types of the buildings. The map is categorized into seven distinct styles. The first is contemporary style,

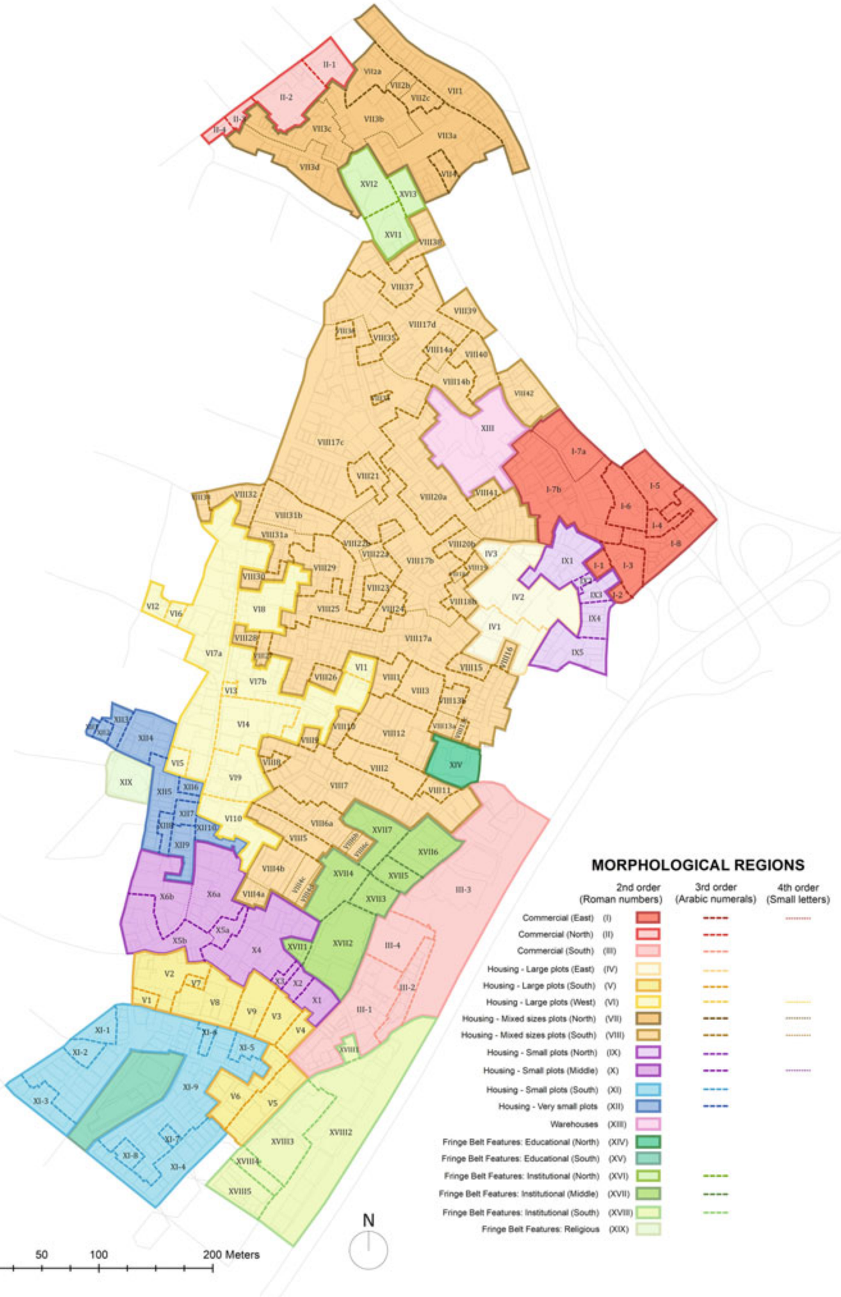

Fig. 7 Second-, third-, and fourth-order morphological regions

constituting most buildings of the area. These buildings represent the Republican period, fundamentally the second half of that period. The second is single-family houses. The third is single-family houses with bay windows. These buildings are a sort of replication of traditional houses with bay windows. The fourth is traditional houses with bay windows. This style includes the typical building of Ottoman culture. The bay window is an important element that shapes the streetscape in Ottoman cities, offering a dynamic view to the streets, increasing the interior space of buildings, allowing more sunlight into the building, and creating a lightened and spacious area. The fifth is the ottoman bath. The sixth is the mosque (Fig. 8). Finally, the last group is made of historical ruins and ramshackle buildings. The combination of four maps—plot layout, building coverage, architectural style, and land and building utilization—enables the identification of third-order morphological regions (third-order regions are tagged with Arabic Numerals in Fig. 7). The composite map of regions is not the superposition of these four maps. Instead, each criterion is addressed one by one: firstly, building coverage; then, plot layout, land and building utilization; and, finally, architectural styles. Plot layout and building coverage had a low contribution to the hierarchy. On the contrary, architectural style and land and building utilization had a high contribution to the hierarchy.

The identification of fourth-order regions is based on building material and height. These two criteria are the most detailed, raising the topic of precision of the character appraisal of the urban landscape. Building materials are classified into four different classes: timber, stone, concrete, and masonry (Fig. 9). They were identified on the basis of the building materials of the façade and the building construction system. The first two are traditional materials, the last two are contemporary ones. Most buildings of the study area are made of masonry. Building height is categorized into eight different classes ranging from 1 to 8 storeys (Fig. 10). A large percentage of buildings are 1–3 storeys. There are some buildings with 4 and 5 storeys. Buildings with 5 or more storeys are in a small percentage. The complexity of the study area did not allow to match the two intermediate maps of building material and height. In these maps, fourth-order regions are tagged in small letters—Fig. 7. The contribution of building material to the hierarchy of regions is medium, and of building height is low.

The identification of second-, third-, and fourth-order regions can help the formulation of regulations for each planning zone, the hierarchical designation of conservation areas, and framing the design of new forms with a strong relationship with extant urban forms. These ideas are of great relevance for spatial planning, particularly for Turkish planning where regulations are very generic and do not acknowledge the specific character of each urban landscape.

Fig. 8 Buildings with distinctive architectural style: 1—contemporary houses, 2—single-family houses, 3—single-family houses with bay window, 4—traditional houses with bay window, 5—Ottoman bath, 6—mosque (photographs by the authors)

6 Conclusions

The historico-geographical approach provides a strong basis for describing and explaining the past and present urban forms. The concept of morphological region that identified within the approach supports the characterization of the urban landscape taking into consideration its historicity and its geographical structure. The application of the concept of morphological region into Istanbul's urban landscape offers a robust basis for the establishment of a more systematic method of morphological regionalization. In this application, a criteria-based methodology was addressed.

Fig. 9 Buildings with different materials: 1—concrete, 2—timber, 3—masonry, 4—stone (photographs by the authors)

Fig. 10 Buildings with different heights: 1—two storeys, 2—four storeys, 3—six storeys, 4—eight storeys (photographs by the authors)

This paper contributes to the field of urban morphology in two main different ways in addition to its contribution to Istanbul's urban landscape itself. The application of the methodology brings light to the special character assessment of Istanbul by revealing the physical changes and transformations of the city.

The first contribution of the paper is that a more systematic, rigorous, and robust method of morphological regionalization has been offered. This provides a more explicit identification of townscape elements and a mapping process. It increases the degree of objectivity in the recognition of morphological regions. Thus, an explicit identification of morphological regions helps a scientific-based character assessment of the urban landscape.

The second contribution of the paper is that by applying the method of morphological regionalization to Istanbul, the potential of the concept and method is demonstrated. The method is useful for a range of urban planning applications. The method presents a basis for form-based zoning for the preparation of municipal plans, regulating and organizing the physical transformations. It provides a powerful scientific basis to the practical management of townscape by a deep understanding and identification of the historico-geographical structure of townscape. It is a substantial tool for the delimitation of conservation areas and their control. This helps to the preparation of effective regulations for the conservation of built heritage. It addresses not only the individual buildings in the townscape, but also the historico-geographical structure of the urban landscape components as a whole, namely, the town-plan, building fabric, and land and building utilization. This helps the permanence of the built heritage by formulating conservation areas of the urban landscape with its all components.

Finally, a comprehensive conservation area delimitation and control, the definition of qualified planning proposals, effective decisions for the future urban landscape management, and the design of new forms with a strong relationship with extant physical form are the prominent aspects that are interconnected with the characterization of the urban landscape. In this regard, the systematization of the method becomes important for planning practice and future urban landscape management of cities.

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Evaluating Urbanity by Measuring Urban Morphology Attributes

Samira Elias and José Nuno Beirão

1 Introduction—The Quality of Urban Space

In this paper, we argue that morphological factors have a predominant influence on people's behavior, due to the affordances generated in the surrounding space, contributing positively to the intensification of socio-spatial interactions, since not all patterns of shape and configuration convey the conditions conducive to a pleasant urban space to enjoy in co-citizenship. The main argument is that there is an essential relationship between urbanity and urban form.

The planned urban space is ordered by elements of the urban form, such as streets, buildings, plazas, squares, etc., which are responsible for shaping the actions of everyday life. These morphological properties respond to specific functions and influence people's senses and behavior. The concept of urban comes from the Latin *urbanus*, which means originating in the city, polished, of good tone. It is attributed to the opposition to the *rural* to indicate the quality of controlled behavior, designating the city's inhabitant as representing the good character of the city (Choay, 1980). Moreover, such property emerges from the articulation of activities and functions in different places in the city (Dickinson, 1959). Each place, public space, involves actions and activities with possibilities of social relation and existence as a way of socio-spatial appropriation (Lefebvre, 1974). They are like landmarks of the city's identity, with political, historical, and cultural symbolism (Carmona et al., 2008). Certeau (1994) emphasizes that it is in the urban space that everyday life, social routine, relations of coexistence, and appropriation are manifested. The urban spaces of the city become qualifiers, both in material terms (the physical form and

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configuration), as well as immaterial ones (historical, cultural, social, and referential), and they condition the urban experience (however, the latter will not be addressed in this article).

Jane Jacobs' observations (1961) became an essential reference in classical literature on urban space. The author develops themes such as vitality, movement, and life on the streets, and the interaction of people in public spaces as an important way to promote safety in the streets and sidewalks. Jacobs' main critique is predominantly focused on the loss of diversity in "produced" cities compared to the diversity of traditional cities—cities resulting from natural growth as opposed to modernist cities. Diversity is understood as something that has an architectural and typological dimension, whether in the building or public spaces, and the social, human, ethnic, and economic dimensions (Jacobs, 1961). The author criticizes the foundations of modern planning and re-urbanization of the time for being abstract and distant from human relationships, constituting monofunctional areas, making personal interactions and choices of use difficult, promoting urban growth indifferent to personal needs, and making it difficult for people to be in the public space because commuting is car-based. Although she does not present tools to systematize her observations, which are based on empirical observation, supports the claim that the diversity of uses and functions can be the best way to promote safety, attractiveness, and socio-spatial interaction. The author emphasizes that the optimization of public attractions for a good and safe life depends on three factors: social life, public space, and buildings, in this order, where the presence of people, activities, events, inspiration, and stimuli constitutes one of the most essential qualities of public spaces.

In *Toward an Urban Design Manifesto*, Jacobs and Appleyard (1987) openly criticize American city planning. American society's emphasis on consumption intensifies "private wealth and public misery." White, windowless facades, surrounded by vacant lots and rapid transit, and precarious and insufficient public transport systems, generate a public life dependent on planned occasions, in internal and protected spaces, distancing urban life from public space and the natural movement characteristic of urban spaces of traditional typology. Gehl (2010), one of the protagonists of studies on the quality of urban spaces, complements by stating that the human dimension has been seriously neglected in the planning of urban spaces in recent decades. The traditional function of the city's public space as a meeting place and social interaction was reduced, while the ideologies of the modern movement gained strength. The new communication technologies have increased this problem because social space has also been partially replaced by virtual spaces. The beginning of the twenty-first century was marked by global challenges that highlight the importance of planning lively, safe, sustainable, and healthy cities while considering the human dimension. The author points out four fundamental objectives to reinforce the social function of urban space—cities with vitality, security, sustainability, and health. It is essential that the inhabitants of the urban space feel invited to establish a connection with their daily activities, such as walking, cycling, or staying in the public spaces of the city, inducing cultural opportunities and social interactions. It emphasizes that the potential for safe urban spaces is reached when more people move through the city and remain in urban spaces and that the concentration of people, residential density, mixed-use, active plinths (building a foundation with active functions), incorporated vegetation in the building shape and peculiar identity, are determining factors to achieve the vitality of places (Gehl, 2010).

A. Jacobs (1993) reinforces that a Great Street is “markedly superior in character or quality” and people often use it when they are comfortable, safe, memorable, and active. It establishes as an indispensable feature so that the streets offer a unique sense of place, a balance of mobility and are economically vibrant and attractive to their inhabitants and visitors. Efficient urban patterns present combinations of use, movement, and flows, among other qualitative aspects of urban space that guarantee the liveliness of the place. These standards have been validated by the test of time and provide qualitative aspects that we recognize in urban spaces with positive dynamics. The balance between the built-up area, open areas, and public space promotes “residential pleasantness”. Low heights, compactness, smaller physical distances, and diversity of urban activities and functions favor the narrowing between everyday life and urban space (Alexander et al, 1977; Dias Coelho, 2014a).

In general, theories on this topic agree that attractive cities should provide public spaces supporting processes that reinforce urban life. The features of everyday life in the urban space and the vitality of streets are characterized by people using the public places of the city, especially the streets, sidewalks, and squares; exercising the freedom and ease of coming and going; with intense interaction in the public–private interface; interactions between groups of people; children playing and carrying out daily activities, such as going to school; elderly people enjoying the urban space; people taking advantage of primary functions, such as shopping in small street stores, buying newspapers at the nearest newsstand; meeting at local cafes; interaction of young people in bars close to their homes; people with “eyes” attentive to collective security, etc. Concentrating on people and activities with acceptable distances to be covered on foot stimulates vitality and tranquility, desirable and valuable qualities to feel safe. Thus, it is assumed that scale, transparency, senses, texture, details, diversity of functions, rhythm, etc., are important attributes that qualify urban space (Alexander et al, 1977; Dias Coelho, 2014a; Gehl, 2010; J. Jacobs, 1961, A. Jacobs, 1993).

For an objective understanding of all this diversity of analysis topics, we need different theoretical approaches, namely through the development and combination of calculable indicators that allow us to objectively interpret the various themes responsible for the qualification of public space.

2 Attributes/Indicators/Performance/Quality

In this paper, we distinguish four concepts: Attributes, Indicators, Performance, and Quality. Attributes are single measures or data, like *area*, *number of floors*, *use*, *number of residents*, and *number of houses*. They are expressed through a single measure, count, or class attribution (a toponomy or simple classification). Indicators express meaningful relations between parts that can be measured and for which there is a mathematical function expressing that relation. They are mostly expressed through ratios that may vary within a predictable variation domain of values and most of them can be normalized for statistical treatment. A specific value within a variation domain or range will inform the indicator's performance depending on the interpretation of the domain representing a system of values varying from a minimum to a maximum value. The qualitative expression of the performance (or measured values) can be defined in three different manners: following evidence (measures and interpretations) given and proved by other authors; selecting reference samples (urban areas generally recognized by their liveliness or positive urbanity) and measuring their indicators assuming that the obtained values of those indicators correspond to the adequate expression of the quality of that particular indicator; or, for higher consistency, by taking as many samples as possible and checking whether the obtained values have consistent correlations with the values obtained from the reference samples. In this paper, we follow essentially the first two methods and leave for future work the analysis of additional samples foe consistency checking.

We assume that performance may be measured by identifying within the range of variation of an indicator a qualitative variation plastically varying from inadequate low < adequate < inadequate high or simply from inadequate to adequate. It is important to point out that this classification interpretation is simplified, since it represents intervals of descriptive values for the comparative evaluation between urban samples, allowing replication of the method.

It is assumed that the urban attributes that express adequate performative qualities, if combined, represent the urban condition capable of sustaining positive urbanities, essentially because they contain the features needed to qualify as safe, active, pleasant, alive, and dynamic urban spaces.

In this sense, some reference cases were selected as examples of the urban quality and the positive dynamics indicated by the literature explored in this research. These are samples that represent urban spaces endowed with a diversity of activities, active and interactive facades, narrow streets, and close connection axes. In other words, they are urban spaces that concentrate urban and economic characteristics in different circumstances, and that are considered meeting points, precisely called centralities (Lefebvre, 1970) and that reinforce the concept of urban vitality and urbanity as they foster generative qualities of socio-spatial interactions and successful urban spaces.

3 Indicators

Dias Coelho (2014a) highlights the systematic study of the city form through the description and interpretation of the urban fabric and its constituent elements. The concept of the urban fabric is outlined by the built city, which is made up of the space and the built elements, the public and the private, that is, the constituent elements of the urban form: the layout, the grid, the street, the buildings, the block, and the parcel.

Following the premise that urban form can be read and interpreted by its morphological, topological, land use and demographic attributes, this study assimilates five different methodological approaches that represent the evaluation and interpretation of urban space: (**A**) Configuration—studies of movement and urban configuration on the road network, developed by Hillier and Hanson (1984), and Turner (2000), in which the configurational characteristics of the layout and the street are analyzed, according to the topological structure of the network, which is rigorously represented by the relations between the manyparts (segments), in this case, the street segments; (**B**) Density and Urban Form—density of the built form and road network (Berghauser Pont and Haupt (2010); (**C**) Occupation—density of occupation (population density and housing density) (Bertaud, 2004) in order to investigate the presence of resident population in urban space; (**D**) Mixed use and diversity—studies on the diversity of functions in urban space—vital for economic development and appropriation of public spaces—based on van den Hoek (2008) analyses the mixing of functions in urban space; and (**E**) Public Private Interface—studies on the public–private interfaces of urban space, here called basement, in order to analyze the constructive characteristics of the facade of the building, by its type and attribute, adapted from Beirão and Koltsova (2015), Karssenberg et al. (2015) and Lehnerer (2009) and focusing on the interaction promoted by the façade porosity (or interaction between inner (private) and outer (public) spaces). Summarizing the representation and calculation of the indicators applied in the evaluation of the constituent elements of the urban space follows Table 1.

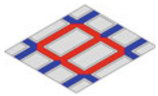
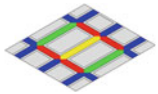
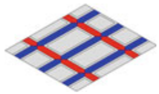
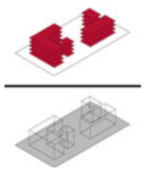
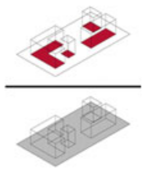
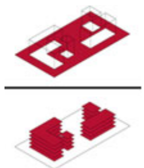
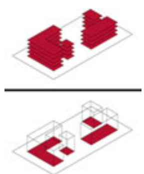
The calculation process involves the application of mathematical functions, through queries using SQL (Structured Query Language), to describe the performance indicators—road network (connectivity, NAIN, and NACH); built and population density (FSI, GSI, OSR, L, N, PDf); land use and occupation (MXI); building basement (TOF, PF, TD).

4 Performance

4.1 Configuration

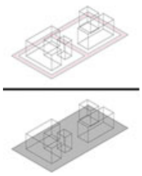
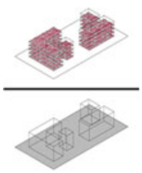
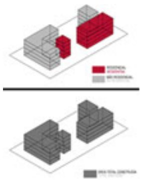
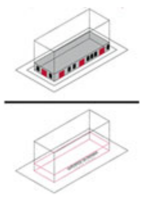
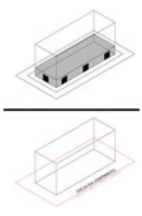
The values of spatial properties presented by Hillier and Hanson (1984) in their Space Syntax method and complemented by Turner's description and angular analysis of segments (2000) are represented by first-order measures, coming from the direct analysis of, respectively, axial maps and street segments maps. These measures help us understand how the configuration of the road system influences the movement, circulation, and possibilities of people's paths in the urban space. When normalized by the angular analysis of segments, the measures of integration and choice are represented by the normalized angular integration (NAIN) and normalized angular choice (NACH) and their values can be compared among systems independently of the system's size (Hillier et al., 2012).

Table 1 Synthesis of the calculation and representation of the indicators

Indicator type	Indicators	Approach	Equation	Diagramatic representation
Network	Connectivity	Measures the degree of road connectivity in an urban system	$UC_G = \frac{1}{n}\sum_{i=1}^{n} U_i$	
	Integration	Normalized angular integration (*to-movement* potential)—*closeness* to all segments	$NAIN = \frac{NC^{1.2}}{TD}$	
	Choice	Normalized angular choice (*through-movement* potential or choice of route)—*betweenness* between all pairs of segments	$NACH = \frac{\log CH+1}{\log TD+3}$	
Built density	Building intensity	Indicates the constructive intensity of an urban space (can be calculated at any level of aggregation)	$FSI = \frac{F(f)}{A(f)}$	
	Ground space índex	indicates the ground coverage area, precisely the footprint of the building projected onto the ground (coverage) (can be calculated at any level of aggregation)	$GSI = \frac{B(f)}{A(f)}$	
	Spaciousness	Indicates the degree of open spaces and assesses the area of available space in view of the intensity of the construction (can be calculated at any level of aggregation)	$OSR = \frac{1-GSI(f)}{FSI(f)}$	
	Level	indicates the average number of floors in buildings (Building Height) (can be calculated at any level of aggregation)	$L = \frac{FSI(f)}{GSI(f)}$	

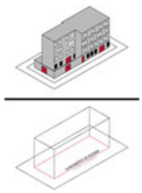
(continued)

Table 1 (continued)

Indicator type	Indicators	Approach	Equation	Diagramatic representation
	Network density	Indicates the network density	$\mathrm{N}(f) = \frac{li + \frac{le}{2}}{\mathrm{A}(f)}$	
Population density	Fabric population índex	indicates the concentration of resident people in an urban fabric (can be calculated at any level of aggregation)	$\mathrm{PDf} = \frac{\mathrm{P}(f)}{\mathrm{A}(f)}$	
Use	Mixed-use index	Calculation between the residential area divided by the total built area (can be calculated at any level of aggregation)	$\mathrm{MXI} = \frac{\mathrm{AR}(f)}{\mathrm{F}(f)}$	
Basement	Transparency of the façade	Total area of transparent surfaces (O) (at the ground floor) divided by the total area of the ground floor façade (F) (can be calculated at any level of aggregation)	$\mathrm{ToF} = \frac{\Sigma \mathrm{O}}{\mathrm{F}}$	
	Permeabillity of the façade	Gives the frequency of doors per 100 m of façade (can be calculated at any level of aggregation)	$P = x/25$ where x is the number of doors per hundred meters $x = d/(l/100)$ and d is the total number of doors and l the total length of façades in the area of study	

(continued)

Table 1 (continued)

Indicator type	Indicators	Approach	Equation	Diagramatic representation
	Territorial depth of the façade (TD)	Measures direct access to streets	TD = E/N where E represents the total number of entrances in a façade and N the total number of territorial steps in the system (total number of links in the graph)	

The process required some systematization operations for the treatment and processing of the data, as well as the correction of axial stubs and unlinks (unlinking the crossings of axial lines on bridges and tunnels). The dataset was prepared for the segment analysis to be processed with Depthmap and analyzed according to the Space Syntax method. The generated variables are Angular Connectivity, Node Count, Total Angular Depth, Mean Depth, Integration, Choice, Segment Length, and the normalization of Choice (NACH) and Integration (NAIN) values, applying the metric radius of 1200 m for the local analysis and 5400 m generated for the global analysis, to evaluate the integration of the spaces analyzed, respectively, for a logic of walking or cycling representing human behavior in urban space.

According to Hillier and Hanson (1984), connectivity analysis (metric radius) quantifies the number of segments that connect to the road system, or rather, quantifies the possibilities of travel through the number of crossings between the roads and the greater the number of nodes or intersections, the greater the degree of connectivity in the urban space. The author clarifies that values above two express good connectivity, and below 2, poorly connected roads.

As for integration, the measure quantifies the topological accessibility of the urban space concerning the other parts of the entire road system, allowing the identification of smaller topological distances. Hillier and Hanson (1984) suggest that urban space is considered accessible (integrated) when they reveal integration values close to 0. Values between 0.4 and 0.9 are considered highly accessible and integrated, and values above 1, are less accessible or integrated and, therefore, represent more segregated streets in the network. Integration values here refer to Hillier and Hanson's real relative asymmetry measure. However, in the segment analysis, Hillier et al. (2012) suggest the normalization of the angular integration that also normalizes the total angular depth, comparing the system with the urban average, starting from the simplified equation of the value of $TD/NC^{1.2}$ or the reciprocal $NC^{1.2}/TD$ to provide higher values for higher integration. The authors explain that the averages for NAIN are stable when comparing streets and cities on the same scale and that the average for NAIN is a very reliable predictive value and allows us to perceive the global differences between the spatial systems of cities. NAIN represents to-movement, i.e., the liability of a street segment becoming a destiny (the liability of someone passing on a street segment). Normalized integration values start to point out more integrated segments at around 1.2 and values below 1 represent structures of a segregated system. However, the use of NAIN is recommended only for large-scale systems and does not seem to capture subtle details as real relative asymmetry did. Methodologically speaking, when studying small areas in a city, the calculation of NAIN is done for the entire system and then cut from the obtained results to be compared and further analyzed.

Concerning choice, this measure assesses the shortest route in the road system and the user's route possibilities. It presents a greater possibility of travel (shortest route) when it expresses values greater than 1 and less possibility of travel (longest route) when it expresses values smaller than 1. The normalized angular choice represents through-movement, i.e., the liability of a segment being the best possible passage for all possible shortest routes and, the measure divides the total choice by the total angular depth of each system segment, represented by the NACH equation: $\log CH + 1/\log TD + 3$. This adjusts the choice values according to the depth of each segment in the system and therefore, the choice value will be reduced by dividing by a higher total depth value because the more segregated it is, the choice values will be reduced because the choice values are divided by the values of higher total depth (Hillier et al., 2012). In other words, it expresses the concept through-movement because the more segregated the space in the network, the smaller is its crossing flow, becoming null in cul-de-sac situations. However, it is essential to clarify that the considered sets of segments (or samples) are calculated at the fabric level of aggregation, in both NACH analyses, NAIN and connectivity analyses. This is possible because the values are calculated on the global system, and then an average of the segment values is calculated for each sample. The comparison in natural system becomes more effective when local radii are applied because NACH is relatively independent of size. The authors show that mean values for the studied sample have variations between 0.76 (NACH_5000_Mean Minimum) and 1.18 (NACH_5000_Mean Maximum). Moreover, 1.4 represents segments with high potential for choice, and 0.80, low potential for choice. Urban activity (shops) seems to show up above 1.2. Such values converge to the values expressed in the Lisbon reference cases, which express successful dynamics and represent centralities within the global context. In this sense, we propose the range of values suggested by Hillier et al. (2012) in formulating the performative quality parameter for the choice.

The authors clarify that systems with values of 1.5 or higher are more interesting and informative systems and identify a dominant global structure. Values close to 1.4 represent an organization of a local structure. Authors argue that maxNAIN and maxNACH are able to capture the foreground structure of cities and meanNACH and meanNAIN the background network (integrated areas that do not allow too much through-movement).

Table 2 Synthesis of connectivity, NAIN and NACH values (Hillier & Hanson, 1984; Hillier et al., 2012)

Parameter classification	Adequate		Inadequate	
Math expression*	≥	≤	<	>
connectivity	2	–	2	–
NAIN	1.2	–	1.2	–
NACH	1.2	–	1.2	–

* ≥ greater or equal than; ≤ less or equal than; < less than; > greater than

Table 3 Synthesis of connectivity, NAIN and NACH values (Hillier & Hanson, 1984; Hillier et al., 2012), for the reference cases

Quality parameter	Connectivity	NAIN	NACH
Lisboa (Campo de Ourique)	3.05	1.22	1.02
Lisboa (Arroios)	3.06	1.16	1.13
Lisboa (Avenidas Novas—Saldanha)	4.01	1.22	1.01
Lisboa (Baixa)	3.44	1.31	1.22

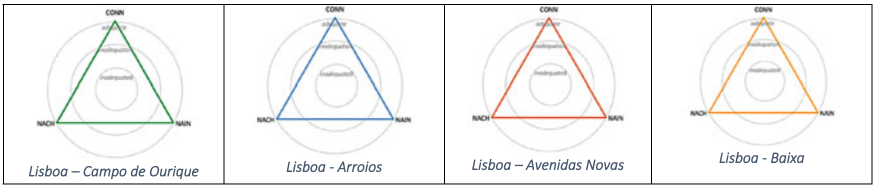


Chart 1 Classification of syntactic measures connectivity, NAIN and NACH

Table 2 shows a synthesis of the qualitative interpretation of configuration indicators.

The study of four reference cases, precisely represented by parts of the urban fabric of prosperous neighborhoods and with favorable economic dynamics located in Lisbon, PT—Arroios, Campo de Ourique, Avenidas Novas, and Baixa, to validate and corroborate with the parameter indicated by Hillier and Hanson (1984) and Hillier et al. (2012), according to Table 3. Moreover, the classification of the reference cases is revealed in the radar chart (Chart 1).

4.2 Density and Urban Form

Density comprises three themes that study different issues and which, when combined, allow us to assess qualitative aspects of cities: built density, population density, and housing density. These three indicators inform different things. The first analyzes the urban built form and, therefore, may include architecture outside the housing scope, namely offices, commerce, and services, as well as industrial equipment and buildings. There is no direct relationship with the housing density indicator as not all the built-up areas will correspond to housing use. Housing density assesses the relative presence of housing (housing units per unit of surface) and therefore does not describe the entirety of the built-up area. Moreover, it is customary in the traditional city to find most commercial ground floors, even when the rest of the buildings are residential. There is also no direct relation to population density because different families may live in the same house or not live at all (a house may be abandoned or under another use). Population density uses the number of people (officially) residing in the sample under analysis. Thus, in areas heavily occupied by the secondary sector or abandoned areas, the expected number of residents tends to be reduced even when the original housing stock (which can be measured by the housing density indicator) is quite large. On the other hand, the household size per dwelling can also vary, either by cultural factors or by the size of the dwelling and often even in contradiction, that is, smaller houses with a more significant number of inhabitants. Finally, there is no direct relation between built density and housing density. An area with tiny houses will have more housing density than an area with large houses because what counts is the number of houses and not the built area. Nevertheless, in two analysis areas with the same base area and the same housing density, if one has a higher construction intensity than the other, then that will mean that the first one has larger houses than the other or that there is an additional part of the built surface that has another use if the houses are the same. The interpretation in a combined analysis of these indicators must be careful, and depending on the indicators we combine, we can draw several different conclusions about the areas we analyze.

When we make use of built density in isolation, we are only looking at the urban form. The rationale presented by Berghauser Pont and Haupt in Spacematrix prevails: the combination of ground cover (GSI) with construction intensity (FSI) gives us an approximate idea of the type of morphology in question. If we focus only on the residential function, and for this function we have a fixed value of built density, the housing density can vary as a function of the average size of the houses. If the houses are large the housing density will be comparatively lower than if the houses are small. The average surface of the houses can be calculated if we take the total surface built for residential use and divide it by the number of existing houses. The average occupancy of the houses can be calculated if we have the total value of the number of residents in the study area, but this average value can be misleading, as these residents may be concentrated in a small number of houses, as is often the case, for example, in the Lisbon center.

The studies by Berghauser Pont and Haupt (2010) understand the built form's effects on the performance and quality of urban space. The shape density comprises a calculation representation in which it expresses the constructed intensity (FSI); the degree of land cover (GSI); the degree of open spaces, which reflects how open space responds to the needs generated by intensity (OSR); the average height of buildings (L); and the network density (N). Its foundation is the concept of aggregation allows us to compare samples within selection and scale criteria and, therefore, without distortions that could lead to misinterpretations and allow us to compare samples. In the case of the present study, we considered the mesh or fabric aggregation level (according to the term used by the authors) as it selects a continuous urban fabric, represented by a morphological unit of urban samples, presented in Table 3). When we talk about ideals of co-presence in urban space and a wide variety of activities and functional diversity, we obtain a positioning of morphologies that is sensitively representative of the performance threshold established through the theoretical doctrines of Jacobs (1961) when represented in the Spacemate graph (Berghauser Pont & Haupt, 2010), Fig. 1. Although some examples demonstrate borderline values concerning the theoretical doctrines of Jacobs (1961), reinforced by Lozano 1990, as stated in Spacemate, both examples can be adopted here as cases of reference on which to base other measures. The authors cover samples in three different regions of Europe—Netherlands, Germany, and Spain—and they map them against different paradigmatic concepts supported by urbanists or specialists such as Unwim (1912), Hoenig (1920s), Le Corbusier (1920s), Gropius (1930), Jacobs (1961), and Lozano (1990), comparing what each author defends as the ideal urban form including some utopian visions. The first four authors represent the modern idealism, where segregation was part of the planning philosophy and diversity was considered a coup against rationalism and therefore they represent the opposite of our present beliefs about what a city should be.

Thus, pattern 5 (Fig. 1), which refers to the quality threshold suggested by Jacobs (1961) is translated through a range of values, which we assume here to be adequate parameters of shape density (Table 3). (a) achievement index (FSI) = 2.2 < FSI < 4.4; (b) occupancy rate (GSI) = 0.42 < GSI < 0.56; (c) number of floors in the building (Level) = 5.3 < L < 8; (d) open spaces (OSR) = 0.13 < OSR < 0.22; (e) network density (N) = 0.010 < N < 0.070.

Network density (N) is measured by the concentration or dispersion of the mesh and represents the relationship between the size of the block and the street length. The authors define other measures derived from the network density indicator such

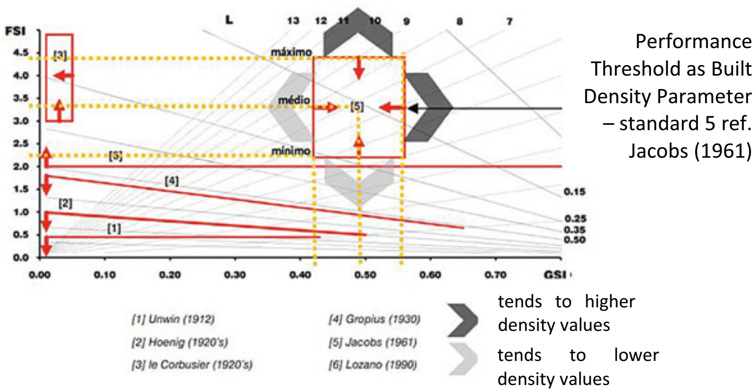


Fig. 1 Quality performance threshold, spacemate

as the average length and width of the road (w and b). The higher the network density, the denser the urban fabric will be, giving smaller dimensions to the blocks (Berghauser Pont & Haupt, 2010). This premise corroborates the studies by Jacobs (1961) and Alexander et al (1977), in which they state that the shorter the distance of physical magnitude, the more accessible and easier the pedestrian route will be. Thus, the N indicator can be interpreted as high values tend to have a higher network density—dense, compact, narrower streets; and the lowest values, a lower network density—extensive layout with wider roads. In a comparative scheme between the referenced case studies by Berghauser Pont and Haupt (2009), and reference cases of successful spaces in Lisbon, we consider the expressed values of these samples to determine a quality parameter for the density indicators of the urban form.

Although the case of Barceloneta expresses values of built density that fit the quality threshold that Jacobs (1961) recommends, the sample we studied has a denser urban network than the other case studies, which is why it is shown in the N indicator (Table 4). The compact city of previous periods has a well-defined structure forming a fabric that cannot always be accepted in current urban planning, essentially because it must include different means of transport, for example. This, in turn, exceeds the limits of the building agglomeration to house the necessary infrastructure for the proper functioning of the city. This perspective gives urbanization a broader role in structuring urban space. Even though the "city plan is the result of its history" (Merlin & Choay, 1988), it is necessary to understand the contemporary social dynamics and processes necessary for current demands.

Table 4 Synthesis of the density values of the urban form

Quality parameter	FSI	GSI	OSR	L	N (m/m^2)	w (m)	b (m)	T (%)
Rotterdam (Wenna)	3.32	0.39	0.18	8.59	0.017	116	31	46
Barcelona (Barceloneta)	2.55	0.48	0.20	5.27	0.070	28	8	50
Barcelona (Eixample)	2.89	0.56	0.15	5.20	0.014	144	29	36
Berlin (Arnimplantz)	2.09	0.42	0.29	5.23	0.010	158	32	30
Berlin (Chamissoplatz)	2.24	0.43	0.26	5.22	0.017	120	20	30
Berlin (Hackesche Hofe)	2.45	0.52	0.20	4.70	0.011	181	13	13
Lisboa (Campo de Ourique)	3.75	0.56	0.14	7.97	0.024	83	8	17
Lisboa (Arroios)	3.08	0.56	0.14	5.49	0.024	83	12	29
Lisboa (Avenidas Novas—Saldanha)	4.89	0.51	0.10	9.78	0.014	142	22	27
Lisboa (Baixa)	4.08	0.57	0.10	6.91	0.040	50	7	28

Tare refers to the difference between fabric aggregation level and island aggregation level

Thus, in a review of the network density parameter (N), a minimum value of 0.010 is assumed, as it expresses the similar network density in two reference cases—Arnimplantz and Hackesche Hofe. Furthermore, there is an essential variation between the other cases analyzed, making it possible to consider the case of Barceloneta (0.070) as the maximum value and reinforcing the importance of a classification interval.

The variations, which can be more or less, make it possible to define the range of values (expressed in Table 5), which will be adopted here as shape density parameters. In other words, based on reference cases pointed out by the studied literature, associated with successful reference cases taken from Lisbon, we look for values that can serve as a system of value to understand what type of urban form expresses an adequate density to hypothetically induce positive urbanity.

The revealed performance is represented on the radar chart for the classification of reference cases and, therefore, serves as a basis for classifying urban types. When the graph completes the five points of the pentagon, in this case, represented by five indicators—FSI, GSI, OSR, L, and N—it represents the sample that corresponds to the quality principles that the literature recommends, and that the quality of the shape density is similar to the pattern of successful urban types (Chart 2).

The classification of the analyzed samples shows that Example, Arroios, and Campo de Ourique represent the density of their form. Furthermore, it is necessary to recognize that the other cases present significant representation in some measures and are considered in the definition of the parameters. They express appropriate characteristics, even if to a lesser degree. The radar chart interprets the classification of urban types concerning the ranges that we have adopted here as appropriate. The graph also represents values that do not fall within the appropriate range. However, it is essential to remember that the parameters adopted in this research are defined from a study based on the literature directed to socio-spatial relations and represented by reference cases considered to express urbanity in their daily lives.

Table 5 Average urban shape density performance parameter

Parameter classification	Adequate		Inadequate	
Math expression*	≥	≤	<	>
FSI	2.20	4.89	2.20	4.40
GSI	0.42	0.56	0.42	0.56
OSR	0.13	0.22	0.13	0.22
L	5, 3	8	5, 3	8
N	0.010	0.070	0.010	0.070

* ≥ greater or equal than; ≤ less or equal than; < less than; > greater than

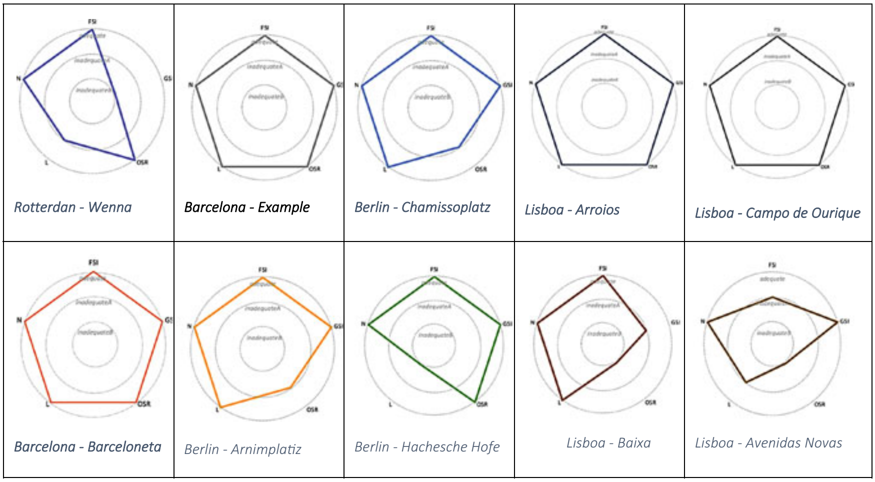


Chart 2 Classification of urban types—FSI, GSI, OSR, L, N measures

4.3 Occupation (Population and Housing Density)

The density of use of the urban form, or population density (Acioly & Davidson, 1998) is an important indicator and parameter of urban design to be used in planning and managing human settlements. And this understanding of the concept, although it seems simple, can vary depending on the territorial and cultural context of an urban space and, in different urban form typologies. Bertaud and Malpezzi (2003) complement the information given by the shape density indicators by describing the intensity of the population's presence in an urban area, helping to understand their modes of interaction and community organization. However, Alexander et al (1977) argues that the random character of local population densities confuses the identity of communities. The author suggests that population densities are generally random, but they are also dependent on subcultures, shopping streets, activity nodes, and the network of local businesses and services, and they may express some pattern when combined with some other attribute. There are many variations involving studies on population density. This is because the population can be transitory depending on the socio-economic and spatial-economic conditions.

In this study, we recognize that the liveliness of a great urban area full of vitality implies the co-presence of people involved in a mix of uses as referred by the many authors mentioned before. This co-presence involves people that live in the area, people that work in the area, and visitors that may visit the place for a wide variety of reasons (where tourism might be the least important). As the census data provides information only about the number of residents, the calculation of density provides only residential density, which is a type of population density, but tell us little about the co-presence of people (at least it represents only a small part of this co-presence of people).

In order to obtain a population density measure that can represent the co-presence of people, we can only do it in a meaningful way by collecting primary data from the streets at pick hours. Such data survey involves several steps and criteria to set the survey plan: (1) identifying the important pick hours; (2) defining criteria to (A) select counting gates; (B) amount of counting gates; (C) select dates, days of the week and other variables to get rid of outlier counts; (3) define criteria for mapping the data (e.g., allocation to built density; allocation and distribution over the public space; allocation and distribution over the total base land area). The data mappings provide different possible visualizations of the distribution of the co-presence of people. When considering two different areas for analysis, and even though the criteria for the surveys might have been the same it is arguable that the measures might be comparable but a normalized distribution should in principle be comparable in terms of the spatial behavior of the distribution rather than by comparing specific values. Once enough evidence provides us with ways to validate the use of the normalized measures, a statistical treatment of the normalized values might provide a range of values for a qualitative ranking of the measure. This is a topic for future work.

Still, the obtained range qualifying as adequate will be an expression of the population co-presence and of its role in the vitality of the urban sample under study, but will tell us little about how to design such a reality. The four samples from Lisbon—Arroios, Campo de Ourique, Avenidas Novas, and Baixa—are neighborhoods that had between 120 and 250 years from plan till now involving many transformations along time, the inclusion of older constructions or even unplanned transformations. The great vitality that we see today is the result of all these transformations (some of greater quality than others) but essentially the quality comes from the present state. The obtained measures on resident population and other co-present users have nothing to do with the original plans for these areas—they are simply the present state of affairs. This means that the measures on population density at the present moment inform us about how social dynamics are characterized at the present state but tell us little about what should be the right population density when designing the urban plan (and this might be because population density is not an indicator of urban form). Nevertheless, when we design an urban plan a population density is usually proposed, and there will be no doubt to accept that it would be nice to know in advance what values for population density tend to produce urban spaces with the qualities observed on the chosen samples. However, it seems more important to observe that in all reference cases, the most dramatic changes occurred not essentially on the urban form but on the functional use or activities of the areas; an initial state predominantly occupied with residential uses progressively accommodate more and more commerce, services, offices and other facilities. As pointed out in the following section, residential, commercial, and other uses tend to appear in approximately equal parts (50/50 percent for residential/non-residential) in the areas studied by van den Hoek (2008). And in some cases (e.g., Baixa) the residential spaces are either used for other activities or simply abandoned for speculative purposes. On the other hand, any urban design manual will state that when designing a new urban area, the design should be developed to accommodate a predominant space for residential uses even though they might advocate the design of mixed-use areas.

Furthermore, census data does not necessarily reflect the exact uses of spaces as many declared residential spaces are many times used for accommodating different types of businesses (at least this is common in the sample areas of Lisbon). This means that even the use of official census data might lead to a false picture of the situation.

Summarizing a population density indicator measured today on a successful urban area will not be able to capture the transformations along time in a way that would inform us on how to propose a nice value for population density in an urban design operation. In conclusion, such an indicator might be argued to be irrelevant in terms of its information about how to design. Still, we will contain this statement for a while just by saying that there might be another way to calculate such value, but in an inverse way, i.e., by ignoring the population and working over the surface capacity of the area (which is a totally different logic). This means starting from the existing urban form and calculating its potential capacity for people co-presence (visitors + workers + residents). But before working this inverse logic, it is important to stress, that maybe much more important for design than population indicators, is to understand what are the formal aspects that allow for the positive transformations that change an initial implementation progressively towards a present set of formal characteristics. This clearly brings several topics that might be developed in a future paper, such as flexibility of the plan, formal characteristics of the constructions, and the flexibility of their relations to public space or to accommodate changes along time in the use of their inner spaces. Potential for change might be an objective traceable concept.

The inverse approach to the population density calculation starts from the base land area and uses building intensity to calculate available surface, then the distribution of available surface per type of use (commerce, services, and residential use), then allocating occupation to these uses to calculate visitors, workers, and residents. In Table 6, we have the main urban form density indicators for five neighborhoods all obtained from cartographic geo-referenced data. As an example, we will consider only one neighborhood to explain the calculation—Lisboa, Avenidas Novas. Let's start with a fabric sample, hypothetically of 100,000 m^2. We know the FSI value (4.89) that allows us to calculate the available gross floor area, GFA, which is 489000 m^2. The following steps involve relative ambiguity that may be reduced by adding several procedures in rigorousness depending on the available data for existing activities and residential use. Still, census data with all the mentioned fragility in rigor might not bring more accuracy than accepting the equal part subdivision mentioned by van den Hoek for residential and non-residential (commerce, offices/services) use, implying more or less equal parts for (visitors + workers) and residents, and accepting that the all built space is in use (hence, this calculation is referring to potential occupation and not a real condition). Furthermore, van den Hoek's conclusions refer observed proportion of uses in areas showing dynamic vitality and therefore it is arguable that the equal proportion of activities may correspond to a positive pattern to be used as reference. The next step in this inverse logic divides the total area of the use by the typical use unit area to calculate the number of surface units per use (number of commercial spaces, offices/services, and apartments). This calculation can be made

Table 6 Synthesis of built density and population density values

Quality parameter	FSIf	GSIf	OSR	L	N/m	PDf	ToF
Lisboa (Campo de Ourique)	3.75	0.47	0.14	7.97	0.024	**0.037**	
Lisboa (Arroios)	3.08	0.56	0.14	5.49	0.024	**0.021**	**0.43**
Lisboa (Avenidas Novas—Saldanha)	4.89	0.51	0.10	9.78	0.014	**0.010**	**0.31**
Lisboa (Baixa)	4.08	0.59	0.10	6.91	0.040	**0.012**	**0.62**
Barcelona (*Eixample*)	2.89	0.56	0.15	5.25	0.014	**0.036**	

in many different ways, the best being the methods that most rely on existent data. For instance, working abstractly with the total area or working with each building will bring different levels of rigorousness. Then we can attribute levels of occupation to the several unit areas of use (e.g., number of residents per apartment type and number of workers per office surface unit).

4.4 Mixed Use and Diversity

Jacobs (1961) argues that the vitality of a city needs the orderly interactions that mixed-use neighborhoods represent. The lack of mixing social groups, shops, workshops, offices, factories, etc., becomes an unsustainable form of monoculture. The mix of uses in an urban space enhances the interest in public use and attracts people to use the streets and spaces at different times for different reasons and influences other parts of the city to generate solid and comprehensive economic dynamics.

The Mixed-use Index (MXI) informs a ratio of a use in comparison to all other uses (van den Hoek, 2008). In this paper, the given values will correspond to the percentage of residential use in comparison to other uses (except where otherwise is specifically stated). Initially, the studies by Hoek (2008) assimilated the presence of people on the streets for different purposes and at different times, based on a balanced value of 50% of mixed use. The author's approach is a ratio between residential and non-residential uses that must be 50/50 to create potential conditions for urbanity. He cites the city ring of Barcelona, and the canal area of Amsterdam, where the proportion of residential versus non-residential space has always been approximately 50/50 since the beginning of the nineteenth century. The author also emphasizes that "(…) Barcelona's metropolitan urbanity, inside the ring, and the Amsterdam canal area are proof of the experience that, in order to create a lively and vibrant city center, the 50/50 proportion works" (Hoek, 2008).

The author proposes the analysis of mixed typologies in several districts of Amsterdam to verify the mixture of residential and non-residential spaces. Thus, this variable indicates the diversity of practical uses, such as residential and non-residential. In predominantly residential areas, people use public spaces to walk with children, meet neighbors, and do other leisure activities. Generally, people identify with local public spaces and their elements for everyday activities. In predominantly commercial areas, the effect is the opposite. Furthermore, when there is a mix, social interactions of leisure, services, sport, culture, school, etc., are likely to happen, which are typical traits easily perceived in European cities.

However, Hoek (2009) and van Nes et al. (2012) suggest that the urban mix expresses multifunctionality even more balanced when it presents a variation of 33% in three primary functions—residential, work, and services.

Nonetheless, according to the information available in the database domain, the MXI indicator values can be established in two groups—residential and non-residential use. The non-residential category corresponds roughly to the sum of commerce + work + services. Therefore, residential use is defined by 33%, represented by the ratio (0.33); and the sum of other uses (non-residential use) total 67%, represented by 0.67.

Therefore, values tending to 0 indicate a higher rate of non-residential use, characterized by few dwellings and a more significant presence of shops and services; and values tending to 1 indicate greater residential use, characterized by many dwellings and few trades and services.

In order to establish an adequate interval, we considered not just this information (based on theoretical support), but also MXI a set of values taken from reference cases in Lisbon (see Table 7). These values were taken from georeferenced information available in the public domain. From Table 8, we can identify a maximum and minimum value setting the Adequate interval between 0.33 and 0.61. Values below the minimum are considered inadequate low (inadequate B = predominantly non-residential), and values above the maximum are considered inadequate high (inadequate A = predominantly residential). However, the sharp limit between adequate and inadequate might be attenuated by calculating the admissible variance for each extreme to define a vague transition between adequate and inadequate.

Once again, these values represent observable MXI values measured in existent reality. They express present functional behavior and do not necessarily imply the existence of such proportions at design stage, but the capacity to adapt along time towards such conditions.

In addition to this discussion, Kim Dovey and Elek Pafka, in Mapping Urbanities—Morphologies, Flows, Possibilities (2018), defend the Functional Mix in

Table 7 Mixture performance of uses

Samples	Arroios	Baixa	Campo de Ourique	Avenidas Novas	van den Hoek (2008)	van Nes et al. (2012)
MXI	0.61	0.39	0.56	0.43	0.5	0.33

Table 8 Facade transparency degree—qualitative assessment

Quality performance	Quality parameter
Low	0–29%
Good to high	30–62%
High to excessive	63–100%

various ways to understand how cities work essentially defined by the Live/Work/ Visit triangle, which main objective is to map the different functional combinations and understand the flow of attractions and productivity that a city can offer. However, the Dovey and Pafka method involves complex and abstract categories, not consistently measurable through data.

The main principle that we can take from MXI values in terms of design recommendations is a no-zoning principle, but regarding the percentage of mixed use for the initial layout the method is still vague (although we may argue that working on existent original buildings only may provide additional evidence). Diversity, however, is another issue because there is a relation between formal diversity and diversity of uses in the sense that different uses will search the spatial/formal conditions that are singular to their spatial/functional idiosyncrasies. Such diversity potential might be expressed by the diversity in building shapes and types and may be given as a leading recommendation for design.

4.5 Public–Private Space Interfaces

Façade Transparency (ToF)

Highly related to spatial dynamics and spatial vitality is the theme of Façade transparency. The transparency of the façade translates the ability to see and be seen through transparent openings (windows, storefronts, and doors) along the facade of a building. Moreover, it becomes an essential factor in the perception of safety and encourages pedestrian activities in urban spaces. Transparency connects people with the interior of the building and provides greater security in the urban public space. Jacobs (1961), as well as Gehl (2010), refer to this feature as a concept—"eyes of the street" as visually permeable façades close to the street promote a sense of security for the inhabitants who walk or practice any other activity on the street. Safety is one of the essential factors to promote vitality. It is on the ground floor, or street level, that people enjoy the possibility of passively or actively interacting with the public space. It is assumed that it is possible to verify how interactive the basement of a building can be and how much this can influence the presence of people on sidewalks and public spaces (Beirão & Koltsova, 2015; Gehl, 2014; Hillier and Hanson, 1984; Jacobs, 1961; Karssenberg et al. 2015; Lynch, 1960, etc.).

Lehnerer (2009) suggests that facade transparency should reach at least 30% to achieve urban dynamics and promote the visual communication necessary to enhance interactions between the interior and exterior of the building, generating a clearer perception of human activities. Above all, it makes it possible to define a standard of building form without barriers so that socio-spatial interaction is possible and provides adequate transparency on the facade of buildings, especially in mixed-use areas. Lehnerer's study is based on investigations to mediate public and private interests with efforts to shape the city, from a selection of example cities that include Berlin, Chicago, Houston, Las Vegas, London, Los Angeles, New York, and Zurich, among other cases. However, the author does not clarify the maximum appropriate degree of transparency. A façade that provides 100% transparency may not always be considered appropriate, as it may compromise privacy in residential buildings or, depending on the climate, excessive reflectivity lighting caused by the sun. The maximum value of 100% can be considered excessive in many cases.

Thus, it is proposed to study four reference cases of neighborhoods considered dynamic, already mentioned earlier in this section, to find an adequate transparency parameter—Arroios (Lisbon); Lisbon downtown; Barceloneta (Barcelona); and Arnimplatz (Berlin)—essentially concerning economic, cultural, and functional dynamics (mix of uses), good socio-spatial interaction (urbanity, walkability, etc.) movement. Above all, to reinforce a threshold of adequate quality from evidence in the urban form already constituted (Evidence Based on Practice and Design), precisely translated by experimentation based on research and successful practices (Dursun, 2007).

The reference cases, Barceloneta and Arnimplatz, Arroios and Baixa, respond positively to the doctrines of Jacobs (1961) as represented in the spacemate graphic and therefore they are used to extract data on façade transparency and permeability.

The façade transparency or transparency of the façade (ToF) used in this study is calculated only at the ground level as this is the level that potentially interacts with the public space. It considers the total area of transparent surfaces at ground level divided by the total surface of the ground level providing a ratio or percentage. Zero represents a totally blind ground floor façade. Accuracy in such a value should include the distinction between transparent and non-transparent glass. Transparency provides visual interaction. Non-transparent glass surfaces do not provide interaction but they are potentially changeable contrary to masonry or concrete surfaces which are hardly changeable and therefore provide a low probability for positive transformation (Fig. 2).

The reference cases express *good* urban diversity, active facades, and use mixes. Furthermore, although the values are tangent to a "raw" average based on median information, it is possible to see that the examples of Barcelona and Berlin are closer to what Lehnerer (2009) points out as active and interactive façades. In the Lisbon examples, Baixa presents a very interactive façade with regular openings and different uses, portraying a prominent opening surface concerning the other examples, except for the example of Arroios, which expresses an average between these cases.

In this sense, we propose a scale of performance degree represented by a percentage representing the balance of transparency of a facade, essentially in the basement of the building (Chart 3).

It should be noted that in the derivation of the percentage value in the index for comparative purposes, the ratio measure is represented by 100% (the maximum degree of transparency) and, therefore, equal to 1, and the normalization is represented as follows: i = X/100, so i = 30%/100 which results in an index equal to 0.3 (Table 9).

Finally, in this section, the performative quality values of the examples mentioned above are assumed to establish an average of transparency of the facade of the basement of the building that can be considered adequate. This premise considers the

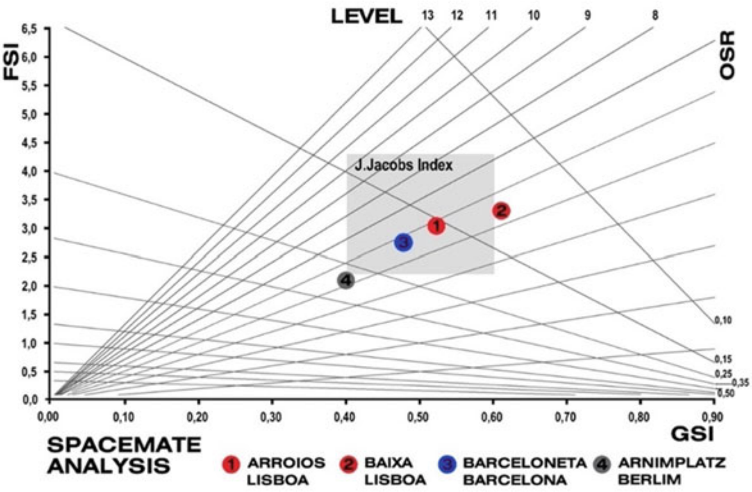


Fig. 2 Analysis of reference cases

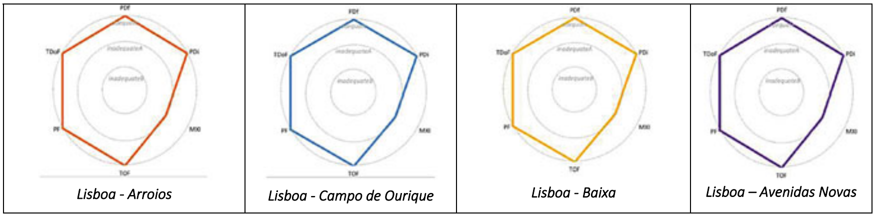


Chart 3 Classification of urban types—PDf, PDi, MXI, TOF, PF, TDoF

Table 9 Facade transparency parameter—TOF

Parameter classification	Adequate	Inadequate
math expression*	≥	<
ToF	0.30	0.30

* ≥ greater or equal than; ≤ less or equal than; < less than; > greater than

parameter established by Lehnerer (2009), not as a minimum value of transparency but as a parameter that indicates that from 30% transparency on it evolves into interactive and active facades and very high values towards 100% may be considered excessive and undesirable with variations depending on climate and cultural contexts. Therefore, adequate transparency is assumed to be between 30 and 100% transparency (0.30 and 1), but a value above 0.62 may be considered excessive depending on the urban context, environment, and culture.

Note that the same concept of façade transparency could be calculated for the total façade or just for the first floors with a similar calculation principle. However, we decided to consider only ground floor because it is the one that establishes direct contact with the public space. Still, following Jacobs' idea that street safety is provided by passive surveillance derived from eyes on the street, the calculation of a transparency index for a wider surface of the façade could contribution to a more in-depth understanding of street safety, provided that the calculation uses the first four floors of the construction (as referred by Alexander et al., 1977) because it is the limit for direct communication between people inside the building and the public space.

Facade permeability

Permeability is measured by quantifying access doors to the building that are immediate to the street. Gehl (2012) suggests that a street, to be inviting and active, must have a variety of functions (directly correlated with the mix of uses and functions) through sufficient openings to allow the occupation of diverse activities and ensure good socio-spatial interaction. The permeability of the facade measure is the frequency of access doors (of façades) for a given length of the façades.

The parameter stipulated by Gehl (2010) derives into five values. The author suggests active (15–25 doors); inviting (10–14 doors); mixed (6–10 doors); monotonous (3–5 doors); and idle (0–2 doors), every 100 linear meters. Therefore, when considering the parameter indicated by the author, an adaptation for classification purposes is proposed, establishing an index on a scale from 0 to 1, adopting the value of 25 as the ideal number of doors. The value may be higher than 1 in cases involving more than 25 entrances (which rarely occurs in a hundred-meter façade but is technically possible).

$$P = x/25$$

where P is a Permeability index;

x is the number of doors per hundred meters; therefore, $x = d/(l/100)$, where d is the total number of doors and l is the total façade length in the area under study. This can be calculated for any level of aggregation (Table 10).

Moreover, the performance degree of the Facade permeability measure is represented by two classification categories, and we assume that values above 0.24, corresponding to six doors in a façade of 100 m length, are sufficient to start generating interactive dynamics and therefore suitable for a positive induction of urbanity.

Table 10 Permeability index

Quality performance	Permeability index
Idle to monotonous	0–0.23
Mixed to inviting	0.24–0.61
Active	0.62–1 (and above)

Table 11 Parameter of facade permeability—PF

Performance classification	Adequate		Inadequate
Math expression*	$\geq$	$\leq$	$<$
Permeability index	0.24	1	0.24

* $\geq$ greater or equal than; $\leq$ less or equal than; $<$ less than; $>$ greater than

Table 12 Facade permeability performance

Quality performance	Lisboa (Arroios)	Lisboa (Baixa)	Barcelona (Barceloneta)	Berlin (Arnimplatz)
PF	0.27	0.39	0.21	0.33

This parameter is based on analytical applications of European cities (Gehl, 2010) that may be considered reference values indicative of positive and successful urban dynamics. When applying these values to the reference cases (Table 11) adopted in this analysis, it was found that the values revealed are close to what the author indicates as inviting, except for the Barceloneta case, which expresses insufficient openings and can be classified as monotonous. This classification is due to the evident characteristic of the neighborhood, which has a low mix of uses and a more significant number of residential buildings, with direct access to each building, smaller window openings than the other cases, and shops located in the vicinity of the blocks.

Considering the values expressed in the reference cases, this analysis assumes that inviting values are already sufficient to generate sound, positive, and successful urban dynamics. It reinforces the idea that this parameter can be replicated for studies in other cities, with different realities from those analyzed here.

Thus, in a compilation of values, the permeability performance of some reference cases is presented (Table 12).

Territorial Depth of the basement

In the facade interface, it is possible to check the territorial depth[1] (Beirão & Koltsova, 2015). Territorial depth refers to the number of territorial steps we must take to get from the street to the front door. A territorial step is identified by transposing an architectural barrier that allows one space to be distinguished from another (for example, an entrance yard with a gate or entrance gate; or a staircase separating two levels). Beirão and Koltsova (2015) address how street life and private spaces connect based on territorial depth. The authors are inspired by the rationale of the interface map present at the foundations of space syntax for reading the street as a space whose dynamics result from the direct relationship of the entrances from public space to private "cells". Considering that different properties shape urban spaces, the study presents a measure to identify how the topological distance of the building's entrance concerning the street can interfere with the public–private dynamics. The

[1] The concept of the term Territorial Depth is attributed to John Habraken in "The Structure of the Ordinary" (1998).

resource of increasing territorial distance has been widely used as isolation between the streets and the building to provide greater security to private life, especially in developing countries, through the materialization of gated communities, featuring isolated buildings, without continuity and/or with "blind" façades towards the public space, conforming hostility and insecurity to urban life. The authors reinforce Hillier and Hanson's (1984) notes by demonstrating that territorial depth is a determining feature in the life of public spaces, as it configures the possibilities of the immediate and active façade, as it is the primary position variable of the entrances to the building in relation to the street.

The measure is adapted from the method by Beirão and Koltsova (2015), as it has a different quantification from the authors' method to be based on descriptive data. However, the result predicts the same kind of result to qualify the territorial distance between the building and the street. The territorial depth of the facade is calculated by adding the number of direct access doors divided by the total number of doors in the morphological unit of the block; 1 is given to a topological step representing the immediate facade to the street; and 2 for two topological steps, which represents a territorial step between the street sidewalk and the building. More steps count in equivalent manner. The territorial depth (TD) of the façade is measured by the equation $TD = E/N$, where E represents the total number of entrances in a façade and N is the total number of territorial steps in the system (total number of links in the graph). This means that a street façade where all entrances open directly to the sidewalk has a value for territorial depth of 1 and tends to get lower as the number of territorial steps in the system increase. This relation inverts the relation found in Beirão and Koltsova (2015) but provides the same logic for interpretation. For an intuitive interpretation, 0.5 represents for instance a system where all entrances have an in-between front yard, and lower values would mean further territorial steps (e.g., a front yard, a small staircase, and a porch). This relation explains how much a façade connects directly private space with public space, but is unable to distinguish between a façade with one door from a façade with many doors. However, this value may be combined with the permeability index, where TD will reduce the permeability index according to its value giving a combined impression of the impacts of permeability + territorial depth.

Assuming that façades will have a higher public space activation the closer they get to the value 1, will consider adequate all façades with a predominant number of direct entrances, i.e., with TD above 0.75.

Therefore, the territorial depth classification parameter is established as follows (Table 13).

Table 13 Territorial depth parameter—TD

Performance classification	Adequate	Inadequate
Math expression*	$>$	$\leq$
TD	0.75	0.75

* $\geq$ greater or equal than; $\leq$ less or equal than; $<$ less than; $>$ greater than

Table 14 Territorial depth performance

Quality performance	Lisboa (Arroios)	Lisboa (Baixa)	Barcelona (Barceloneta)	Berlin (Arnimplatz)
TD	0.97	1	1	1

The reference cases Arroios, Baixa, Barceloneta, and Arnimplatz reveal 1 topological step. It means that they are facades without barriers between the building and the street, a predominant characteristic of traditional cities (Table 14).

The compound version of permeability index and territorial depth that we shall call the Absolute Permeability Index (AP*i*), clearly distinguishes a street with houses with a front yard from a street with houses with a direct façade to the street.

In a compilation of measures of the density of use of the form, the diversity of use, and the public–private interface of the basement, the revealed performance is represented in the radar chart for the classification of the reference cases and, therefore, serves as a basis for the classification of urban types. When the graph completes the five points of the pentagon, it means that the analyzed sample expresses the quality principles that the literature recommends.

5 Discussion (on Quality and Lessons Learned for Urban Design)

Research is a term appropriated by both science and design. But their methods and purposes do not overlap completely meaning that the implications of scientific results in design contexts may require reinterpretation in face of such contexts. It is of general consensus that science's purpose is to understand reality, the world as is, in a way that we can explain its phenomena to the extent that we may be able to replicate such phenomena by setting experiments where the conditions that generate the phenomenon are replicated and the same result is always obtained and explained by the same theoretical (mostly mathematical) support. Science accepts the world as is. Science just wants to understand it; to extract knowledge. Such knowledge is recognized as useful for design purposes, but once this is so, design is more concerned to understand the world as it ought to be; to find ways to improve reality. How can we act over a reality and change it with the optimistic and positive purpose of improving it? Design tries to look into the future, by understanding the present phenomena, and produces new experiments that do not intent to replicate the past, but on the contrary, tries to improve it (H. Simon, 1969; N. Cross 1982, 1990).

Urban design is a particular field of design that takes urban settlements as the object of their work and focuses on how to design new urban settlements. Urban science, on the other hand, studies urban phenomena and tries to understand how cities work (how they emerge, grow, prosper, and decay?). In general, it wants to understand cities' dynamics. The underlying idea of urban design is that lessons learned from urban science may be used in urban design to design better cities. Until this point, such purpose sounds logical if not essential. However, there are some issues breaking the linearity of this logic. (1) Urban settlements are unique objects with a unique context and history. (2) Urban settlements are complex systems within larger complex systems following the logic of complexity. (3) Urban settlements are under continuous transformation, and they change radically over time. The implications of these three points are, and this is the purpose of this discussion, that observations taken today from specific areas of cities might inform us about what they are presently as well as about their present dynamics, but not necessarily about how to design these spaces. In fact, similar forms might have different occupations and such occupations might change radically over time. What we see today as being a "good city form" might have been designed with an entirely different purpose in mind (if designed at all). Some urban areas might have had radical transformations along time and even had difficult decaying moments.

In this research, the main purpose was to define an objective system of values for evaluating and interpreting how much certain morphological features expressed by means of morphological indicators may influence the "urban quality" of an urban area with the intention of finding consistencies that may eventually allow us to extrapolate rules for future designs. In order to do so, we resorted to two main methods: (A) literature review; (B) data extraction from reference samples. The first method provided us already validated information on some of the indicators we needed. This was the case with the configuration indicators and the spacematrix indicators (the latter with some additional evidence gathered from our own selected reference samples). The second method allowed us to measure values on the selected reference samples and take them as reference values. This is where the obtained values require some additional discussion.

Let's concentrate on mixed use. From the literature review, we got the information that the most active areas of the urban samples taken for their studies presented result that the percentage of residential occupation in these areas would vary between 27 and 37% (Hoek, 2009). Roughly one-third residential to two-thirds non-residential. A look into the Lisbon samples (Arroios, Campo de Ourique, Avenidas Novas) shows similar percentages and seems to be confirming Hoek's conclusions. However, these areas have been originally mostly residential and their changes through time have changed drastically such occupation. The importance of this realization is that figures obtained from the analysis of the samples as they are today do not necessarily inform on how to design new urban areas but on how our designs should be allowed to evolve in order to adapt and support the referred qualities of urbanity along their existence. Furthermore, mixed use is not a morphological indicator. It just expresses the mix of activities that occupy a certain urban area. So, extrapolations on how to design future urban plans require a more careful approach requiring the analysis of usage data at the initial stage of urban implementation after which a comparison between initial and present states would allow us to identify which type of structures (including which type of morphological and configurational features) can easily allow changing their uses and adapt, and which do not. This topic requires further work.

Other non-morphological indicators like those on population density and residential density also require further analysis regarding their correlations to form-based density indicators. The main topic of criticism here is that none of these indicators express the idea of co-presence of people in an area. Co-presence, according to several authors (J. Jacobs, Gehl, Hillier, and others) seems to be the characteristic that reflects the positive urban dynamics of an area. Population density reflects only a proportion of people officially dwelling in a given area and tells us nothing about people commuting to the area to work on a daily basis, a piece of information certainly essential to evaluate co-presence and therefore an essential part of local urban dynamics. This issue also requires further attention to be given in a future study. Moreover, real estate abandonment and real estate speculation can change drastically the interpretations of population density and types of occupation in buildings. Finally, temporary residence, both through hotels or Airbnb temporary rents introduce additional complexities to the understanding of urban dynamics and furthermore on eventual extrapolations towards creating design guidelines for the future.

6 Conclusion and Future Work

This study is intended to create a system of objective values that allows evaluating and interpreting how a set of morphological parameters of urban design can influence (possibly in a decisive way) the qualities and, social and economic dynamics of the resulting public space; a set of qualities which we express through the concept of "urbanity". One of the positive aspects of this approach is the formation of the concept of performative quality, which expands the possibilities of studies on the theme of urbanity. It is understood that the concept of performative quality is decisive in the formation of urbanity and hence in the way we design and adapt the built environment.

This article presents the studies, supporting references, and arguments that allowed us to list the set of indicators that once combined may constitute a composite indicator of performative quality. In a following article, we will show the application of this methodology on specific case studies, where the methodology is put to the test, and the theory of interpretation of evaluations is developed in more detail, reinforcing, and validating the guiding principles of this research, as well as the methodology here presented. Proposals will also be made for future developments of the work that may incorporate more indicators of qualification of the public space, namely indicators related to the qualities of the horizontal surfaces of the public space as qualifiers to the attributes of the positive forms and vertical limits that were the object of attention in this article. Sidewalk surface and its direct relation to activities seem also to be essential for enhancing performative quality in public spaces and in streets in particular.

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Developments in Architectural Design Automation

Plausible Layout Generation Using Machine Learning, Evolutionary Optimisation and Parametric Methods

Daiva Marcinkeviciute and Wassim Jabi

1 Introduction

Before an architectural competition is announced it is common practice to create a room program with required sizes, adjacencies and travel distances between different spaces, as well as multiple other requirements (for example, daylight). Then test planning is performed—a preliminary design of the building with a goal to make sure the proposed building program is feasible. The test design is also used to calculate and revise the anticipated building costs. The project is however not meant to be built; the actual concept of the building is proposed at the competition.

Test planning is a repetitive, time-consuming task, especially difficult when the topologic relationships of the rooms are complex. At the same time, it does not require high-quality architectural design or creativity. Thus, performing it automatically would liberate the time of architects to work on real architectural projects that are going to be built. While the design of built objects must consider the complex space syntax and aesthetical principles, the test planning can be performed based on simplified rules. This makes test planning an excellent candidate for automatic building layout generation.

The research on generative design and layout generation is still relatively young. There were many attempts to generate layouts using multiple different methods, but they were mostly focused on single-family homes, that have only several rooms and a few simple topologic relationships. The layout generation of more complex, especially multi-storey buildings still has many unresolved issues, especially when

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it comes to multi-level circulation. Therefore, further research is needed before more complicated buildings can be efficiently generated in daily practice.

The existing layout generation tools perform in a rather limited way, by either randomly placing the rooms into a given building envelope or subdividing the envelope based on a tree diagram. However, they do not produce efficient logical circulation. An architect on the other hand does not randomly place the rooms but works based on topological principles, first drafting the overall shape and structure of the building, and then laying out the rooms. This approach could be incorporated into a new layout generation method, based on architectural knowledge. It could help to generate more plausible buildings with functioning vertical connections and circulation.

As layout generation is a very broad area, considering the limited time, the scope in this paper is reduced to one building type: school buildings. They were selected because they typically feature a combination of big and small rooms that is difficult to standardise. Plus schools often have a relatively complex but still manageable topological structure. This paper is focused on only generating the ground floor, but the algorithm is designed in a way, that it can be expanded to generate multi-storey buildings (ensuring vertical connectivity and statical plausibility). The algorithm is integrated into the Rhino/Grasshopper environment, as it allows high level of interoperability with other tools for ML, simulation and generative design.

The following research objectives were defined: investigate existing layouts and break them down into planning steps and topological principles; pack these principles into an algorithm that generates school layouts; generate layouts based on a prewritten room program; connect the generative algorithm with an evolutionary solver and optimise the layouts using topologic requirements as optimisation criteria; and, finally, validate the quality of the newly generated layouts according to the requirements in the room program.

2 Related Work

In this section, a survey of the related work of other researchers will be presented.

The automatic layout generation was covered in multiple research papers with a large range of proposed methods. In 2021, Schwartz subdivided the current building generation techniques into three categories: top-down, bottom-up and advanced computational frameworks.

In the top-down approach, a building envelope is created and subdivided into spaces. In the bottom-up approach, the spaces are placed according to their connectivity requirements and allocation is performed starting at room level and going to the building level (Schwartz et al., 2021).

Advanced computational frameworks can combine multiple methods, such as optimisation algorithms and agent-based systems, using k-d tree data and ML (Schwartz et al., 2021).

In the current research, several ML methods are being used for layout generation. The most used method in the current research is Generative Adversarial Network (GAN) (Chen et al., 2020). Nauata proposed a house layout generator, built upon a relational graph-constrained generative adversarial network called House-GAN (Nauata et al., 2003). Para proposed another graph-constrained GAN-based model for layout generation that enables novel capabilities for conditional layout generation (Para et al., 2011). Chaillou proposed an approach, based on stacking models. Using GAN, that first generates a building outline on an empty lot, then generates a room layout inside this boundary and finally places the furniture within the rooms (Chaillou, 2020). The GAN method was combined with graph convolutional network in the research of Chen. His algorithm first translates the verbal description of the house to a structural graph representation and then predicts the layout of rooms with a graph conditioned layout prediction network and generates the interior texture with a language conditioned texture GAN (Chen et al., 2020). All these papers focused on generating layouts for one-storey single-family homes.

Lately, the GAN efforts have been focused on site layout generation. Tian used Pix2Pix GAN to generate an urban fabric by colour-coding building programs and using existing built environment GIS data. To achieve better results, the training data was filtered by different constraints, such as lot shape, orientation, density and purpose of buildings (Tian, 2020). Yao applied a multi-step approach, integrating GAN with a genetic algorithm to generate the layout of residential areas. He used GAN for the layout generation and the genetic algorithm to define the building heights (Yao et al., 2021). Liu used GAN to generate campus layouts, given lot boundary and surrounding streets. The layouts were colour coded by function. He also applied two steps of generation: first generating rough zoning and then using the results to generate a detailed layout (Liu, 2020). In 2021, Zhao used GAN in combination with genetic algorithms to generate hospital layouts, also using multiple steps of generation (Zhao et al., 2021).

Another ML method using Graph Neural Network (GNN) for layout generation was proposed by Huin in the research paper called Graph2Plan. The solution allows the user to input the room count, location and required adjacencies. The training set is then filtered by the user input and selected graphs are fitted into a user-defined building boundary, to find the best match. Only good matches are used to train the graph neural network, which converts the graph into a raster image of the floor plan (Hu et al., 2004).

ML was also used to pick the best match of the apartment layout from a gallery, which was then placed into an available space within a building. The gallery was created by standardising a range of existing apartment layouts. An ML algorithm chose the best match based on the given proportions, shape, entry location and interior and exterior walls. The chosen layout was then reconstructed and adapted to better match the given space (Green, 2020).

In conclusion, while the GAN method has been very popular lately, so far, it still faces many issues. First, it produces low-resolution pixel images, that often are blurry and cannot be vectorised. The generation results are also frequently unrealistic (Schwartz et al., 2021). The main issue with GAN though is not allowing the user to input a room program or any requirements. The only way to influence the output is by filtering the training data. The research has shown that selecting appropriate data (for example, buildings that are similar in size, use, topological principles, etc.) is essential to achieve good results with ML. Also, better results were achieved by subdividing the generation process into 2–3 steps, where first the approximate zoning was generated and then the generated image was detailed in further rounds of GAN generation. Using ML to select existing layout parts from a library and fit them into the available space is a more basic approach that has shown good results.

Another area of advanced computational frameworks is evolutionary computation, which according to the research of Ekici, is the most used method for optimisation of generative design. He has carried out an overview of over 100 papers, where genetic algorithms were used for optimisation of building shape and layouts. He found that evolutionary solvers were used to optimise mostly sustainability criteria, quite often costs and in a few cases functional and structural goals (Ekici et al., 2019).

Most of the reviewed papers share several research gaps: The attempts to generate layouts were mostly focused on single-family homes. There were few attempts to generate bigger, more complex buildings, that would implement a complex room program with multiple topological constraints. One problem that still must be solved before more complex buildings can be generated is circulation. Circulation needs to be solved on multiple levels: primary circulation with building entrances, horizontal and vertical connections, as well as secondary circulation that connects all the rooms.

3 Research Design and Methodology

To develop the layout generation algorithm the Rhino–Grasshopper environment was chosen, as it offers a high level of interoperability with many different tools for ML, evolutionary algorithms and other simulations.

An algorithm is written to perform the following steps (see Fig. 1):

1. The user inputs a closed curve, which marks the approximate building shape.
2. A matching building layout with primary circulation and spaces that will hold rooms is chosen from a gallery and scaled, rotated and mirrored to match the sketch of the user in the closest way possible. The layout is selected using ML.
3. The user chooses a csv file containing a room program. The rooms and secondary circulation are placed according to the room program. They are placed parametrically based on a set of rules.
4. The layout is evaluated and optimised according to room connectivity and daylight. The room placement is optimised using an evolutionary solver.

To create a simplified user interface in Rhino, the Grasshopper Plugin ‘Human UI’ is used (see Fig. 2).

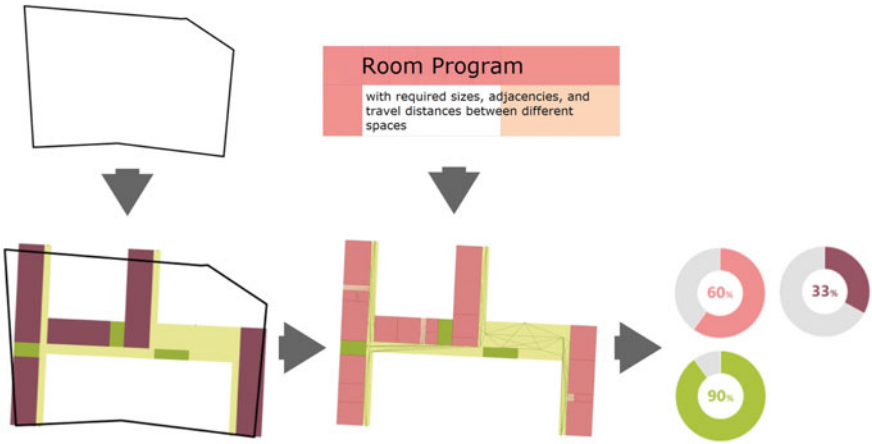

Fig. 1 Layout generation steps

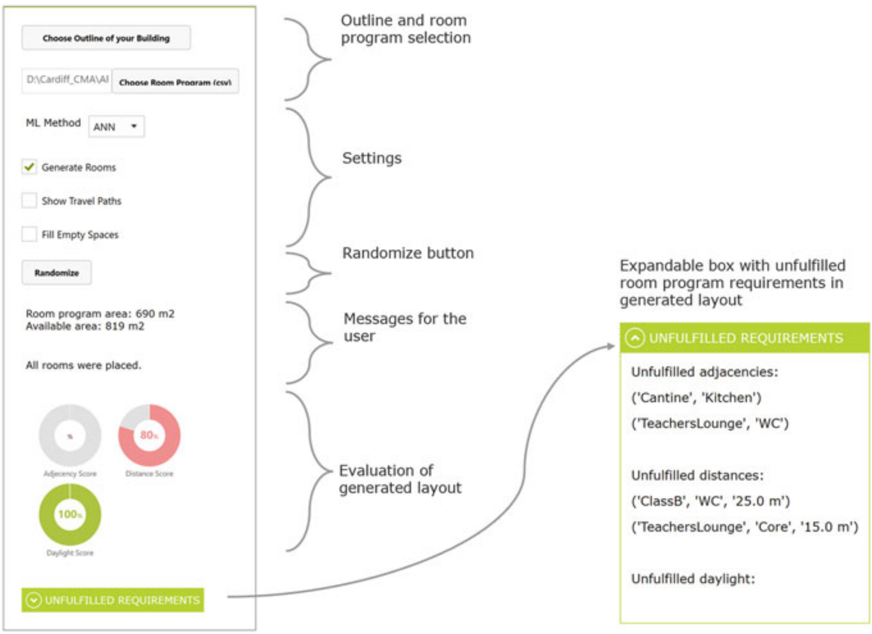

Fig. 2 User interface

4 Placing the Building Shape and Primary Circulation

First, a gallery of existing simplified school layouts was created. Multiple school layouts were selected from literature based on the following criteria: the school must have multiple stories (to have both vertical and horizontal circulation), the total area of the rooms on the ground floor (except circulation) must be between 350 and 1000 m^2, the school must be plausible for the cold climate zones (circulation inside). It cannot have an open floor plan and it must be possible to break it down into clearly defined areas.

The selected layouts were broken down into the main components: building shape, entrances, main horizontal circulation, vertical circulation and spaces holding the remainder of the rooms (all zones are sketched respecting the main load bearing walls of the building). Once the layouts are simplified into components, they are varied geometrically, but maintained topologically to obtain more options of the building shape, all sharing similar circulation logic and proportions (see Fig. 3).

A closed curve is drawn around the building to get its simplified shape, that will be used in ML to find the best-fitting layout (see Fig. 4).

The simplified outline of the layout is first manipulated by slightly tweaking and stretching it into different directions, as well as mirroring it. The goal of this is to obtain multiple closely similar shapes representing the same layout to increase the training set for ML. Then the shapes are described in a vector of numbers that can

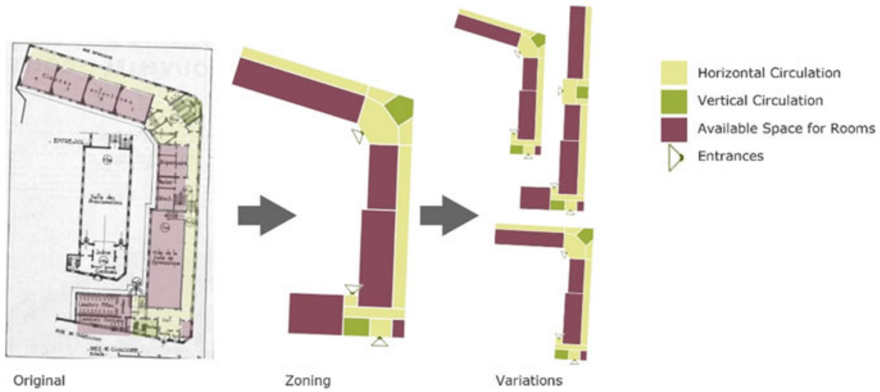

Fig. 3 Creating schematic layouts

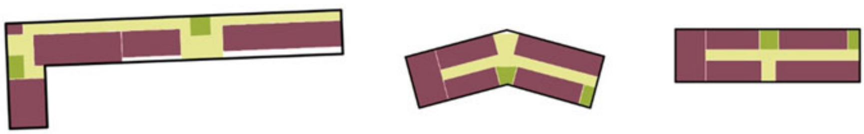

Fig. 4 Sketching the shape of the layout

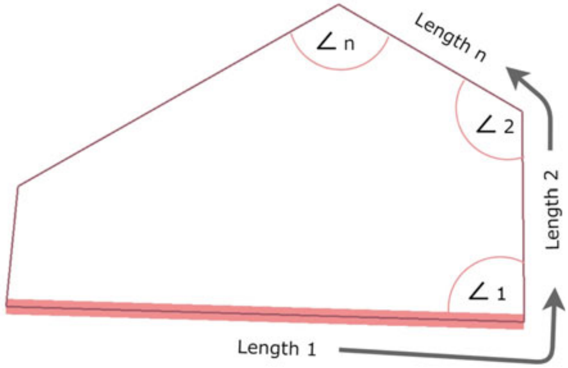

Fig. 5 Shape example

be interpreted by ML. As the shapes must be recognised also when they are rotated or mirrored, first the longest line is found, and the description of the shape always starts there (i.e. the longest line is always the first line in the vector). The vector is put together as follows: area/perimeter ratio raised by the power of 3; length of the first line; angle between first and second line (in radians); length of the second line; angle between second and third line (in radians); and so on until all the lengths of sides and angles of the shape are in the vector. Then the lengths are unitised (mapped into values between 0 and 1).

As all the vectors must have the same lengths, if a shape has less than eight sides, the rest of the vector is filled with 0 values.

For example, the vector of a five-sided shape can be [2.81, 1, 1.49, 0.42, 1.77, 0.49, 1.92, 0.75, 1.79, 0.29, 1.48, 0, 0, 0, 0, 0, 0] (see Fig. 5).

The collection of vectors is used in the ML software as the training set. The shape sketched by the user is also described with a vector and is used as input.

The scale of layouts is limited, as the circulation can lose its logic at higher scale values. Thus, the algorithm allows scaling layouts by a maximum of 10%. Therefore, only the layouts of a similar size to the input can be considered.

Before the shapes are fed into ML, they are filtered by size (see Fig. 6).

The neural network chooses the most similar shape from the filtered shapes. Then the chosen shape is rotated, mirrored and scaled (by max 10%) to fit closely into the input shape.

5 Machine Learning Experiments

To find the best ML approach, different techniques were tested.

The vector that describes the shapes was assembled in four different ways:

- By area/perimeter ratio, the lengths of the line and angle (see Fig. 5):
  - Unitised (all lengths mapped into the range from zero to one).

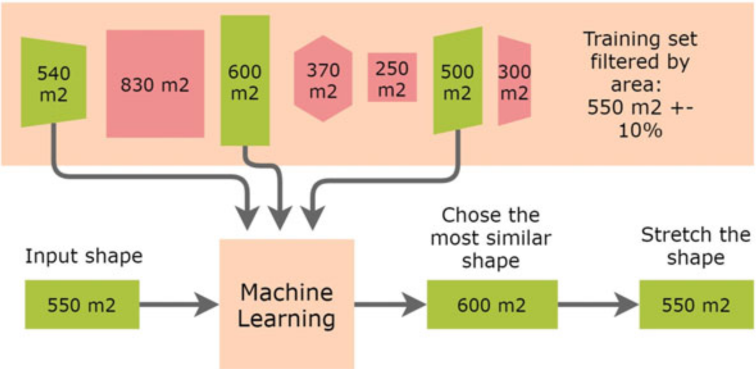

Fig. 6 Filtering and selecting the shape

  - Non-unitised (original lengths used in the vector).
- By dividing the curve into thirty equally spaced points and measuring the distances from each point to the centroid. Thirty points were sufficient to represent all the forms in a recognisable manner and did not overload the algorithm with superfluous data. These distances then were put into a vector with thirty values:
  - Unitised.
  - Non-unitised.

To test the efficiency of these different approaches, first, all the training data was split into two groups: 90% for training and 10% for testing. It was split in a way that every label was present in both groups. The data in both groups was shuffled. Then the Artificial Neural Network (ANN) by Lunchbox was trained with the bigger dataset, and the smaller dataset was used as an input. The output labels were compared with the actual ones. In all the cases, the artificial neural network guessed correctly in ~85% of the cases.

As the output data in this research is categorical (layout number), both artificial neural networks and decision trees can give good results. Thus, two different approaches were set up in the Grasshopper definition and trained: the artificial neural network and a custom decision tree, programmed in Visual Studio Code and adapted to run on a parallel server and work in Grasshopper through the Hops component, based on two tutorials (Steve Baer, 2021; W3Schools, 2021).

To compare the results of the ANN and the decision tree, two different methods were applied. First, all the training data was split into two groups: 90% for training and 10% for testing. It was split in a way that every label was present in both groups. The data in both groups was shuffled. Then the ANN and the decision tree were trained with the bigger dataset, and the smaller dataset was used as an input. The output labels were compared with the actual ones. While the ANN guessed correctly in ~85% of cases, the decision tree guessed correctly in ~95% of cases, showing superior results.

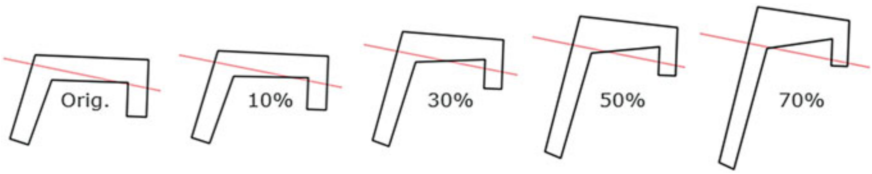

Fig. 7 Deformation of the shapes

In the next step, six different layout outlines were taken from the gallery and gradually transformed. All the shapes were tapered along the same axis by 10, 30, 50 and 70%. They were scaled to keep the area of the original shape (Fig. 7).

On each step, the transformed outline was fed into the ANN and the decision tree as an input and the output result was observed (see Figs. 8, 9, 10, 11, 12 and 13).

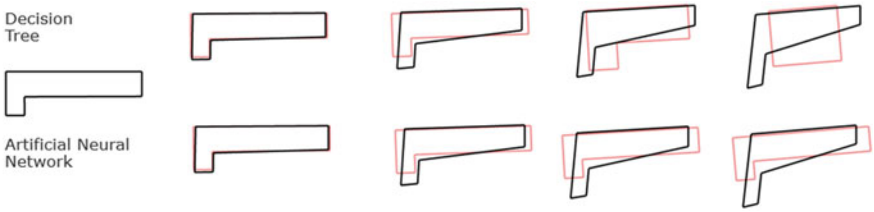

Fig. 8 Layout recognition. Shape 1

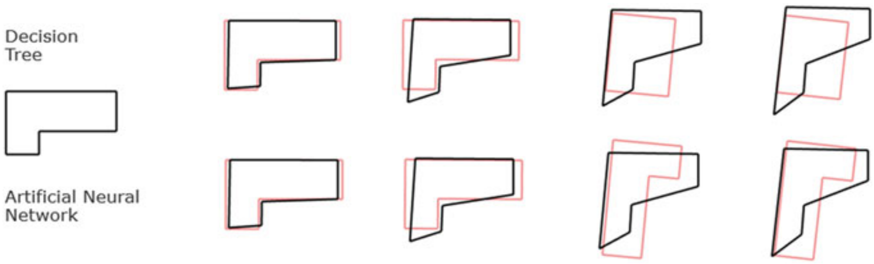

Fig. 9 Layout recognition. Shape 2

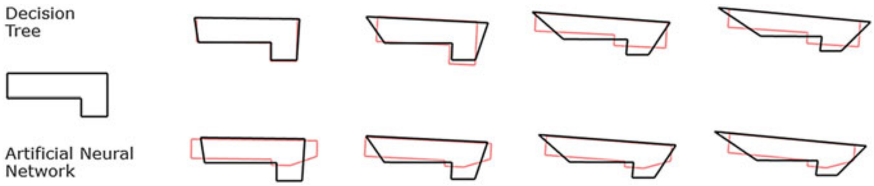

Fig. 10 Layout recognition. Shape 3

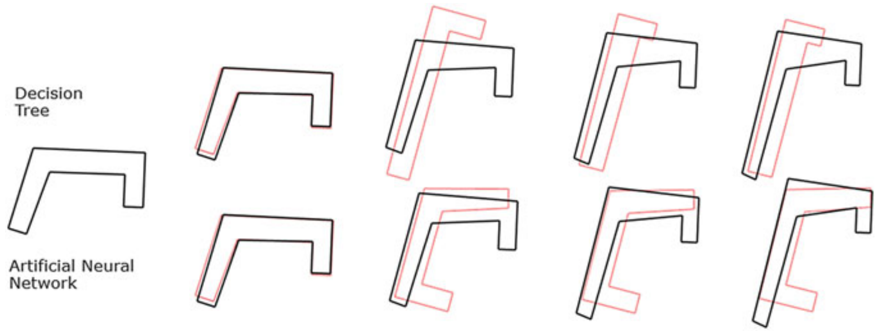

Fig. 11 Layout recognition. Shape 4

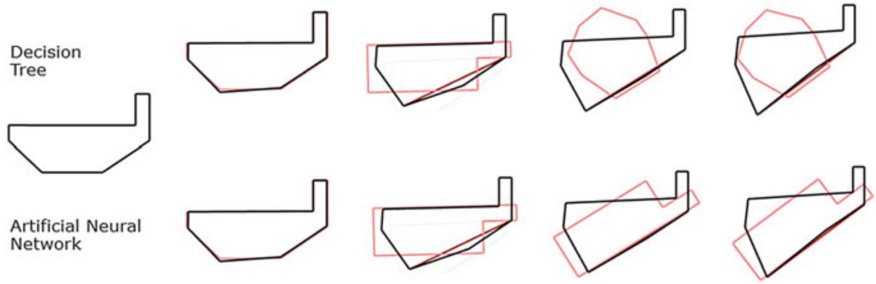

Fig. 12 Layout recognition. Shape 5

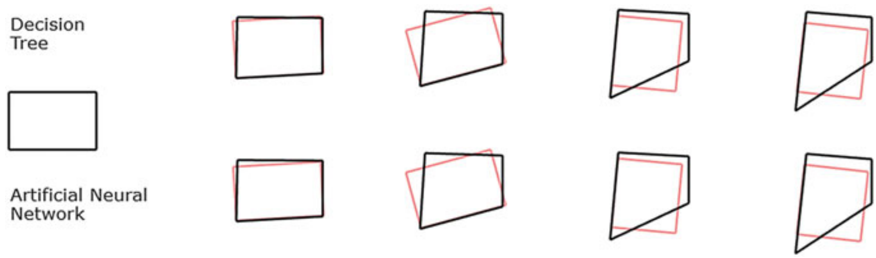

Fig. 13 Layout recognition. Shape 6

The following visual observations were made: As seen in examples 1, 2, 3 and 5, once the outline is transformed by a large factor (70%), the decision tree chose a less similar shape than the ANN. As seen in examples 3 and 6, when the outline is transformed by a small factor (10%), the decision tree recognises the original layout; meanwhile, the ANN interprets it as a different, but similar layout. In conclusion, the decision tree performed better at recognising closely similar shapes; meanwhile, ANN performed better at interpreting shapes that are significantly different from the original.

6 Placing Secondary Circulation and the Rooms

Once the main components of the layout are fitted, the rooms are placed according to the imported room program in csv format (see Fig. 14). The following information for room placement is defined in the program: the number of rooms, the size, the minimum width and the height of the room. The program also defines the following goals for optimisation: the required daylight coefficient (the area of windows divided by the floor area), the required adjacencies (marked in the adjacency matrix as 0) and the required distances (marked in the adjacency matrix as numbers higher than 0). Required distances can be set between the rooms, or from a room to the core and/or entrance of the building.

A set of prewritten rules (see Figs. 15 and 16) define how a room should be placed, depending on its size and proportions. Rooms are either distributed along the main circulation axis or they are placed along secondary circulation, either by putting a corridor in the middle and arranging the rooms on both sides or by placing a room at the end of the block and connecting it with a corridor to the main circulation. To place a more varied combination of bigger and smaller rooms, these rules can be applied recursively.

Once all the rooms are placed and depending on their size and position, the leftover spaces are either turned into a 'generic' room, included in an adjacent room, or turned into a circulation space (see Fig. 17).

While both the available spaces and the rooms must be orthogonal for the algorithm to work, the main circulation can come in any shape, which allows non-orthogonal buildings.

To calculate the travel distances between the rooms, an algorithm first finds the middle point in a wall shared by each room and a corridor and places a dot that represents a door. All these points are connected into a visibility graph representing the travel paths. Only the paths within the circulation system are considered, when calculating the travel distances.

Once all the rooms are placed, the Opossum evolutionary solver evaluates and optimises the criteria defined in the room program: adjacencies (rooms are considered adjacent, if they share a wall that is large enough to fit a door), travel distances (distances are calculated from door to door via circulation spaces) and daylight (the ratio between exterior wall area and floor area). Each layout receives a score for each of the three criteria (0–100%).

Room	Number	Size	Length	height	Daylight_Q	Entrance	Core	ClassB	ClassS	Cantine	Kitchen	WC	GameRoon	TeachersLo
ClassB	3	60	11	3	0.2	n	n	n	n	n	n	15	n	n
ClassS	4	40	8	3	0.2	n	n	n	n	n	n	15	n	n
Cantine	1	120	6.5	3	0.1	n	10	n	n	n	0	n	n	n
Kitchen	1	50	4.5	3	0	n	n	n	n	n	n	n	n	n
WC	4	10	4	3	0	n	n	n	n	n	n	n	n	n
MediaRoom	1	70	12	3	0	n	n	n	n	n	n	0	n	n
TeachersLounge	1	70	5	3	0.1	20	10	n	n	n	n	0	n	n

Fig. 14 Room program example

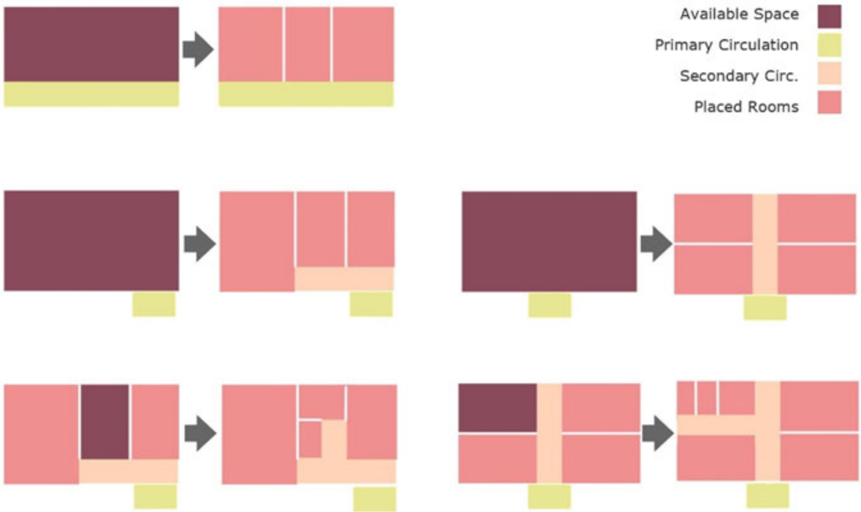

Fig. 15 Concept of placing rooms and secondary circulation

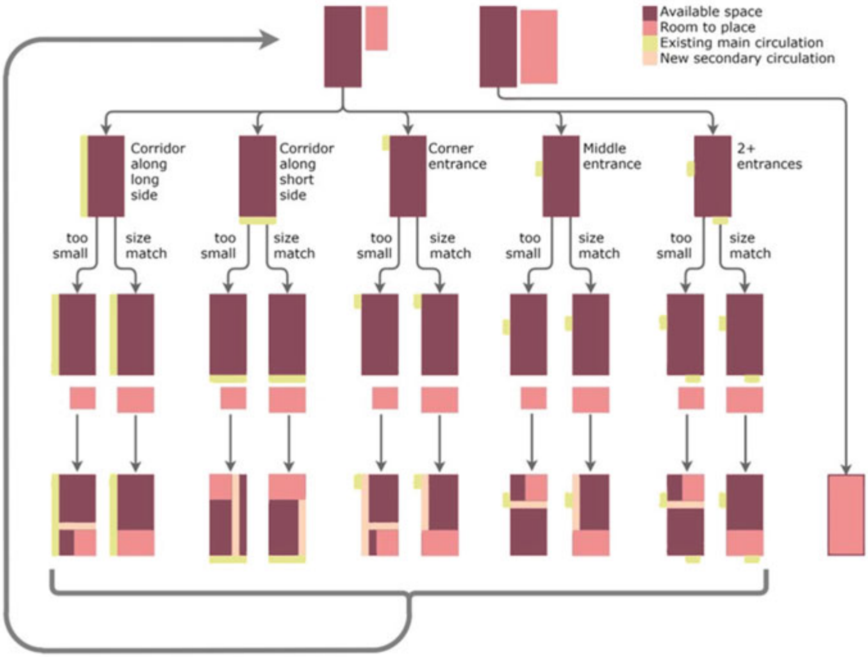

Fig. 16 Rules for placing rooms and secondary circulation

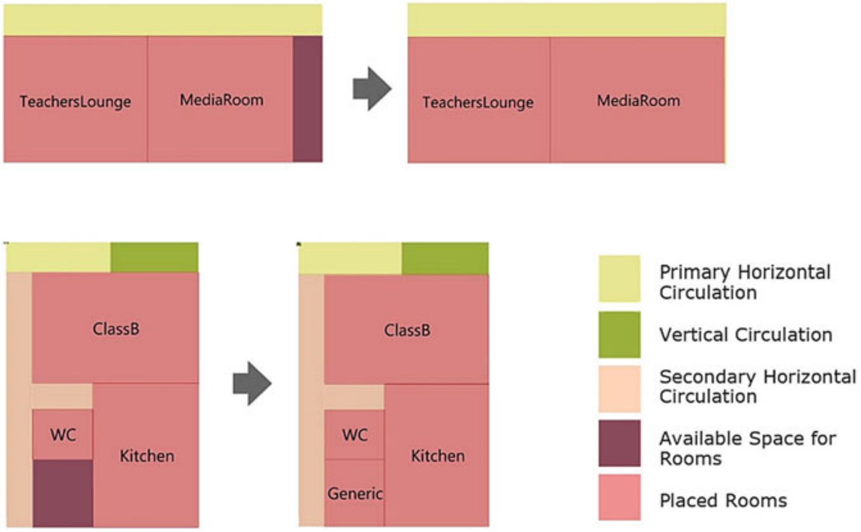

Fig. 17 Filling empty spaces

7 Results

The result is a schematic 2D layout of the ground floor of the school, where the rooms are represented as rectangles. The layout contains all the rooms from the room program. The movement paths within the building are represented with lines. The evaluation of the space connectivity and daylight criteria is calculated and visualised.

Multiple layouts were generated using a room program with the following requirements: Daylight Coefficient: 0.2 for classrooms, 0.1 for the canteen and teachers' lounge. Adjacencies: canteen adjacent to kitchen; teachers' lounge and media room adjacent to a WC. Distances: a WC within 15 m from each classroom, a core within 10 m of the canteen, teachers' lounge within 10 m from core and 20 m from entrance.

As the required distances are very short, the evolutionary solver could not optimise all the goals to 100% (see Figs. 18 and 19).

The same room program was changed by increasing the required distances, to make the goals more achievable. While daylight requirements stayed the same, the media room was no longer required to be adjacent to a WC and the distances between the classrooms and WCs as well as between the canteen and the core was increased to 25 m; meanwhile, the distance between the teachers' lounge and the core was increased to 15 m.

This time the evolutionary optimisation achieved 100% of the goals within 5 min (see Fig. 20).

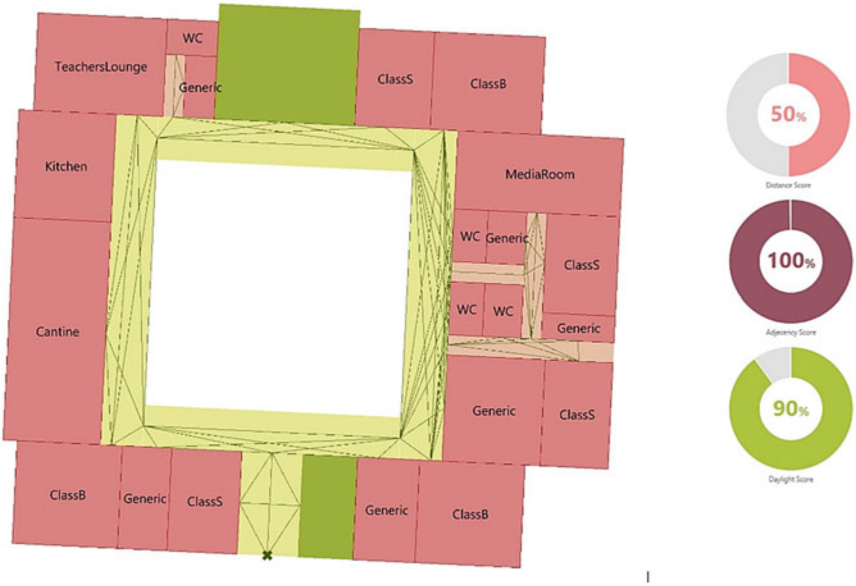

Fig. 18 Optimised layout (5 min, 87 iterations)

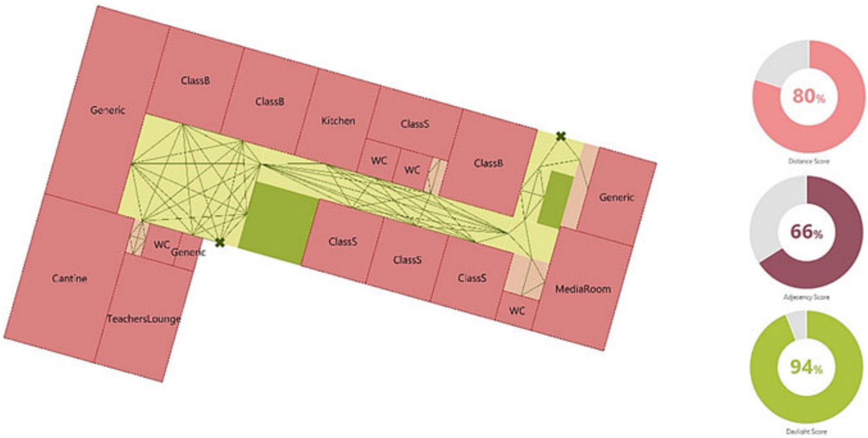

Fig. 19 Optimised layout (5 min, 102 iterations)

8 Next Steps and Improvements

The algorithm can be expanded by copying the schematic layout from the gallery vertically to create a multi-storey building. This way the vertical circulation as well as the façade and main load bearing walls would overlap vertically. Possibly the

Fig. 20 Optimised layout (5 min, 72 iterations)

gallery could contain the schematic layout of the ground and the upper floor and use the upper floor zoning for higher levels. Then the rooms from the program could be distributed on all the levels according to the parametric workflow described in this paper. The algorithm checking the travel distances between the rooms would have to be adapted for a multi-storey building to include also vertical connections. This way multi-storey buildings could be generated and evaluated.

Laying out the building shape and the main zones could also be done parametrically based on a set of rules, like the ones, used to lay out the rooms. Different rules could be defined for different categories of schools, according to their shape and topologic relationships. This would allow more flexibility and more diverse results. Also, more functional zoning could be added (for example separating the loud and quiet zones of the school or formal and informal learning areas).

At the moment room placing algorithm only places orthogonal rooms into orthogonal spaces. It could be improved to handle non-orthogonal shapes.

By adding the height to the room objects a topologic cell complex representing the building can be created. This would allow multiple further simulations, such as thermal and structural performance and access to views. The resulting conceptual model could also be used to generate more detailed building elements, using vertices, edges, faces and cells as references. The vertices of the visibility graph could be used to generate doors.

9 Conclusions

A new method for layout generation was created which combines computational methods and architectural patterns learned from existing buildings. It addresses complex buildings with hierarchical circulation. The school layouts were chosen and broken down into planning steps based on topological principles. A two-rounds approach was applied, where the zoning and main circulation are placed first and then the rooms and secondary circulation are laid out next. The steps were combined into an overall algorithm. This resulted in plausible layouts that could be generated from a room program where all the rooms are accessible via a hierarchical and functional circulation system. Confirming precedents from the literature, the two-rounds approach has proven to deliver good results.

For placing the zoning, a gallery of zoning layouts was used. ML helped select the best-fitting layout from a gallery of precedent layouts. Two ML approaches were tested: an ANN and a decision tree. Both approaches have shown good results: while the ANN was better at interpreting new shapes that are significantly different from the training set, the decision tree was better at interpreting shapes that are more closely similar to the input shape. A layout gallery, however, takes a lot of time to assemble and limits the amount of possible building shapes. Thus, placing the zoning could also be broken down into algorithmic steps (just as the room placement was broken down in this project), and generated parametrically for any given building shape.

Room placement was improved using evolutionary optimisation based on the topologic requirements defined in the room program. Three criteria (adjacencies, distances and daylight) were optimised, but the number of criteria to optimise is flexible and can be expanded according to the needs of the user. The success of maximising the optimisation criteria was dependent on the strictness of criteria (the easier criteria are set up in the room program, the easier they all can be fulfilled). While it took many iterations to achieve good results (50–200), the process is fast and automatic, and is still incomparably more efficient than sketching and evaluating different options manually (minutes versus weeks). The optimisation success also depended on the schematic layout of the gallery. The same room program could be successfully optimised in one schematic layout but can fail in another one.

While the current workflow is set up to only generate the ground floor, it can be expanded to generate multi-storey buildings.

To sum up, the algorithm can be used for test planning. It can check the plausibility of a room program on different building shapes within minutes. This not only frees architects to work on projects that are going to be built but also allows them to change and optimise the room program more easily, as it can be checked much faster than before.

The research brought together architectural knowledge and computational methods, like ML and evolutionary simulation. It showed, that extracting patterns found in existing architecture and incorporating them into the workflow can significantly improve plausibility of the generated results (in comparison to examples in the literature review). This approach based on combining human and artificial intelligence could uncover new opportunities for automatic building generation.

10 Related Software and Tools

Layout generation tools (Rhino–Grasshopper environment):

- Yconst, PackRat. 2018.
- Tabari, M., Termite Nest 2021.
- Vestartas, P., OpenNest. 2021.
- hellguz, Magnetizing Floor Plan Generator. 2020.

Other layout generation tools:

- MINC, Finch. 2021. (in development)
- TestFit Inc, Testfit. 2021
- Matterlab, Refinery Toolkit. 2020. (Dynamo environment)

Machine learning tools (Rhino–Grasshopper environment):

- Miller, N., LunchBox for Grasshopper. 2020.
- Zwierzycki, M., Owl. 2019.
- Greco, L., Dodo. 2019.
- Felbrich, B., Crow—Artificial Neural Networks. 2020.

Evolutionary solvers (Rhino–Grasshopper environment):

- Rutten, D., Galapagos. 2019.
- Delft, T., Optimus. 2020.
- Mohammed Makki, M.S., Yutao Song, Wallacei 2021.
- Olsen, C.B., Biomorpher. 2020.
- Vierlinger, R., Octopus. 2018.
- Wortmann, T., Opossum. 2021.

Other related tools:

- Jabi, W., Topologic. 2020.
- Andrew Heumann, M.S., Nate Holland, Brian Ringley, Human UI. 2019.
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Tian, R. (2020). Suggestive site planning with conditional GAN and urban GIS data. In *The international conference on computational design and robotic fabrication.* Springer.

W3Schools. (2021). *Machine learning—Decision tree.* [cited 2021]. https://www.w3schools.com/python/python_ml_decision_tree.asp

Yao, J., et al. (2021). *Generative design method of building group-Based on generative adversarial network and genetic algorithm.*

Zhao, C., et al. (2021). Two generative design methods of hospital operating department layouts based on healthcare systematic layout planning and generative adversarial network. *Journal of Shanghai Jiaotong University (science), 26*(1), 103–115.

Experimental Form-Finding Method. Case Study: 'Weather Pavilion'

Tomáš Baroš, Lenka Kabošová, Martin Baroš, and Dušan Katunský

1 Introduction

1.1 Nature-Adaptive Design/Bio-Background

Digital simulation software packages help architects and engineers to envision complex weather and loading stimuli that affect their designs as early as in the conceptual design stage, which enables digital form-finding (finding an appropriate architectural and structural shape Veenendaal & Block, 2012) and the creation of architectural/structural design with material properties, geometric behavior, or manufacturing requirements embedded in the digital model (Hu & Li, 2014). Employing weather characteristics as a form-finding factor in architectural design leads to unexpected forms and innovative environment-inspired solutions (Loonen et al., 2010). Architecture, perceived through the lens of evolution, just like organisms, should gradually 'evolve' too to develop a natural resistance to the adverse effects of the

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environment (De Luca et al., 2021; Natanian et al., 2019; Pellitteri et al., 2009). Concepts for nature-driven architecture are only one step from developing solutions for adaptive architecture, responding to environmental triggers through real-time shape or material changes (Barozzi et al., 2016; Beesley & Omar, 2009; Meagher, 2015; Orhon, 2016; Persiani et al., 2016; Schleicher et al., 2015). Architecture or architectural structures adapting to acting loads or redistributing them have been emerging in the past decade (Kontovourkis et al., 2017; Körner et al., 2018; Senatore et al., 2018; Tamke et al., 2015), benefiting from interdisciplinary collaboration or utilizing capabilities of digital software.

1.2 Digital Form-Finding and Algorithmic Design

Physical models used to be the only way for experimental architectural form-finding, enabling an intuitive design process through interactive shape exploration. In the digital workflow, too, a real-time (instant) response is required. The huge benefit of digital designing is the interdisciplinarity, entwining parametric design, generative design, and various simulation tools and plugins, which enables the designer to integrate the desired criteria (boundary conditions) while iteratively evaluating the design's performance and, again, changing the design if necessary. The execution time of simulations implemented in this process needs to be minimal. Optimization and generative algorithms employed in architectural design are parallel to natural selection (preserving and adding up all that is good, working towards enhancements concerning adaptation to ambient conditions). This principle, used in architecture, urbanism, or structural design, leads to a gradual evolution of the best solution or a group of well-performing solutions under specific external conditions (Duering et al., 2020; Funes & Pollack, 1999; Malkawi et al., 2005).

1.3 Structural and Shape Optimization in Architecture

The use of the genetic algorithm for structural and parametric optimization during the architectural design process points to potential, but quite a few studies pay attention to the possibilities of the interactive (real-time) application of optimization methods.

When genetic algorithms are involved in the design process, it is usually for solving complex design tasks where the solution is not straightforward. The automated process is, thus, not distorted by the designer's view, so unforeseen design solutions emerge that could otherwise remain unknown. In the optimization task, rules or boundary conditions must be complied with, often controlled, and determined by the designer/engineer. Here, gained expertise of an engineer is actively employed in solving problems. In this way, a synthesized design approach originates, utilizing the capabilities of computers and merging them with the knowledge of the designer (Erhan et al., 2014; Malkawi et al., 2005; Vasilkin, 2018).

1.4 Tensegrity (Tensional Integrity) Systems

Form-finding often focuses on achieving a lightweight appearance of the final design. Experimentation with tensegrity structures reveals possible applications of this novel structural system (discontinuous compression bars (struts), which remain in equilibrium by tensed elements (tendons) in architecture (Motro, 2003; Peña et al., 2010). All elements are interdependent, so a slight change in the potential energy of the structure induced by the applied forces results in a transformation of the shape as a whole (Abdelmohsen et al., 2016). That is an advantage when designing kinetic and adaptive structures. The real-time shape adaptation of the final design can be made possible either by replacing some compression members (struts) with active telescopic struts (Spisak & Kmet, 2017) or replacing some tensile elements (tendons) with linear actuators (Jun et al., 2017). Alternatively, the potential of the tensegrity system for a reversible passive shape change when subjected to the loads can be employed (Kabošová et al., 2019).

1.5 Goals of the Paper and Architectural Philosophy

The 'Weather Pavilion' in Košice, Slovakia, is created digitally, demonstrating a novel design method. The main form-finding factors are external weather influences (wind (intensity and direction), temperature, air density, and barometric pressure) represented by one acting Forming Force. The tensegrity system is elected as the structural system because it can optimally distribute the acting loads while maintaining a lightweight appearance. It must be stated, however, that the design is not focused on achieving the true tensegrity, ergo, tendons in pure tension and struts under pure compression.

The task of this experimental form-finding is to create a design methodology centered on the coherent impact of the weather on architecture and how it can condition its form. Although naturally, multiple influences are acting on architecture (whether small-scale pavilions or large-scale urban solutions), this paper deals with weather effects represented by one Forming Force. The concrete architectural result is not the target as the proposed approach applies to any structural element, this being the essence of parametricism (Fig. 1). Unique to the site's ambient conditions, the architecture created this way is an evolution process—a form emerging from repetitive pre-defined elements, combined as a reaction to the acting ambient influences. The design is developed interdisciplinary, evolving from the specific environmental and climatic conditions of Košice, Slovakia.

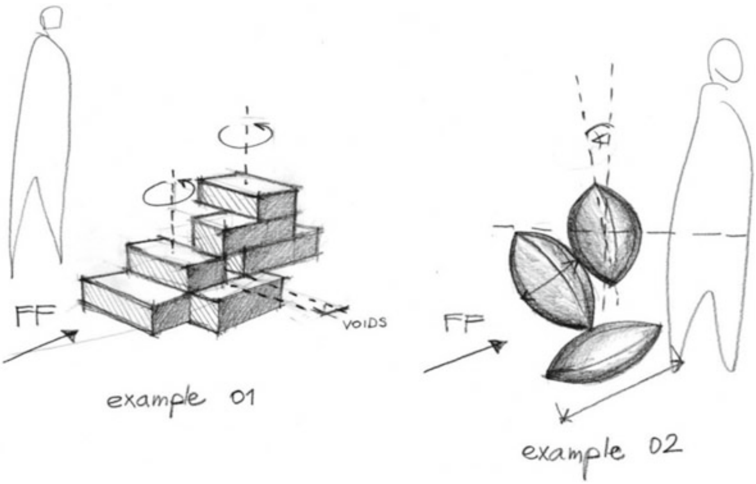

Fig. 1 Various Applications of the method. Left: a parametrically-created brick wall, reacting to the effect of the Forming Force. Right: inflated ETFE membranes, creating a pavilion that optimally withstands the acting Forming Force

2 Methods

The conventional approach to design considers the weather stimuli and their influence on the structural, insulation, and thermal requirements for buildings, which is derived from the natural need of people to create a shelter from outdoor conditions. However, often these criteria have a minimum effect on the resulting architectural form and are usually considered after the overall architectural concept is developed. Moreover, compared to the common practice of designing architectural structures, which determines the normative wind load values through an extreme or average value, the proposed method works with detailed (hourly-acquired) data incorporating multiple weather parameters that affect the wind. These are unique for the specific location and its microclimate. The proposed methodology and new processing and utilization of the weather data create greater architectural diversity in the environment. The presented design approach is an add-on to the conventional one while exploring possibilities of architecture materializing from weather data.

Reflecting nature's guides, the growth of any form (like our tensegrity pavilion) is influenced by external stimuli (weather data in our case study). The weather will determine the formation, resulting in a different pavilion at different times of the year. As in real life, the Forming Force (a result of the actual weather data) in the digital model changes in time and with a specific location. Therefore, the weather-induced form of the pavilion can assume different spatial configurations.

The design goal—a visual plausibility and minimum spatial displacement of the designed structure—is considered in the form-finding process. Generative algorithms are engaged in the AAD (Algorithm-Aided Design) approach for shaping the

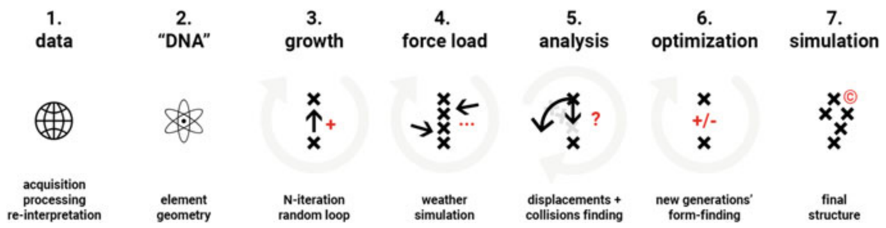

Fig. 2 Scheme of the proposed form-finding method

pavilion, depending on the external conditions. The digital form-finding workflow utilizes the AAD tool Grasshopper for Rhino, and the process is divided into seven phases (Fig. 2):

Data

Weather data pre-processing and reinterpreting through *Anisoptera*[1] Python scripts. Formulas based on specific weather data are implemented into the form-finding process.

'DNA'

Weather data as a form-finding factor forming the architecture's DNA (specifications) in Grasshopper.

Growth

A random growth of the first 7 tensegrity (or other structural) units is enabled by incorporating the Loop plug-in for Grasshopper.

Force load

Material, structural, and geometric relations are integrated into the weather-driven form-finding through Karamba 3D for Grasshopper.

Analysis

Structural analysis is performed through Karamba 3D.

Optimization

Spatial optimization is achieved through Galapagos for Grasshopper.

Simulation

Employing Butterfly for Grasshopper, the wind flow affected by the proposed pavilion will be analyzed (see the Future work section).

[1] This Python-based script is employed in the form-finding process in Grasshopper and developed by the authors.

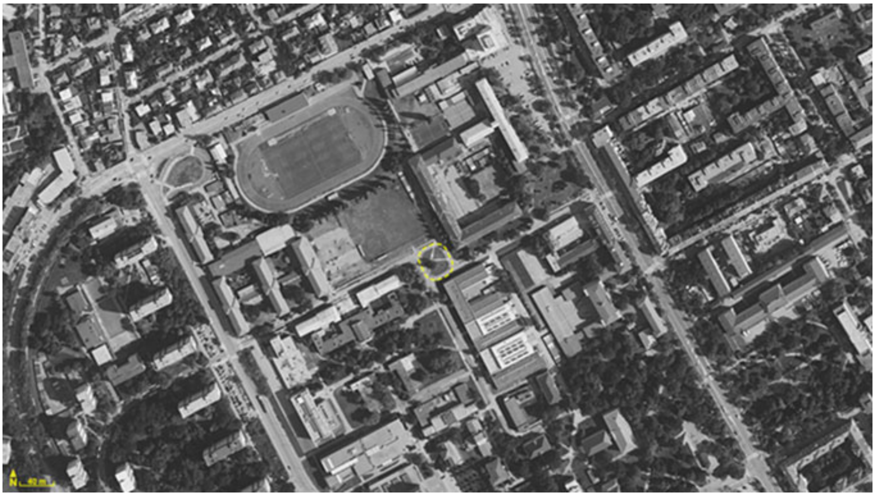

Fig. 3 Site satellite map (the roundabout is marked in yellow)

2.1 Weather-Triggered Form-Finding

The proposed form-finding method investigates the automation and autonomy of the architectural design through the design of the temporary tensegrity pavilion. The pavilion originates from the weather forces. Once created, it has the task of demonstrating the impact of dynamic weather changes and, functionally, creating a new space: a relaxation zone. Structurally, it consists of three ‘pillars’ resulting from three generations of growing tensegrity units. Each ‘pillar’ consists of 21 tensegrities. The pavilion complements Juraj Bartusz’s statue, located at the roundabout—a green island with a walkway crossroads in the TUKE campus (Fig. 3). Each ‘pillar’ is formed independently, and the whole process takes place autonomously using the Grasshopper environment coupled with Python scripts (*Anisoptera*). After the growth of the first generation with seven tensegrity units, the second and third generations follow on from their heritage.

Once constructed, the pavilion should passively (without using sensors) adapt its spatial configuration while redistributing the acting forces. The shape change results from the structural design based on retrospective weather data, impacting the structure as a Forming Force.

2.2 Data

The weather data acquisition took place at the meteorological station in Košice for the period from September 1, 2019 to March 20, 2022. In the form-finding process, data for the calendar year 2021 are used. The data contain information in a half-hour interval, and for the case study in question, selected measured quantities and parameters are considered.

First, the data must undergo conversion from a semicolon-delimited format to a final vector representing Forming Force for a given time slot. This transformation process is decomposed into three main components and two helper ones, developed within the new Grasshopper plug-in *Anisoptera* (not yet available online).

2.2.1 Data Processor (Component)

The Data processor takes a path to the.csv weather file as an input, reads it, creates lists of values corresponding to the given columns, converts units to desired ones, and finally outputs timestamps and all physical quantities needed. These include temperature (T), barometric pressure (p), dew point (DP), relative humidity (RH), wind speed (v), and wind direction (d). Unit conversions required were: millibar to Pascal, Fahrenheit to Celsius, and miles per hour to meters per second.

2.2.2 Filter (Component)

Inputs of this component are timestamps, physical quantities mentioned above, the starting time from which the desired interval starts, the ending time at which said interval ends, and one of the two parameters: the number of values or length of the interval in seconds. The starting and ending time is written in the following format dd.MM.yyyy HH:mm. The time slot is divided into n parts where n is equal to the number of values input parameter, or it equals ending time minus starting time, all of it divided by the length of the interval parameter. The median of each part for each of the corresponding physical quantities is computed and outputted in tuples (T, p, DP, RH, v, d). The list of these sextuplets is the filtered data output parameter.

2.2.3 Translator (Component)

The Translator component takes in the list of sextuplets (T, p, DP, RH, v, d), and the height for which it outputs Forming Force vectors (x, y, z) should be computed. X and y indices of the vector are calculated using standard linear algebra formula and represent the angle from the y-axis. Z index is equal to the vertical acceleration vv (Eq. 7). This vector is subsequently normalized and multiplied by the peak velocity pressure q_P (Eq. 1).

2.2.4 Accessor (Component)

The effect of this component is equivalent to the List Item from Grasshopper (getting an item at said index). However, the Accessor enables the user to change its implementation to get the desired output conveniently.

2.2.5 Iterator (Component)

The Iterator component passes the input value through and acts as the middleman between the Loop and Accessor.

2.2.6 Ignore (Component)

This is just an unimplemented component that does not take in nor output any parameters, and it is there just for ease of use of the second loop. The output of the whole first part of the workflow script and data processing is *Forming Force*. Equations 1–7 define it.

Formulas entering into data re-interpretation for Forming Force (Eurocode 1, 2010):

$$q_p(z) = [1 + 7 * l_v(z)] * \left(\frac{1}{2}\right) * \rho * v_m^2(z) \tag{1}$$

where

$q_P(z)$ is the peak velocity pressure at height z, which includes mean and short-term velocity fluctuations.

ρ is the air density, which depends on the altitude, temperature, and barometric pressure to be expected in the region during windstorms.

$$v_m(z) = c_r(z) * c_0(z) * v_b \tag{2}$$

where

v_m(z) is the wind velocity at height z above the terrain. It depends on the terrain roughness and orography and the basic wind velocity v_b (value from meteorological data).

c_r(z) is the roughness factor. It accounts for the variability of the mean wind velocity at the site of the structure due to the height above ground level and the ground roughness of the terrain upwind of the structure in the wind direction considered.

$$c_r(z) = k_r * \ln\left(\frac{z}{z_0}\right) for z_{min} \leq z \leq z_{max} \tag{3}$$

$$c_r(z) = c_r(z_{min}) for z < z_{min}$$
$$k_r = 0,19*\left(\frac{z_0}{z_{0,II}}\right)^{0,07} \tag{4}$$

where

z_O is the roughness length, for terrain category III, taken as 0.3 m.

k_r is the terrain factor depending on the roughness length z_O calculated using $z_{O,II}$ = 0.05 m for the terrain category II.

z_{min} is the minimum height defined for terrain category III, e.g., 5 m.

z_{max} is to be taken as 200 m.

$c_O(z)$ is the orography factor, taken as 1.0 because effects of orography may be neglected when the average slope of the upwind terrain is less than 3°. The upwind terrain may be considered up to 10 times the height of the isolated orographic feature.

$$l_v(z) = \frac{k_l}{c_0*ln\left(\frac{z}{z_0}\right)} for z_{min} \leq z \leq z_{max}$$
$$l_v(z) = l_v(z_{min}) for z < z_{min} \tag{5}$$

where

$l_v(z)$ is the turbulence intensity at height z and is defined as the standard deviation of the turbulence divided by the mean wind velocity.

k_l is the turbulence factor; the recommended value is 1.

σ_v is the standard deviation.

$$\rho = \frac{p}{R*T} \tag{6}$$

where

p is the air pressure.

T is the air temperature.

R is the constant 8.3143 J/(K.mol).

$$vv = g*\frac{(\rho_2 - \rho_1)}{\rho_1} \tag{7}$$

where

vv is the vertical acceleration.

ρ is the air density.

g is the gravitational acceleration, value in situ—for Východoslovenská lowland, it is 9.809508 m.s^{-2}.

The chosen calculation procedure includes the influence of several input parameters from the meteorological data, so we approach the actual wind behavior and its effect over time during the simulation.

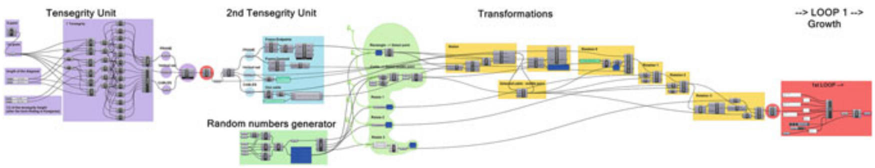

Fig. 4 The first tensegrity unit and the transformations necessary for creating the next one

2.3 'DNA'

The script workflow begins by defining the geometry of one tensegrity unit. The unit consists of a rectangular frame with a 0.5-m arm, a center vertical rod (with a length found within a short form-finding process through the Kangaroo Physical engine), and eight tendons connecting the corners of the frame with the vertical rod. The tensegrity unit prepared in this manner enters the growth loop to create the first generation of the resulting pavilion structure (Fig. 4).

The joints between individual tensegrity units are solved as spatially rigid. Mechanically, it is a firm snapping of the tensegrity unit frame to the tendons of another tensegrity unit.

2.4 Growth

The Loop procedure's recursive algorithm is provided within the *Generation2* plug-in for Grasshopper. The creation of one pillar takes place in seven iterations, with each iteration representing the growth of just one new element. The first and last components of the Loop are *Identity* and *Identity2*—from the *Anisoptera* plug-in, replacing the same type of output for the input of the following iteration. The input geometry is first redistributed into a frame, a vertical rod, and tendons to establish the 'DNA' of the pavilion—the rules of growing geometry—defined by the Euclidean transformations of each tensegrity unit. The principle of transformation is determinate (n + 1 element is attached by one of the corners of its frame to the center of one of the eight tendons of the nth element). The selection of corners and tendons is random, provided by a random generator—*Rnd* component, as is generating random values from the selected domain for individual transformations.

2.4.1 *1st Transformation*

The initial modification is the position translation ('*1st Transformation*'). The n + 1 element is moved by a translation vector determined by two points.

2.4.2 Anti-Collision Rotation

After the '*1st Transformation*' movement, the rotation of the n + 1 element is performed through the '*Anti-collision rotation*'. To avoid collisions between the elements, there is a rule applied. Implementing the if/then condition, the angle is either +45° or −45° to the previously randomly determined tendon.

2.4.3 *1st and 2nd Rotation*

In the case of the '*1st Rotation*' and the '*2nd Rotation*' of the n + 1 element relative to the nth, random rotation angles are determined. The intervals from −80° to + 80° were defined for the first generation of 7 tensegrity units, −60° to +60° for the second, and −40° to +40° for the third.

2.4.4 *3rd Rotation*

The 0–360° rotation of the consecutive element around its axis utilizing the '*3rd Rotation*' is the same for all generations.

After the last modification, the n + 1 element takes the place of the initial geometry in the Loop. The output parameter becomes the input parameter in the procedure loop for the growth of the n + 2 element (Fig. 5). All loop outputs are stored in the data *Store* container after each iteration.

After the end of growth, that is, after seven iterations, the whole structure is assessed from a static point of view, considering the interaction of all units and the

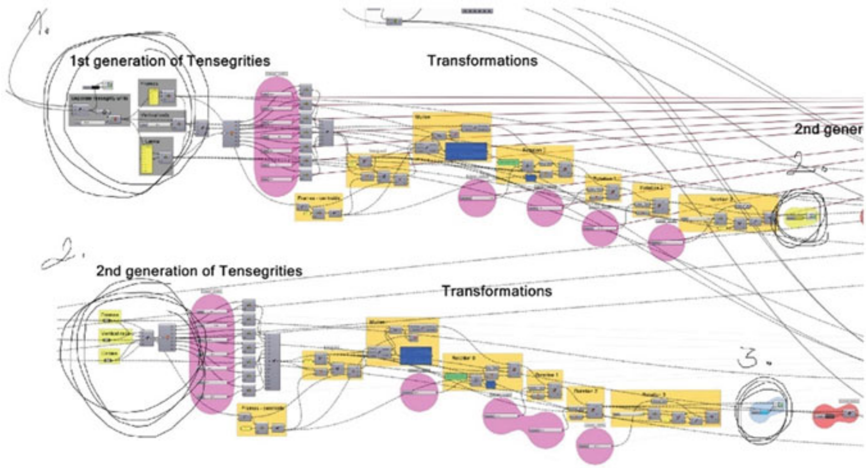

Fig. 5 The transformations within Loop 1 (growth loop)

influence of the weather loads. The system behaves as a rigid spatial cantilever stressed by all corresponding loads (gravity, tendons pre-tension, and Forming Force). The whole pavilion is a connection of three pillars, and thus the spatial rigidity of the entirety is ensured. As a part of future work, stretching a membrane over the entire structure is considered, leading to further structural optimization by removing the tendon elements and replacing them with the membrane.

2.5 Force Load

Within this part of the Grasshopper script, the second loop (Loop 2) is applied to simulate the weather effects. For the pavilion design, the load acting on the structure (seven elements of the first generation) is represented by Forming Force (explained in the section 'Data') resulting from the data for the period from 1.1.2021 to 31.12.2021 in 24-h intervals. Parametrically, we can set half-hour intervals and thus obtain denser, real-time data for assessment. That is, however, a subject of future research (and conditioned by the computer parameters). In the weather simulation loop, processed meteorological data appear, resulting in geometry (i.e., seven elements (1st generation), which is assessed using the parametric structural engineering tool Karamba 3D (explained in more detail in section 'Analysis')). Using the *Anisoptera* plug-in, specifically, *Iterator* and *Ignore* components, exactly one incoming vector from the generated list of Forming Forces is sent into the Loop 2 for each iteration with the initial loop component *Ignore (Anisoptera)* and the final *Analyze1* (Karamba 3D). The critical displacement value for the 1st generation structure is assigned to a specific Forming Force vector. The result gives Forming Forces based on the most unfavorable displacements for each month of the year. The Forming Force for April is the worst/most dangerous for the first generation, therefore the whole tensegrity pavilion is subsequently subjected to it (Fig. 6). The output of Loop 2 is the list of displacements for the assessed period.

2.6 Analysis

The assessment process in Karamba 3D has the individual tensegrity elements defined through specific material properties (CFRP (Carbon Fiber-Reinforced Polymer) struts and steel tendons), and cross-section parameters are assigned. Anchor points are connection nodes between elements.

In this case study, loads represent gravity, pre-tension of steel tendons, and wind force as Forming Force. The wind force is applied to nodes (elements' endpoints), considering the future shared load transfer between nodes and membrane. The Finite Element Method (FEM) is applied, and the 3D model is processed with *Analyze* (Karamba 3D), which calculates the deflections of a given geometry using first-order

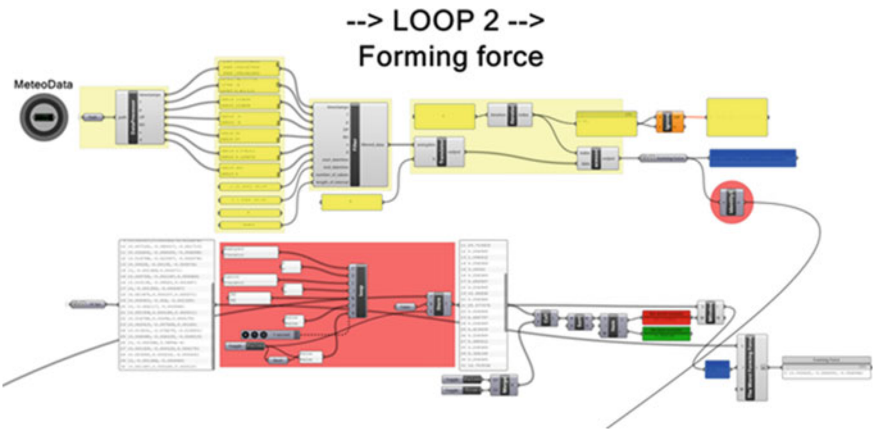

Fig. 6 The workflow of Loop 2 (weather simulation loop) producing the Forming Force

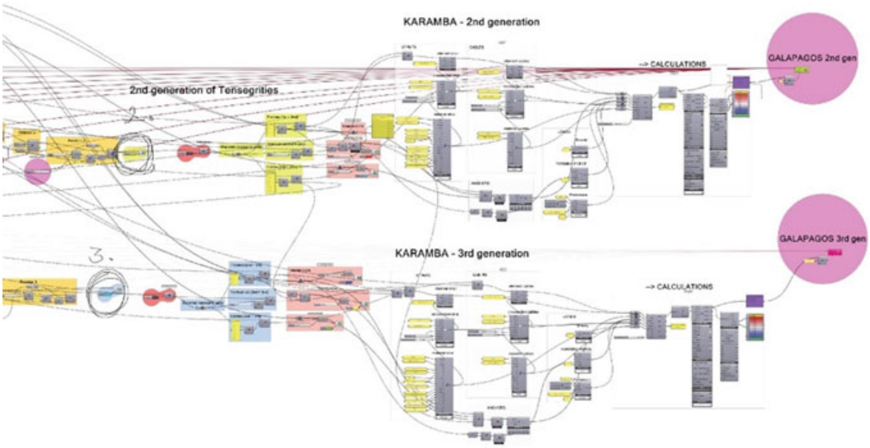

Fig. 7 The Karamba 3D structural analysis and Galapagos optimization of the 2nd and 3rd generation

theory. As a part of the weather simulation loop, we find the maximum displacement of the geometry due to the acting Forming Force (Fig. 7).

2.7 Optimization

The growth of the second and third generations of elements is carried out through optimization with the Euclidean transformations in four steps, i.e., *1* × *Move* +

3 × *Rotation*). However, there is no random selection of motion vectors and rotation angles but employed optimization process via evolutionary solver Galapagos (see Fig. 7), working with the Coupling and Coalescence algorithms. The solver seeks the optimum (trying to converge to the global optimum). Genetic algorithms are stochastic optimizers and rarely converge to absolute optimality. The algorithm seeks a feasible solution to minimize the fitness function (the displacement of the whole structure). To select the tendons on which new elements are placed and to determine rotations, optimization takes place in 50 generations considering the *Fitness*—minimum displacement. The spatial optimization process is applied to the second and third generations of tensegrities and is dependent on the magnitude and direction of the acting Forming Force. Displacement of the designed structure is the output of the Karamba 3D analysis. The optimization stopped after the predetermined number of iterations with two local optima found. The maximum displacement of the form-found structure is around 6.5 mm.

Although the presented approach refers to pure structural optimization, it is assumed in this paper that the optimization in the framework of structural engineering assessment entwined with the acting weather influences is crucial shape-defining criteria determining the visual appearance of buildings. Considering the subtlety of the tensegrity structure, other formative events can be here disregarded.

2.8 Simulation

This step will be performed in the next project stages. The final structure consisting of three 'pillars' growing throughout 3 generations will be assessed by Computational Fluid Dynamics (CFD) simulation through the OpenFOAM-based plug-in Butterfly for Grasshopper. If CFD improves the location's wind comfort, it means approved design and the whole form-finding process is finished, ensuring the structure can withstand worst-case loading scenarios.

3 Results

A digital form-finding method introduced in this paper is based on the principles found in nature. It consists of random growth of the emerging architecture and finding the best fitting structural solution under given weather characteristics. The form-finding process confirms the ability of the optimized structure to effectively distribute the loads caused by the average wind flow during April, which causes the highest loads on the pavilion. The result is an architectural performance through weather conditions, demonstrating the power and naturality of ambient influences (Fig. 9).

The proposed experimental form-finding method is demonstrated on a pavilion with its shape affected only by external factors. Nevertheless, the design method can be also employed for creating existing building extensions, where the influences of

Fig. 9 The visualization of the tensegrity 'pillars' forming the 'Weather Pavilion'

the interior environment of buildings and the corresponding parameters are already considered.

3.1 Pros of the Method

- Entwining architecture, structural engineering, meteorology, programming, and wind performance assessment into architectural digital form-finding. An interdisciplinary weather-based design approach is a result.
- Optimization of the structural performance of architecture and its response to the environment through multiple generations, resembling the principles in nature. Best-fitting solutions are the outcomes.
- Considering local meteorological data in the design. Half-hourly intervals can be used to affect the emerging structure. That leads to nature-adaptive architecture.
- Considering the cumulative effect of weather parameters on architectural and structural performance: temperature (T), barometric pressure (p), dew point (DP), relative humidity (RH), wind speed (v), and the wind direction (d). All are jointly considered during the conceptual design phase.
- New Grasshopper components are developed for weather-driven designing. The designed plug-in named *Anisoptera* could be further enhanced and later freely available for Grasshopper users.

3.2 Cons of the Method

- The *Anisoptera* components are not yet available online, and there is no fixed date on the release.
- At this point, the computational power of conventional personal computers limits the amount of weather data that can be processed and the size of the structure that can be optimized. Hence, only three generations of tensegrity structure were designed and evaluated.

3.3 Future Work and Possible Further Applications of the Method

- The real-time adaptability of the pavilion. The responses of the structure to the real-time weather changes. If performed through other than the passive adaptation principle, this would require sensors and computer-controlled geometric modifications. The shape change depends on the information obtained from sensors.
- The pre-real-time adaptability (shape change) of the pavilion. Based on the forecasted weather, the pavilion might change its shape every hour/half hour. Here is a parallel to the reaction/behavior of animals to perceived danger (threat).
- The 'skin' of the pavilion. Design, material-finding, and form-making of the pavilion's 'skin' as a multipurpose tensile membrane responding to the climate in real time. The thermoregulation of the human body can be an inspiration. When overheated, the skin dilates the vascular capillaries, distributing heat to the skin, on which sweat begins to form, cooling the skin. Moreover, the pavilion skin (membrane) might respond to humidity, temperature, and pressure with changing porosity and topographic surface changes. In addition to these properties, the membrane will participate in the transmission of wind loads and, fused with the three 'pillars', respond as one compact and interrelated structure.
- CFD (Computational Fluid Dynamics) analysis. The simulations through Butterfly for Grasshopper will determine which one of the structurally optimized tensegrity pavilion designs will provide the best outdoor wind comfort for pedestrians. The structure will be simulated with the employed 'skin'.

4 Conclusion

The vision of this paper is that the weather, an invisible force that affects the durability of a building and determines its structural requirements, becomes an architectural form-finding element. The nature-inspired form-finding method is introduced through a case study tensegrity pavilion in Košice, Slovakia. Sensing the local environmental conditions, the pavilion's structure and shape grow, adjusting the emerging form to varying weather factors: wind speed and direction, temperature, air pressure, dew point, and relative humidity, and consequently increased acting loads. These loads (the decisive factor is the influence of the wind) are represented by the Forming Force affecting the tensegrity-like structure of the pavilion. The whole concept of the pavilion is bio-inspired. The developed Grasshopper algorithm, through the iterative loop and employing components of the new plug-in *Anisoptera* blended with well-known tools such as Karamba 3D and Galapagos, searches for the optimum structural configuration concerning the actual input weather data. This climate-collaborative approach is a meticulously described procedure of designing an almost self-finding shape toward a harmonious state. First, the pavilion's fundamental structural tensegrity element is defined, the attributes are assigned, and the topology is determined. In the digital form-finding process, the form of the pavilion gradually emerges and progresses in its functional behavior and structural control.

The resulting shape of the 'Weather pavilion' is generated autonomously with a minor intervention from the architect. Hence, the subjective opinion or prejudice (human factor) does not interfere with the natural design process (evolution). This case study does not aim to dehumanize architecture, the contrary. It fuses the architect's experiences and design skills with new possibilities that help streamline the design process leading to unexpected results.

The work carried out in this phase is reduced almost exclusively to a methodology for optimizing the structural design, however, the method proposes a formal, explicit, and automatic creation of architecture merged with a geometric optimization process, which is not the traditional one in structural engineering or architectural practice.

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Modelling the Relationships Between Ground and Buildings Using 3D Architectural Topological Models Utilising Graph Machine Learning

Abdulrahman Alymani, Wassim Jabi, and Padraig Corcoran

1 Introduction

The built environment may be considered a collection of three-dimensional (3D) elements that are typically topologically connected. This may be represented by a graph of connected vertices and edges, where a vertex represents an element, and an edge represents the relationship between two or more adjacent elements. One of the crucial relationships that architects and urban designers must acknowledge and analyse is the connection between a building and its surrounding ground (Berlanda, 2014; Porter, 2015, 2017). Understanding this building/ground relationship is inherently a geometrical and topological problem. Computational/algorithmic methods may assist the process and reflect on both geometry and their associated topological graphs using combinational logic.

The principal distinction between geometry and topology is that the latter abstracts away the concepts of form and physical distance yet retains the notion of connectivity. Consequently, complex designs may be identified more efficiently and analysed at far higher levels of abstraction than would be possible solely through geometry (Jabi, 2015). Prior published research has illustrated the ability to capture several 2D photographic image snapshots of 3D models, after which they are matched to an image-based query (Kasaei, 2019; Sarkar et al., 2017) (see Fig. 1). Nevertheless, these approaches do not comprehensively capture the 3D and topological information embedded in the data.

Even if 3D datasets are available, it may prove challenging to recognise them because of their varied formats in terms of appropriateness, usability, and licencing. To address these shortcomings, this paper concentrates on methods from a recent branch of Machine Learning, called Graph Machine Learning (GML), which can

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Fig. 1 Most machine learning systems rely on 2D pixel-based image recognition

classify an entire graph, predict node properties or predict inter-node connectivity. Several studies have investigated this GML promising approach (Kriege & Mutzel, 2012; Orsini et al., 2015; Vishwanathan et al., 2010). Nevertheless, numerous strategies have been hindered by the fact that they must break graphs down into smaller substructures, called paths and walks, then draw similarities based on a summary of the graphs' characteristics. Such restrictions are circumvented by DGCNNs, which categorise graph-based information using end-to-end deep learning (Zhang et al., 2018).

It is pervasively acknowledged that Machine Learning models require extensive data for training. Therefore, this paper proposes a novel proof-of-concept workflow in the generation of a sizeable synthetic dataset with embedded semantic information for 3D prototype building. Relationships were encoded using a software programme known as Topologic, which is underpinned by graph theory.

The proposed workflow focuses on enhancing the representation of 3D models based on non-manifold topology (NMT) and embedded semantic information, which may be adopted in relation to different Machine Learning models. The process is initiated by using shape grammars (Stiny, 1980) to create a building/ground relationship grammar rule. Subsequently, a formal mechanism for defining languages used in 3D spatial designs is established. During the next phase of the process, the Topologic software library automatically and generatively creates a large synthetic dataset of building/ground precedents. Following this, the models are labelled and transformed into topological graphs, comprising comprehensive semantic data that are then passed on to a Graph Machine Learning system.

The remainder of this paper is organised as follows. Section 2 summarises the historical architectural approach of the building and ground relationship as well as the Toma Berlanda taxonomy of how the building meets the ground. Section 3 presents an overview of the Graph Neural Network and discusses several studies that implement GML in the architectural discipline. Section 4 provides an overview of NMT and discusses the Topologic toolkit. Section 5 describes the methodological steps in detail. Section 6 lists the shape grammar (rules) for generating architectural precedents for building/ground relationships. Section 7 shows the experiment's architectural precedents iterations. Section 8 reports on the predictive model's accuracy, alongside a validation of the DGCNN model with predicting the types of new unseen examples of architectural building/ground relationships. Finally, Sect. 9 concludes by reflecting on the advantages and disadvantages of generating a sizeable synthetic dataset with embedded semantic topological graphs as a formal design method, alongside an outline of prospective future work.

2 Motivation

It is imperative that digital aids assist architects in identifying building performance characteristics at the earliest stage of design for them to make informed design decisions. It can be expensive, time-consuming and error-prone to perform this task manually. As a result of this framework, similar precedents can be introduced into the design process, so that designers can estimate the performance consequences of their decisions quickly. Building classification has so far relied on 2D visual representations of building features. By using only pixel images, the system is unable to utilise 3D information. In contrast to 2D pixels, topological graphs do not require the encoding of 3D models because they are not constrained by 2D pixels. A key takeaway of this paper is that the ground should be considered at the earliest possible design stage before the complexities and rigidities of a fully developed building information model (BIM) take hold.

3 Building and Ground Relationship

> Before placing stone on stone, man placed a stone on the ground to recognise a site in the midst of an unknown universe, in order to take account of it and modify it (Vittorio, 1982).

According to this quote from Vittorio, discussions in architecture have occurred concerning the building and ground problem for a very long time. Thus, this research commenced by investigating how the relationship between the building with the ground is prefigured, through a reading of extant theoretical texts and monographs. The historical framework considered is the last 100 years, from the beginning of the modern period until the contemporary period. Berlanda describes this particular historical period as:

> The modern movement until the dissolution of disciplinary boundaries between architecture and landscape architecture, whereas the field of investigation expanded over different geographical and cultural areas (Berlanda, 2014).

Technology now permits architects to use materials and load-bearing structures without a requirement for traditional foundation platforms. Furthermore, technology

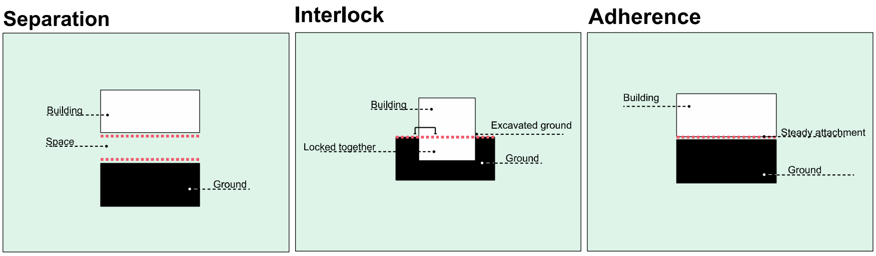

Fig. 2 Main building and ground relationship categories

now provides inexpensive means of moving the earth and altering its configuration. Accordingly, a wider vocabulary has become more common to objectify the noun "ground", for example, *raised*, *stacked*, *carved* and *exposed*. Adjectives have extended the meaning of adjustments by architecture, to include both building and ground. Nevertheless, all types of relationships with the ground may be derived from the initial categories, which are interlock, adherence as well as separation (Berlanda, 2014).

According to the Toma Berlanda lexicon, the current building/ground relationship taxonomy may be distinguished into three main categories, namely, separation, adherence and interlock. Additionally, the building touches the ground via different categories: grounded, ungrounded, foundation, plinth, artificial ground as well as absence of level. The building's relationship with the terrain is further defined according to topography, landing and grounding as well as strata and earthwork-landform. Finally, the metaphorical relationship involves feet on the ground, anchoring, roots and clouds (see Fig. 2).

4 Graph Neural Network (GNN)

GNNs can be adopted to focus on one or more graph analytics tasks, based on the graph structure and node contents as inputs (Wu et al., 2019): node-level tasks, edge-level tasks and graph-level tasks. In an end-to-end learning framework, GNNs (for example, ConvGNNs) can be trained in *supervised*, *semi-supervised* and *unsupervised* ways, depending on the learning task and available label information (Wu et al., 2019). In this study, we adopted *supervised* learning for graph-level classification. Classification at the graph level aims to predict an entire graph's class label. For this task, end-to-end learning may be achieved through combining graph convolutional layers, graph pooling layers and/or readout layers. In contrast to graph convolutional layers, graph pooling layers serve as down-sampling layers, because they coarsen each graph into a substructure over time. In a readout layer, node representations are collapsed into graph representations. An end-to-end framework for graph classification can be constructed by applying a multi-layer perceptron and a SoftMax layer to graph representations (Ying et al., 2018; Zhang et al., 2018) (see Fig. 3).

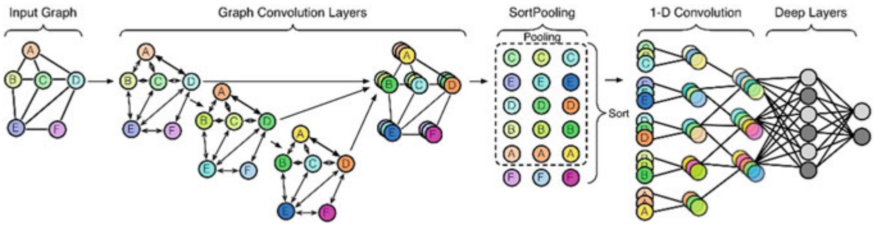

Fig. 3 The general structure of DGCNN (after Jabi & Alymani, 2020; Zhang et al., 2018)

4.1 Application of Graph Machine Learning in Architecture

Numerous GML have been used in the architectural field. Eisenstadt et al. proposed a workflow to apply deep learning techniques to architectural design problems during the early design phase as a means of enabling auto-completion of unfinished designs. Their paper addressed the challenge of transforming semantic building information into a tensor format that libraries can interpret. Eisenstadt et al. focussed on sharing information regarding the type of rooms within a building and the type of connections between them. Their adopted methods first involved converting the original floor plan and its Semantic Building Fingerprint (SBF) into a multi-layer map, one-hot encoded map and a textual map. Subsequently, classification was performed to evaluate all three approaches. Their results evidenced that the model could process and comprehend the latent structure of the select relation map types and the data they contain (Eisenstadt et al., 2021).

Lu et al. proposed a novel synthetic workflow for synthetically generating room relation graphs from structured architectural datasets. They presented a method for decomposing vectorised floor plans to generate the intended organisational graph for further graph-based deep learning. The workflow aims to synthesise a graph representation of the room relations in structured floor plan data, by extracting geometric information from it. Applying this contribution, future research can train neural networks on enhanced floor plan parsing, analysis and generation (Lu et al., 2021).

4.2 Topologic

Jabi (2015, 2016) have investigated a novel method of 3D modelling, namely, non-manifold topology (NMT), which has the potential to be highly compatible with early design stages and input requirements for building performance simulation (BPS). Jabi proposed an approach where BPS may be performed entirely without simplifying polyhedral models produced by BIM software. Their results demonstrate that NMT holds significant potential for representing building surfaces and spaces in a manner that allows future conversion into detailed BIM models and for conducting building performance simulation. In conjunction with NMT and a versatile 3D software environment, architects may adopt a more topological approach to design and analyse the performance of buildings during the initial stages of development by adopting simple 3D massing models that enable design creativity and flexibility to be maintained.

Jabi et al. (2018) also demonstrated the potential of Topologic for preparing structural analysis. Topologic Structure permits users to build structural models and rapidly apply structural loads. Using a list of vertices and indices, Jabi constructed a topological shape and applied structural loads. The method adopted for creating a model was achieved by using an array of vertices and a list of vertex indexes, defining a list of locator points, then applying varied structural loads to these sub-shapes. Resultantly, the topological model is highly compatible with the requirements of structural analysis software.

5 Methodology

This paper's experimental workflow adopts two primary technologies. The first is Topologic, a library that enhances 3D model representation by embedding semantic information into non-manifold topologies. The second is an end-to-end DGCNN, enabling the machine to learn the classification and prediction task. The experimental workflow involves two stages. The approach begins with a system that generates 3D models of architectural precedents with topological building/ground relationship variations. Topological and semantically rich dual graphs were derived from the architectural precedent's geometric models. Subsequently, the dual graphs were imported into DGCNN to classify the building/ground relationship topology. After running the DGCNN, eight new scenarios were tested to validate the workflow (see Fig. 4).

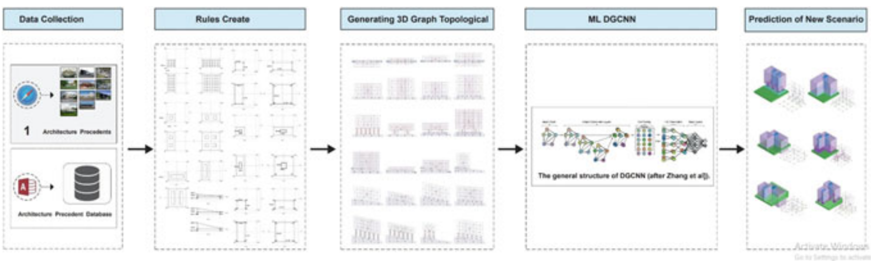

Fig. 4 Flat Ground (FG) generating rules

6 Generating the Building/Ground Case Study (Rules)

During this stage, we used the 3D modelling software 'Rhinoceros 3D' and the plugin 'Grasshopper' to create the building/ground relationship dataset using a computational prototypical design ('building/ground relationship pattern'). This computational design prototype is derived from the collected architectural data. In this section, the data collection is divided into two forms, based on their relationship with the ground. This relationship with the ground can be generalised into two forms, namely, Flat Ground (FG) and Sloped Ground (SG).

6.1 Flat Ground (FG)

1. **Ground (G)**: The ground plate is fixed at 14 × 14 m, with a fixed height of 1 m (see Fig. 5).
2. **Plinth (P)**: The plinth dimensions are then calculated to be a certain percentage of the ground plate with equal offsets. The plinth can be 80%, 40% or 20% of the ground area. However, the plinth height is fixed at 1 m (see Fig. 7).
3. **Building (B)**: The building geometries are then placed with appropriate offsets and spacing. The building width is varied, following the plinth dimensions. The height of the building is varied, although all buildings maintain the maximum equivalent height of 9 m. The building height could be one, two, or three floors (see Fig. 6).
4. **Columns (CL)**: For the separation relationship, the columns exist to separate the building from the ground. The columns are diverse with three forms: small, medium and large. All columns are set within the building and plinth dimension. The columns' height is also diverse at one, two or three metres (see Fig. 9).
5. **Core (CO)**: The core is added to the central area of the building geometry. The core has a fixed ratio from the building area of 1:9 (see Fig. 8).
6. **Subdivision**: The building geometries are subdivided internally into a grid of cells.

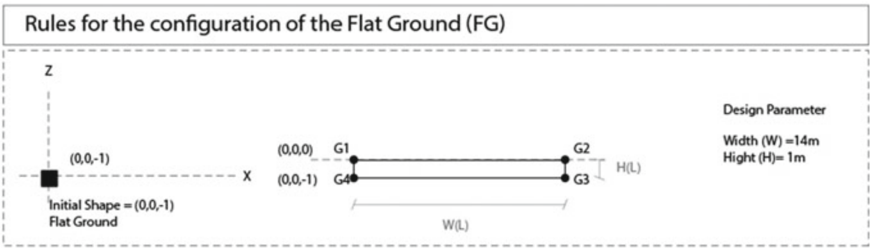

Fig. 5 Flat Ground (FG) generating rules

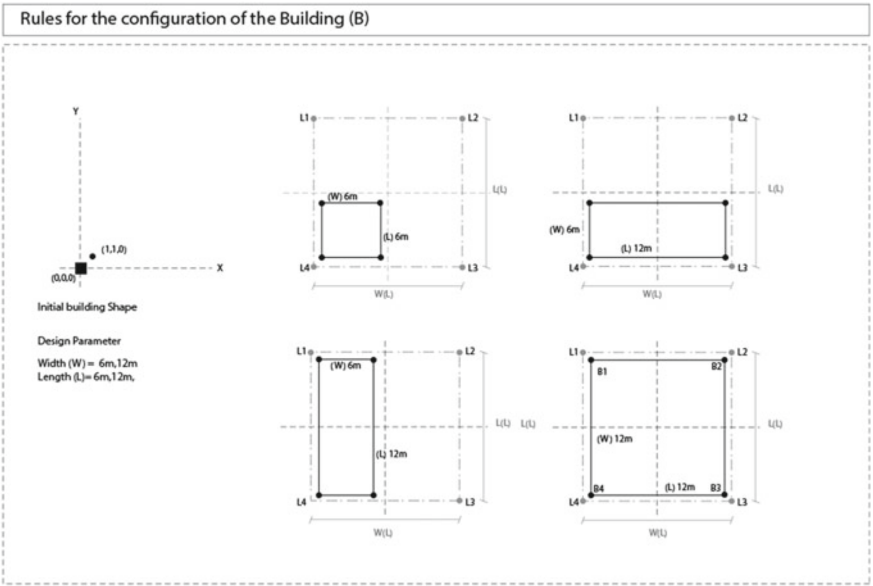

Fig. 6 Building (B) generating rules

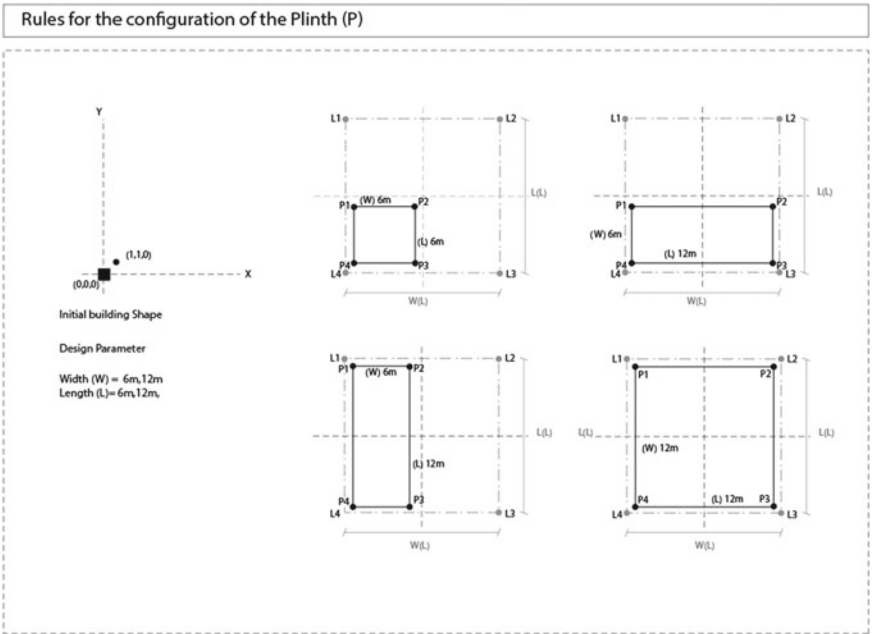

Fig. 7 Plinth (P) generating rules

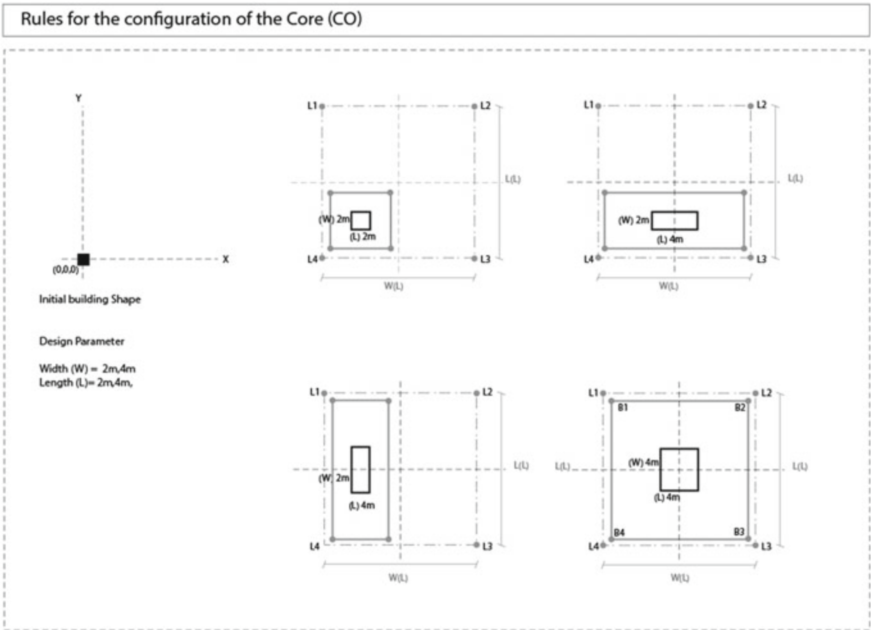

Fig. 8 Core (CO) generating rules

6.2 Sloped Ground (SG)

1. **Ground**: The ground plate is varied. One ground plate edge is fixed, with the opposite side being changeable to three heights: 2-unit, 3-unit and 4-unit (see Fig. 10).
2. **Plinth**: The plinth dimensions are then calculated to be a certain percentage of the ground plate, with equal offsets and similar slope.
3. **Building and Columns**: The plinth, building and columns have exactly similar rules and iteration as mentioned in relation to the flat ground.
4. **Core (CO)**: The core is added to the central area of the building geometry. The core has a fixed ratio to the building area of 1:9.
5. **Subdivision**: The building geometries are subdivided internally into a grid of cells.

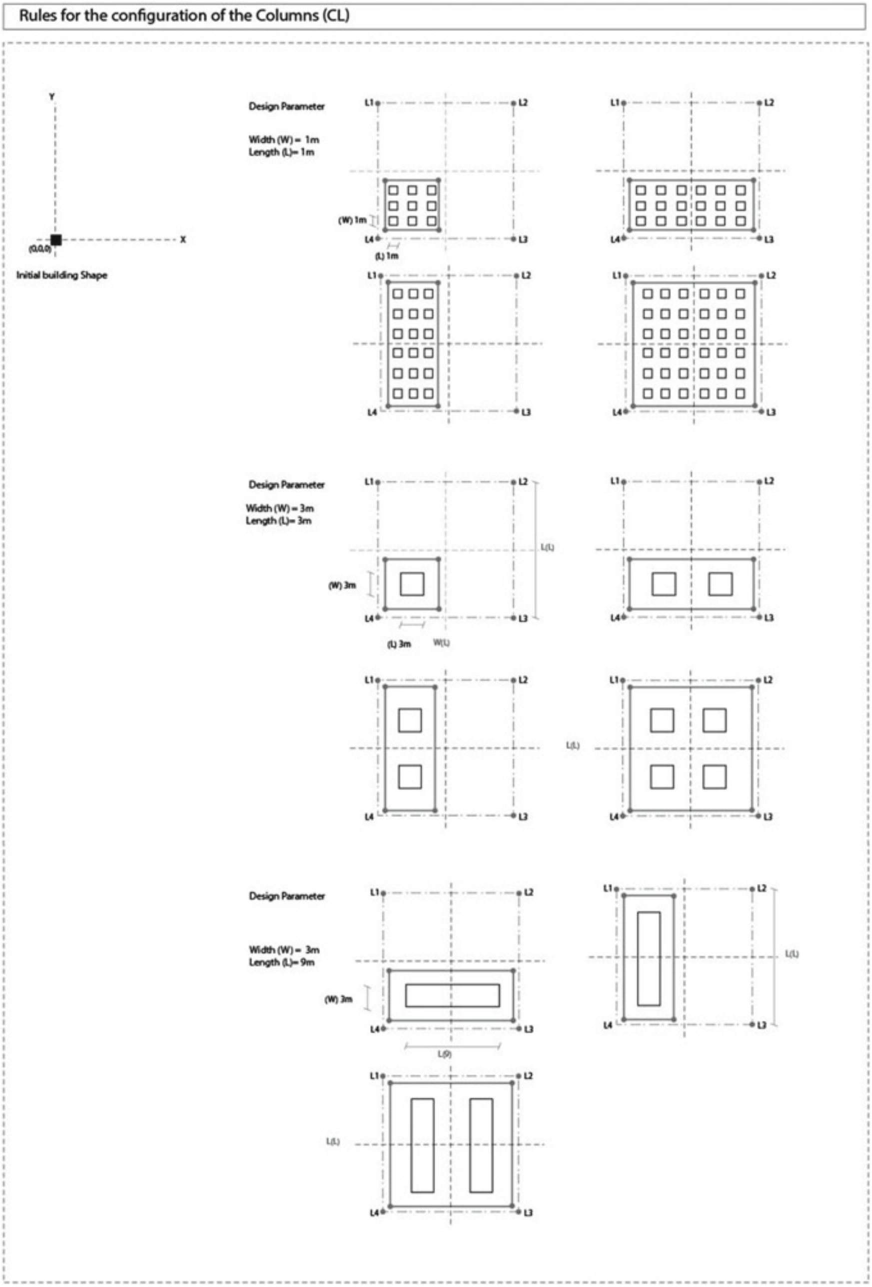

Fig. 9 Columns (CL) generating rules

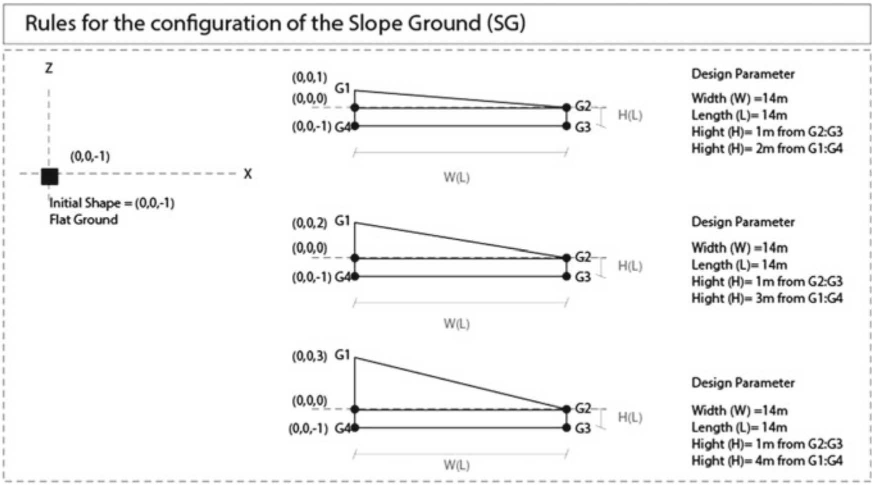

Fig. 10 Flat Ground (FG) generating rules

7 Generating the Building/Ground Case Study (Iteration)

7.1 Flat Ground (FG) Iteration Form

The flat ground has three types of relationships, namely, separation, adherence and interlock. In total, 240 iterations were produced in this section. For separation, the building columns either on a plinth or set directly on the ground. Regarding the adherence iteration, the building may be either on a plinth or can be set directly on the ground. This creates another approximately 24 iterations. Finally, for the interlock iteration, the building can have one unique form to integrate with the ground, producing a further 36 iterations (see Fig. 11).

7.2 Sloped Ground (SG) Iteration Form

The sloped ground has three types of relationships, namely, separation, adherence and interlock. In total, 684 iterations were produced in this section. Regarding separation, the building columns can be either on a plinth or set directly on the ground. This formed 540 building/ground separated relationship iterations. Concerning adherence, the building may be either on a plinth or set directly on the ground. This creates approximately 72 iterations. Finally, for the interlock iteration, the building has one unique form to integrate with the ground, which produces another 72 iterations (see Fig. 12).

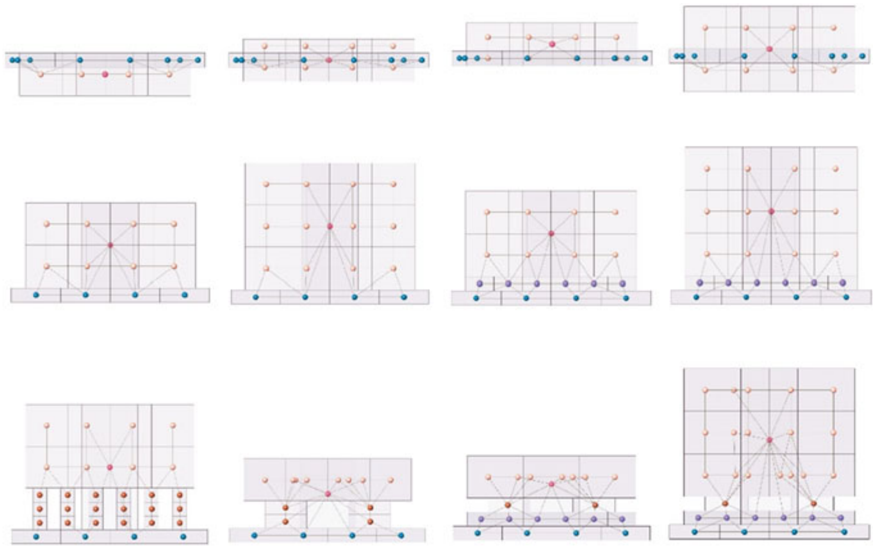

Fig. 11 Sample of automatically generated building/ground typologies for Flat Ground (FG)

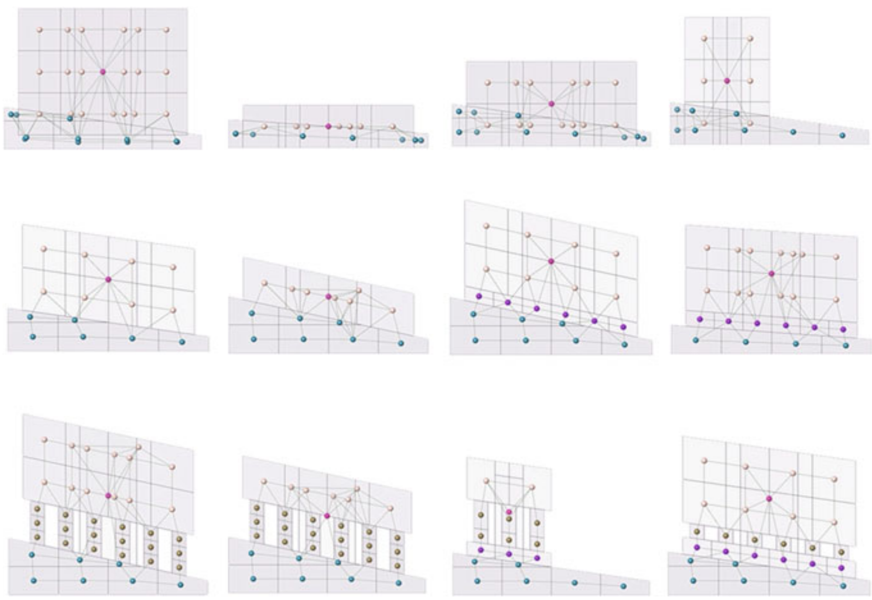

Fig. 12 Sample of automatically generated building/ground typologies for Sloped Ground (SG)

8 Experimental Results

Originally, the experiment dataset comprised of three sections, namely, training, validation and testing. Among the 900 graphs, 35% were for training, 35% were for validation, while a further 30% were for testing. A laptop computer running the MacOS Catalina 10.15 operating system, powered by a Quad-Core Intel Core i7 CPU running at 2.7 GHz with 16 GB of memory, was used to run all experiments. PyTorch was adopted to deploy DGCNN.

8.1 Deep Graph Convolutional Neural Network (DGCNN)

In a previously published paper, the following default parameters were adopted to set up the DGCNN, which were largely retained throughout this experiment. These unmodified parameters were as follows:

- Decay parameter: The largest power of 10 that is smaller than the reciprocal of the squared maximum node degree.
- Sorting Pool k: Set such that 60% of the graphs have more than k nodes.
- Two 1-D convolutional layers. The first layer has 16 output channels with 2 filter dimensions and a step of 2. Having 32 output channels, the second 1-D convolutional layer has a filter size of 5 and a step size of 1.
- The dense layer is followed by a layer of SoftMax output, followed by 128 hidden units.
- A 0.5 dropout rate is applied at the end.
- DGCNN uses a nonlinear hyperbolic function (tanh) in the graph convolution layers as well as a rectified linear unit (ReLU) in the other layers. DGCNN does not use validation set labels for the training.
- For optimising the neural network parameters, the Adam optimiser was adopted.

To tune the hyperparameters, 630 graphs (70% of the training and validation data) were used. Several hyperparameters were varied to enhance performance, including the number of epochs, the learning rate as well as batch size similar to Jabi and Alymani (2020). According to our previous experiment result (Alymani et al., 2022), the optimal performance model was saved and tested on the test data. The model parameter was as follows: the number of epochs was 200, the learning rate was 1–e5 and the batch size was 1. The model achieved 96.7% accuracy with 0.129 loss (see Figs. 13 and 14).

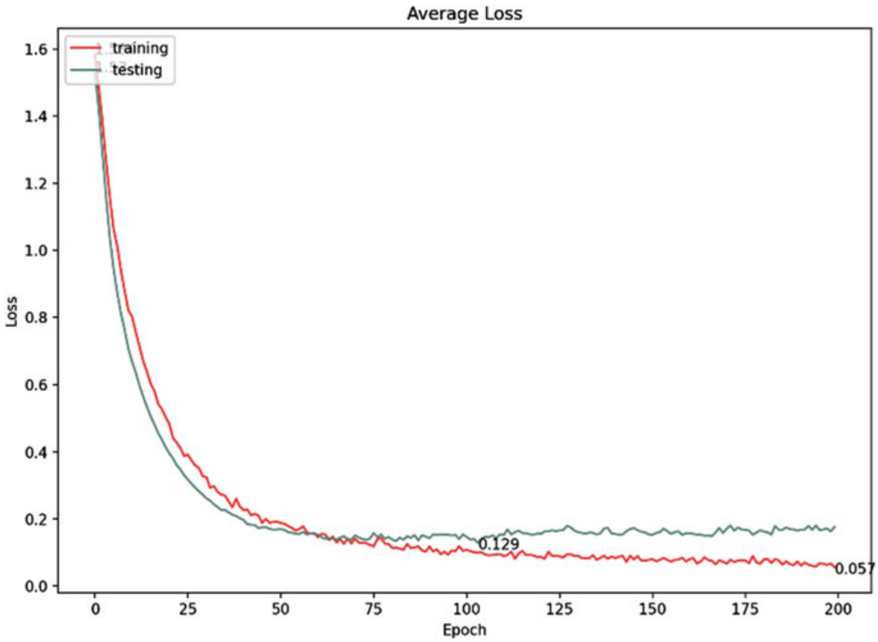

Fig. 13 Best DGCNN model average loss

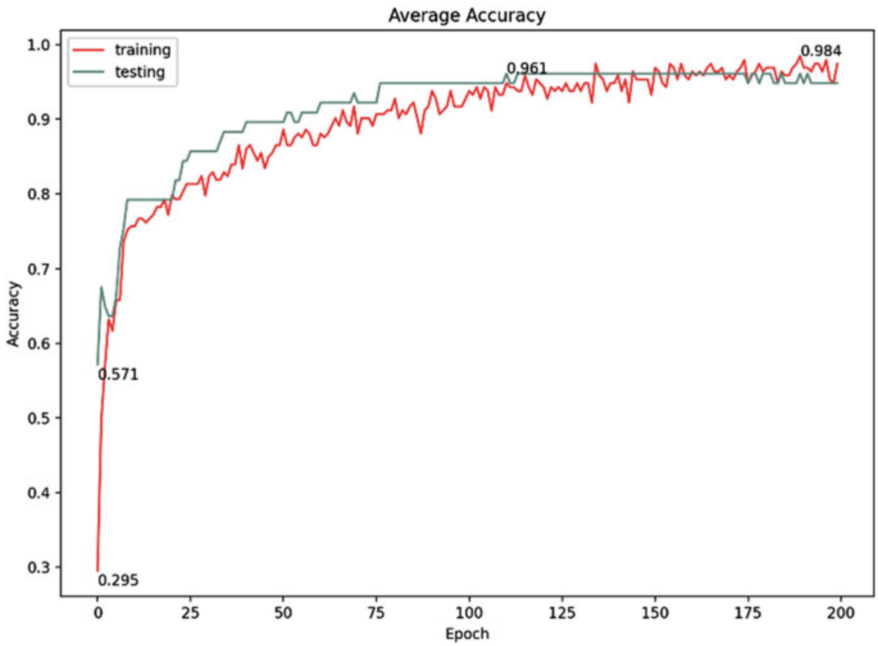

Fig. 14 Best DGCNN model average accuracy

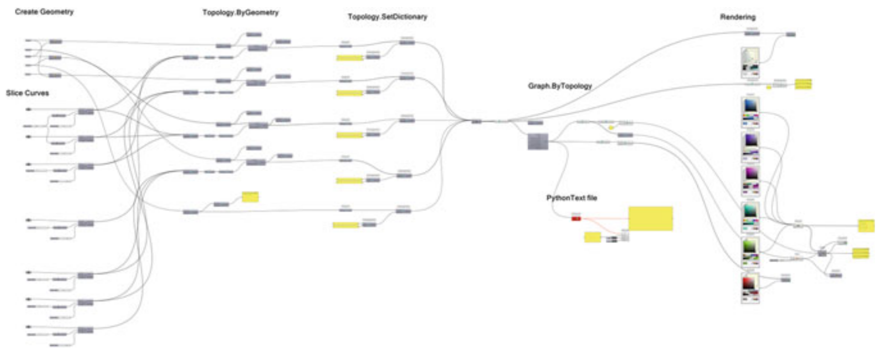

Fig. 15 Grasshopper definition to create new building/ground scenarios

8.2 Prediction of New Building and Ground Relationship Scenario

Following the training and validation of the DGCNN, the best-trained model was saved. We created a set of new test scenarios that were not part of the data used to build the DGCNN model, using a Grasshopper definition (see Fig. 15). The new design considers several new building and ground precedents. The new scenario applied similar rules and similar nodes categories, although these new precedents adopted different approaches to the ground.

The eight new architectural precedents were conducted and fed into the best-saved model. The first four scenarios were designed on flat ground (FG). However, the four additional scenarios were designed on sloped ground (SG). Despite all scenarios having different topological elements compared with the trained ones, all eight new scenarios were predicted successfully.

Scenario No.1 (see Fig. 16) has two cores, with the models not being trained to classify the two cores' topology; the DGCNN predicted this case as separation with plinth 100% true. Regarding scenario No. 2 (see Fig. 16), the model has an L-shaped building, which is not pre-trained to classify this topology. Even so, the model successfully predicted the building/ground relationship as adherence with a plinth with 54.6% accuracy. Scenarios No. 3 and No. 4 (see Fig. 17) had two buildings at different height levels from the ground, with both being successfully classified as separation and interlock with 99.5% and 100% accuracy. In Scenario No. 5 (see Fig. 18), the two buildings have a different interlock level with the ground, with the case predicted successfully with 95% accuracy as interlock. In Scenario No. 6 (see Fig. 18), the columns are set into the sloped ground. The two buildings are separated from each other, and the model was not previously trained. Nevertheless, the model successfully predicted the new precedents with 70% accuracy. In Scenario No. 7 (see Fig. 19), the plinth followed the ground's slope, with the model predicting the case with 95% accuracy. Finally, in Scenario No. 8 (see Fig. 19), the building dips completely underground and the model predicted this case with 85% accuracy.

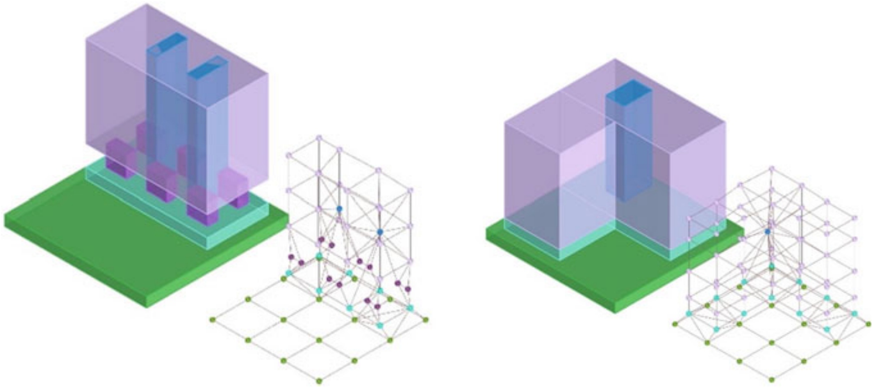

Fig. 16 Scenario No. 1 (left), Scenario No. 2 (right)

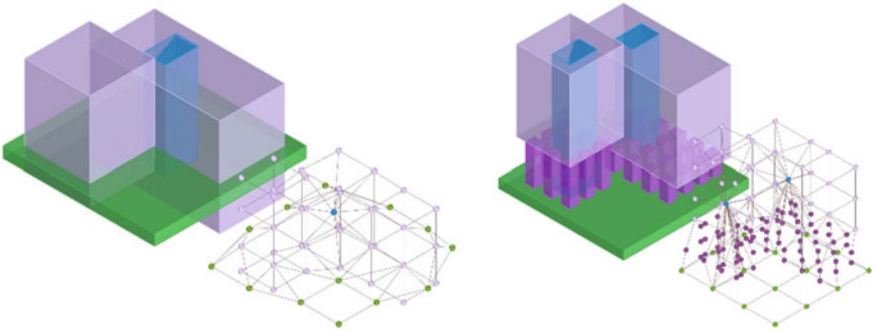

Fig. 17 Scenario No. 3 (left), Scenario No. 4 (right)

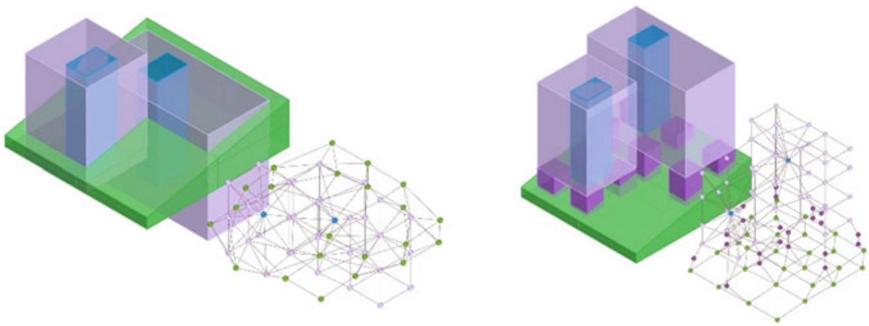

Fig. 18 Scenario No. 5 (left), Scenario No. 6 (right)

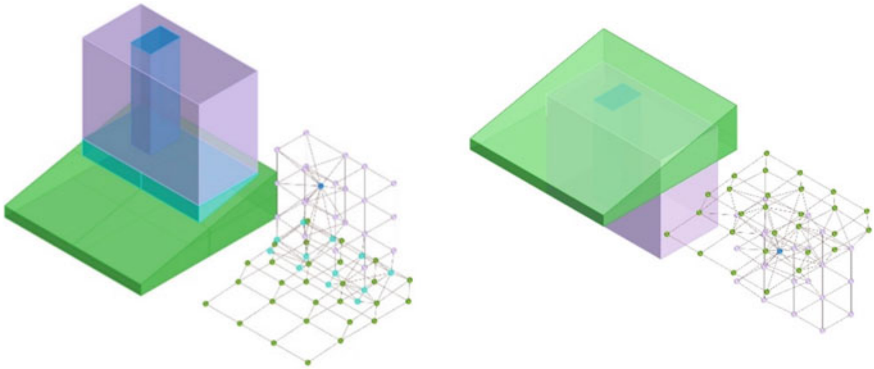

Fig. 19 Scenario No. 7 (left), Scenario No. 8 (right)

No. of scenario	Class 0	Class 1	Class 2	Class 3	Class 4	Prediction true/false
	Separation (%)	Separation with plinth (%)	Adherence (%)	Adherence with plinth (%)	Interlock (%)	
1	0	**100**	0	0	0	True
2	0	0	0	**54.6**	43.4	True
3	0	0	0.05	0	**99.5**	True
4	**100**	0	0	0	0	True
5	0	0	5	0	**95**	True
6	**70**	30	0	0	0	True
7	0	0	5	**95**	0	True
8	0	0	15	0	**85**	True

9 Conclusion

Through a novel workflow using 3D graphs rather than 2D images, this paper applied machine learning to classify architectural topology forms. With assistance from a topology-based 3D modelling environment, we were able to automatically generate dual graphs from 3D models. Subsequently, those graphs were exported to a state-of-the-art deep learning graph convolutional neural network. The performance of the model was optimised by varying several hyperparameters, for example, the number of epochs, the learning rate as well as the batch size.

Our experiment results established that the dataset of 900 graphs—with a testing ratio of 20%, a learning rate of 1e-5 and a batch size of 1—provided the highest prediction accuracy (95.6%). This paper's principal contribution is that the model was able to classify new unseen models that didn't follow exactly the typologies used in training. The model successfully predicted all eight new scenarios with high prediction accuracy results. Consequently, based on more semantically relevant and structured data, our approach offers tremendous potential for recognising architectural forms. Our future work will focus on comparing this novel workflow to other approaches, by considering further datasets and different building/ground topologies.

The paper was limited to a synthetic dataset extracted from 500 architectural precedents, given the dearth of 'real' datasets. To make real datasets suitable for dual graph extraction, it may be necessary to undertake intervention and translation, although this is costly and time-consuming. Moreover, the building/ground relationship rules and slicing rules created in Sect. 6 must be followed, otherwise the predictions will be inaccurate.

As a consequence of our findings, several new research areas have been identified. First, instead of simply classifying the overall graph, node and edge classification can be investigated. Second, our plan is to develop a system that recognises topological relationships as the designer constructs them, suggesting precedents from a visual database. A further future project will involve using this technique as a fitness function within an evolutionary algorithm, as a means of generating and evaluating design options.

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Associative Synthesis with Deep Neural Networks for Architectural Design

Immanuel Koh

1 Introduction

In this paper, the term 'associative synthesis' can be understood from a computational and deterministic perspective, such as 'associative modelling' in parametric architecture and 'example-based synthesis' in procedural modelling as well as from a creative and speculative perspective, such as 'bisociation' (Koestler, 1964) in psychology and 'unconscious' in psychoanalysis or surrealism. The former is an explicit mode of association using quantifiable parameters (e.g. numerical values, geometric operations, primitive shapes, etc.) for composing the computational directed acyclic graphs (DAGs) like those in the Grasshopper3D plug-in for the Rhino 3D-modelling environment where designers could visually 'drag' and 'connect' different parameters as components on a canvas, and thus associating them. The latter is an implicit mode of association using qualitative parameters from the designer's personal experiences and speculations drawn from his/her linguistical, cultural, social and even political backgrounds. It is the intention of the paper to combine these strands of objective and subjective associations and observe their interplay as we explore their 'associative' affordances, in particularly, the objectivity of deep neural networks and the subjectivity of the human mind when creating architectural designs. In other words, utilising the explicit computational graph of deep neural networks (DNNs) to play the objective role of generating and classifying design candidates within a learnt latent space, and, at the same time, using the implicit subconscious and intuitive characteristics of the human designers to play the subjective role of design interpretation and architectural translation in mapping the outputs of the DNNs to the intended design solution space. The co-creation process is thus associative locally as well as globally within the entire design process. Locally, in deciding what input data sources to be

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associated with what output targets when training a specified deep learning model. Globally, in deciding how the output targets are to be associated with plausible architectural concepts or forms. The paper thus aims to answer the main research question of 'How might deep learning models be appropriated for architectural co-creation through an associative design synthesis process?'. Such a proposition will indeed require thorough project illustrations, with not just one, but several, across a variety of datasets and corresponding architectural appropriations. The issues pertaining to such a co-creative process, with its inherent strengths and weaknesses, will also be evaluated to construct a more effective framework for the process of architectural design. In the coming sections, three projects will be discussed in detail, illustrating the local and global associative and messy interplay during the creative process.

2 Method

To better answer the research question of 'How might deep learning models be appropriated for architectural co-creation through an associative design synthesis process?', each of the three projects will be presented in the following order, namely, brief, speculation, concept, data, model and synthesis. The projects are designed to provide different degrees of associative affordances. All projects implement a variety of deep learning models using the deep learning library TensorFlow. Project 1 asks the question of whether deep learning models could be used to learn the formal characteristics of sculptures in generating landscape architecture? It leverages the effectiveness of segmentation models in design dataset creation and conditional generative models in design generation. Project 2 asks the question of whether deep learning model could be used to learn the fictional architecture of anime film with the existing architecture of reality? It leverages the effectiveness of unconditional generative models in design generation and image captioning models in design interpretation. Project 3 asks the question of whether deep learning model could be used to learn and recognise formal progression in recent architecture history for generating the next-in-trend architecture? It leverages the effectiveness of unconditional generative models in design generation, discriminative models in design classification and interpretation model in design classification explanation.

2.1 Project 1

2.1.1 Brief

Designing a sculpture park for Henry Moore.

2.1.2 Speculation

Might a deep learning model be used to learn the formal characteristics of sculptures for generating landscape architecture?

2.1.3 Concept

The fluid and monolithic forms of Henry Moore's sculptures, with their textured material surfaces often made in bronze or stone, while essentially physical and three dimensional, are highly vivid even from their two-dimensional representation as photographic imagery. Without the surrounding background scenes, these standalone sculptures are akin to a relief image. The project is inspired by such an association between the intricacy of surface articulations at the scale of a sculpture and that of a landscape. It aims to extract these features in two dimensions as a basis for generating a two-and-a-half-dimensional landscape.

2.1.4 Data

The dataset consists of 1000 photographic images web-scraped from the online Henry Moore Foundation collection. Founded in 1977, the foundation owns one of the world's most comprehensive collection of works by renowned British sculptor Henry Moore. The data cleaning process leverages a deep encoder–decoder network (BASNET) with an additional residual refinement module for the respective task of saliency prediction and saliency map refinement. In other words, the model provides us the ability to extract the main silhouette and outline of the sculpture in any given photographic image in the collection while removing its background. Both versions of BASNET, namely, boundary-aware salient object detection (Qin et al., 2019) and boundary-aware segmentation network (Qin et al., 2021), are tested with our dataset. It is observed that although the background removal results from either version are generally satisfactory, they are not perfect. A curatorial process is needed to identify the small number of failed outputs containing residual image artefacts before manually cleaning them in Adobe Photoshop. Therefore, the final dataset contains (1) RGB photographic images of individual sculpture in white background, (2) black outline of the individual sculpture in white background and (3) black silhouettes of the individual sculpture in white background. The images are all resized as 256 × 256 pixels to fit the expected input image size of our selected deep neural network models.

2.1.5 Model

Paired image-to-image model called Pix2Pix (Isola et al., 2018) and unpaired image-to-image model called CycleGAN (Zhu et al., 2020) are tested. These two different

Fig. 1 Left column showing the inputs, middle column showing the ground truth and right column showing the generated outputs by different models—first row using CycleGAN with outlines as inputs; second row using Pix2Pix with outlines as inputs and third row using Pix2Pix with silhouettes as inputs

models are trained with the two pairs of datasets (first pairs being RGB photographic images and their outlines, second pairs being RGB photographic images and their silhouettes), thus creating a total of four separate models of which three of them are shown in Fig. 1. Upon comparison between the generated outputs and their respective ground truths, it is observed that although their materiality might differ (e.g. varying colours in stone or bronze), the forms remain generally similar (e.g. the positionings and postures of Moore's signature 'Mother and Child' motif). In terms of the models' performance, those trained with the outline imagery dataset tend not to generate fully filled textures, especially when the overall areas are relatively larger. The pix2pix model trained with the silhouettes imagery dataset turned out to yield the best results.

2.1.6 Synthesis

The Pix2Pix model conditioned with the silhouettes input imagery is chosen for the subsequent architectural appropriation. Four different sites are chosen to demonstrate how such a deep learning model might be incorporated when given a physical site as a context to generate preliminary landscape architectural designs as shown in Fig. 2. The holes within each silhouette serve to notate the existing trees and other significant

Fig. 2 Four different sites are chosen. First and fourth columns show the satellite imagery of these sites. Second and fifth columns show the silhouettes obtained from masking the internal and external boundaries on site. The masking is drawn intuitively to provide the designers the option to include/exclude design constraints based on specific features on site, such as any existing trees and buildings. Third and sixth columns show the generated outputs of the pix2pix model, thus suggesting plausible surface articulation as landscape architecture

Fig. 3 (Left) Rationalisation of the generated 2D imagery as different 3D geometric articulations by sampling of the image pixel alpha values. (Right) An architectural visualisation of how the generated design might sit on site

vegetations on site as design constraints during the deep model generative process. The vividly textured forms generated in two dimensions are subsequently computationally rationalised (via image sampling of the alpha values) as three-dimensional massing before being further refined into a landscape architectural design as shown in Fig. 3.

2.2 Project 2

2.2.1 Brief

Designing an anime architecture for Studio Ghibli.

2.2.2 Speculation

Might a deep learning model be used to learn the fictional architecture of anime with the existing architecture of reality?

2.2.3 Concept

The critically acclaimed animation studio founded by Hayao Miyazaki is known for its innovative use of different architectural scenes (both real and imagined) in framing its creative narratives and developing its provocative characters. More significantly, the consistency in style and colour palette across all its films for the past 30 years have provided, not only the quantity as training inputs for our deep learning models, but the quality for evaluating the model's outputs. The project is inspired by such an association between the fictional architectural expression in anime and the less-forgiving reality of conventional buildings. It aims to extract these features in two dimensions as a basis for generating a latent narrative for architecture.

2.2.4 Data

The dataset consists of 2047 still frames at 2560 × 1440 pixels extracted from 17 anime films produced by the renowned Japanese Studio Ghibli, namely, The Secret World of Arriety (2010), Howl's Moving Castle (2004), Spirited Away (2001), Kiki's Delivery Service (1989), Princess Mononoke (1997), Whisper of the Heart (1995), My Neighbour Totoro (1988), Ponyo (2008), Castle in the Sky (1986), From Up on Poppy Hill (2011), When Marnie Was There (2014), The Cat Returns (2002), Nausicaa Valley of the Wind (1984), The Wind Rises (2013), Ocean Waves (1993), Porco Rosso (1992) and Pom Poko (1994). Figure 4 shows 11 of these films. For the purposes of fitting the input size expected by our deep neural network, each image is resized and centre-cropped to 1375 × 1375 pixels.

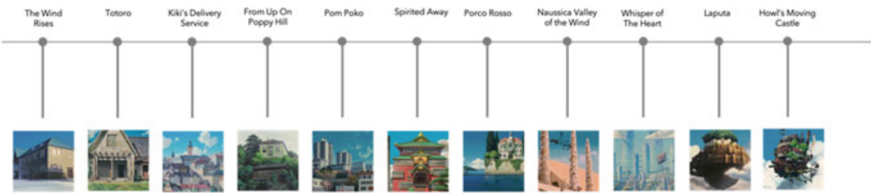

Fig. 4 Sample range of architectural expressions found in 11 of the 17 films by Studio Ghibli. They range from familiar and realistic-looking building types, to highly fictional-looking static architecture and to gravity-defying mobile architecture

2.2.5 Model

A vanilla generative adversarial network with a convolutional neural network architecture or DCGAN is initially used (Goodfellow et al., 2014; Radford et al., 2016) with our dataset of 2047 images. However, the generated outputs at 256 × 256 pixels have been less than satisfactory despite them showing colour palettes similar to those used by Studio Ghibli, with composition akin to landscapes and buildings in the films. Therefore, the more recent StyleGAN2 (Karras et al., 2020) architecture is used and pretrained with two different datasets separately, namely, church buildings and cars. In the former (Fig. 5), trained at 256 × 256 pixels for 25,000 epochs, architectural façades with varying levels of abstraction can be observed, with a number of them showing elevational and perspectival views, likely due to similar viewpoints to those found in the church building dataset used for the pretraining. In the latter (Fig. 6), trained at 512 × 512 pixels for 25,000 epochs, architectural façades can likewise be discerned. More significantly, however, are the presence of visual elements belonging to more to automobiles than buildings. As shown in Fig. 7, four of them have been selected to illustrate traces of the car body such as roof panel, fender, wheel arch and windscreen. From a design-by-analogy (Goldschmidt, 2001) or bisociative creative perspective, this second StyleGAN2 model has greater affordance for design speculation and formal exploration.

Fig. 5 Outputs generated with our model trained on the anime dataset via transfer-learning techniques on top of a StyleGAN2 model pretrained with church photographic imagery

Fig. 6 Outputs generated with our model trained on the anime dataset via transfer-learning techniques on top of a StyleGAN2 model pretrained with automobile photographic imagery

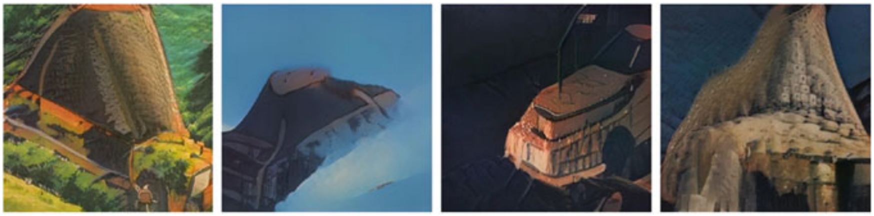

Fig. 7 Selected generated outputs exhibiting interesting automobile features that can be found in both our anime dataset and the automobile dataset used by the original pretrained StyleGAN2 model

2.2.6 Synthesis

Apart from having learnt a latent space of Studio Ghibli's anime-based architecture itself the basis for generating and interpolating new architectural imagery, to complement the generated narrative architecture (Coates, 2012), another deep learning model is used. This deep neural image captioning model or im2txt model (Vinyals et al., 2017) based on a deep recurrent architecture is capable of generating description sentence (6–10 words) given any image. 100 of our previously StyleGAN2-generated images are used as inputs to obtain the output captions for evaluation. As shown in Fig. 8, sample outputs are observed to be fairly descriptive, but at times with unexpected (yet interesting) perceptual differences as compared to

Fig. 8 Sample outputs generated by the im2txt model. (Left-to-Right) 'a car parked in front of a building'; 'a train travelling down tracks next to a tall building'; 'a city skyline with a bridge and a clock tower'; 'a group of people riding horses down a street'

what a human might typically infer from the same image. The fact that the im2txt model is trained with photo-realistic images rather than fictional and anime-like images containing higher degree of visual abstraction or exaggeration, such interpretive differences are not surprising. Nonetheless, creative linguistic augmentation to the architectural visual narrative remains interesting and poses potential for future exploration.

2.3 Project 3

2.3.1 Brief

Designing the unbuilt Serpentine Pavilion in 2020.

2.3.2 Speculation

Might a deep learning model be used to learn and recognise formal progression in recent architecture history for generating the next-in-trend architecture?

2.3.3 Concept

London's renowned Serpentine Gallery has been commissioning the design and construction of the Serpentine Pavilion every summer since 2000. Only leading architects who have yet to complete a building in England at the time of invitation are eligible for this commissioning. Several of the past invited architects had made the commissions the defining moments of architectural history, setting future trends to come. The Serpentine Pavilion has thus been the site of architectural experimentations despite its temporary presence during the summer. During the COVID-19 pandemic in 2020, the staging of the pavilion was however postponed to the following

Fig. 9 Images of the past 20 Serpentine pavilions from 2000 to 2019

year for the very first time. The project is inspired by how previous iterations of the pavilion designs might make implicit associations with present and future pavilion designs and architectural trend in general. It aims to extract these design features as a basis for learning a latent space of possible Serpentine pavilions. Given the consistent underlying parameters embedded in all the past 20 pavilions such as site, cost and duration, it is strategically framed for an exploration on how the 2020 pavilion design might self-generate from its own history and thus filling the unprecedented gap year.

2.3.4 Data

A total of 4635 images representing all 20 past pavilions are web-scraped (with Selenium). Figure 9 shows the 20 different designs of the past pavilions. Both the generative and classification models use the same dataset, except that for the latter, images belonging to a specific pavilion (or year) will be labelled as a different class, thus yielding a total of 20 classes.

2.3.5 Model

Similar to the previous project, the more recent StyleGAN2 (Karras et al., 2020) architecture is used and pretrained with the church building dataset prior to the transfer learning with our own dataset. Within 20,000 epochs, the model converges and is observed to generate convincing interpolation of architectural language found in the 20 past pavilions. At times, the church typology of the pretrained model can be seen, such as the more recognisable pitch roofs. Figure 10 shows a curated array of the generated outputs from the model. In the case of the classifier used to quantitively analyse these generated outputs, the EfficientNet B3 (Tan & Le, 2020) is used as a pretrained model before performing the transfer learning with our own labels for 350 epochs. Its accuracy of 80% to 90% is sufficient for the purposes of the analysis. In addition, a final model called iNNvestigate neural network (Alber et al., 2018) is used to further interpret the classification results through the visualisation of the model's neuron activations when predicting pavilion class with which the image belongs to.

Fig. 10 Curated sample outputs generated by the StyleGAN2 model trained with images of the past 20 Serpentine pavilions

2.3.6 Synthesis

With the abundance of generated pavilion designs from the learnt latent space, how might one go about curating them prior to translating into their three-dimensional forms? In other words, what are the criteria for selecting an output that should bear potential for architectural translation? There are generally three scenarios observed from the generated imagery that might help distinguish good and bad forms, namely, well-formed designs should be unreadable, novel designs should not simply replicate its source designs and well-interpolated designs should not be locally repetitive as shown in Fig. 11. Having established an intuitive means for the designers to select potential design candidates, it would be highly beneficial to somehow quantify these judgements, first via the EfficientNet B3 and again via the iNNvestigate neural network mentioned in the previous section. For the former, it is observed that the more promising designs tend to be those that comprise two to three yearly editions of the serpentine pavilion as shown in Fig. 12. This concurs with the intuitive criteria discussed earlier on where the interplay among defamiliarization, legibility and diversity is crucial. To seek a deeper understanding of exactly which architectural features (i.e. pixels) in a given image might have contributed to the final classification, a selection of the images is applied with gradient analysis, guided backpropagation and layerwise relevance propagation (LRP) from the iNNvestigate neural network library. For example, Fig. 13 shows that it is the swopping roof of Zaha Hadid's Serpentine Sackler Gallery that has triggered the neuron activations and thus contributing to it being recognised as belonging to a specific pavilion class.

Fig. 11 Sample outputs that have less design potential. First row shows designs that are too familiar (e.g. similar to Sou Fujimoto's 2013 pavilion); Second row shows designs that are visually illegible for further geometric rationalisation and Third row shows designs that are highly self-repetitive

After aforementioned analysis, a few promising-looking generated pavilion designs are selected for further three-dimensional translation into a building to be placed on the same site and to be scaled in its architectural representation. Given the limited available space of this paper, one example will be discussed here. A novel graphic organiser is proposed to illustrate how the understanding gained from the classification model has enabled a more effective mode of architectural interpretation and geometrical translation. As shown in Fig. 14, the graphic organiser consists of a top bar showing the similarity distribution of the given generated output image (i.e. Output Image 49) as compared to the 20 different source pavilions, classified according to the EfficientNet B3 model. In this particular example, the generated

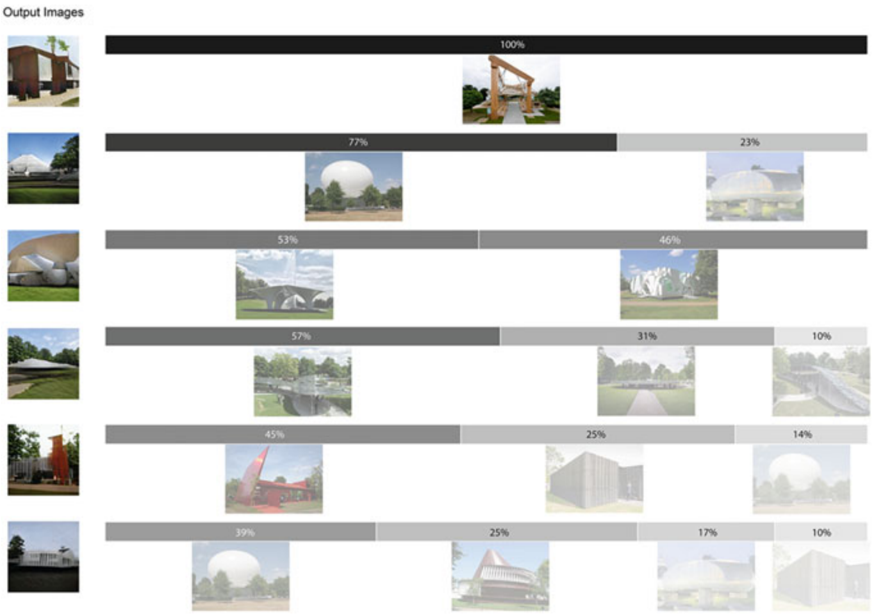

Fig. 12 A chart illustrating the design diversity derived from different percentages of the 20 source pavilions represented in the training set, in accordance to the classifier

design is recognised with 29% resemblance to the 2011 source pavilion by Peter Zumthor, 17% resemblance to the one in 2018 by Frida Escobedo and 50% resemblance to the one in 2019 by Junya Ishigami. The graphic dashed line connecting each source pavilion to the generated pavilion is annotated with textual description and technical drawings. These textual descriptions are in fact the results of articulating the observed architectural features found in the imagery and analytical drawings, in view of the indicated ratio of resemblance. Such articulations include Zumthor's 'internal partitioning slices', Escobedo's 'subtraction using rotated rectangle' and Ishigami's 'positioning of supporting spokes'. This process of explicit visual and textual articulations will then serve as the driving mental formulation to construct the new three-dimensional pavilion from the original two-dimensional imagery.

What proceeds next is thus the digital modelling of the form and the fabrication of the form as a physical model. Since it is essentially a subjective leap in an individual's formal and spatial imagination, it is possible to generate more than a single interpretations during the digital modelling process as shown in Fig. 15.

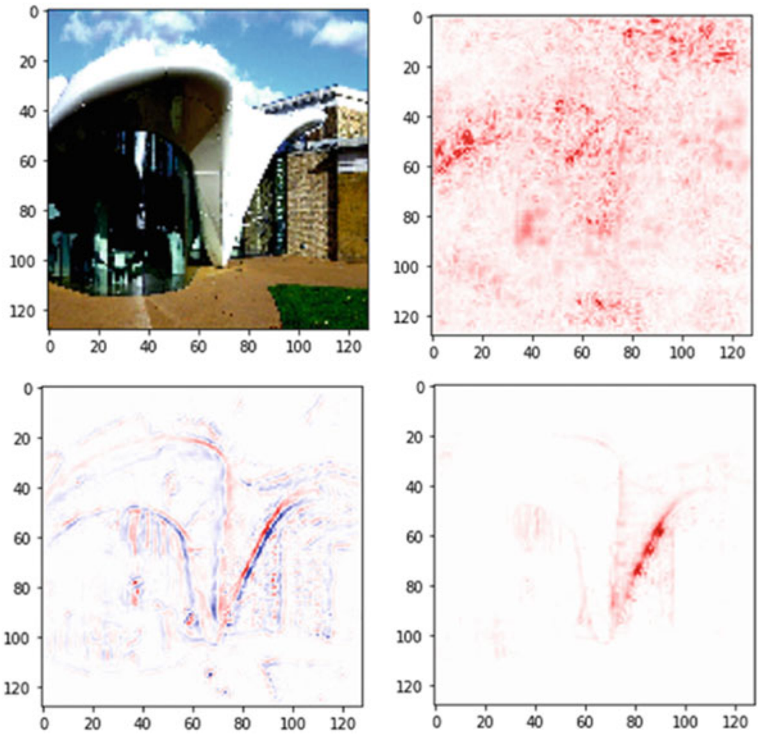

Fig. 13 (Top-left) Input image of Zaha Hadid's Serpentine Sackler Gallery; (Top-right) Results of applying gradient analysis; (Bottom-left) Results of applying guided backpropagation; (Bottom-right) Results of applying LRP. Red pixels indicate the salient parts of the input image, while blue pixels indicate negative activation

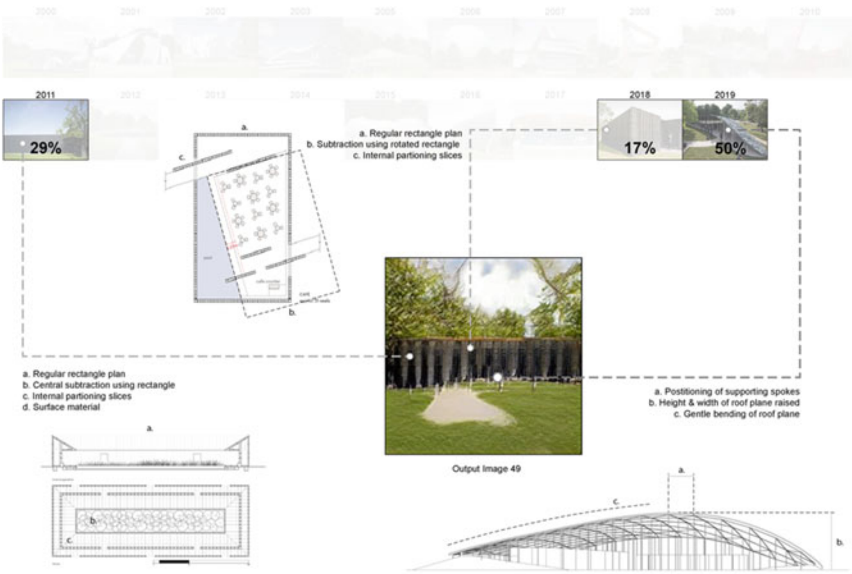

Fig. 14 The graphic organiser proposed aims to incorporate the resemblance ratio outputs from the classification model and the generated image output from the StyleGAN 2 model, while referencing observed architectural features found in the existing technical drawings (e.g. plans and sections)

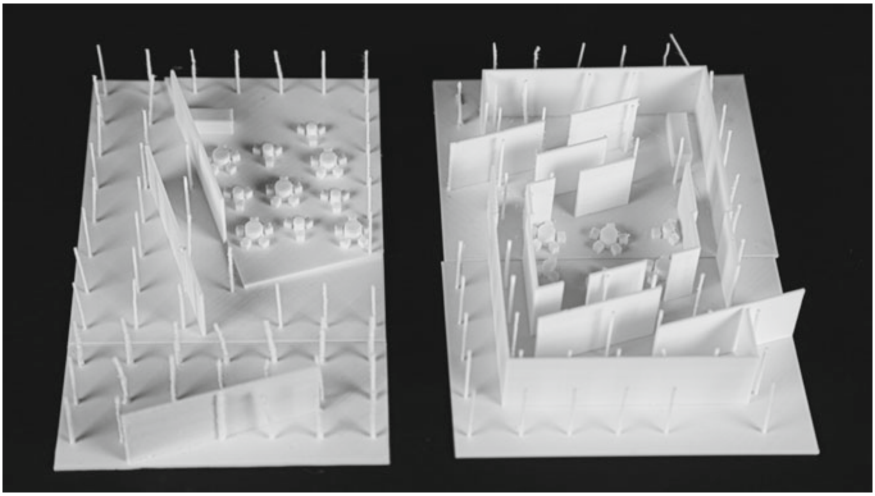

Fig. 15 The results of two different architectural interpretations represented as 3D printed physical models

3 Conclusion

The paper has illustrated a series of design research projects leveraging the imagery impressions synthesised by deep models and the formal interpretations translated by human architects. This co-creative process is shown to be messy where strategic labour distribution between the human and machine could yield not only more productive synergy, but potentially more creative processes and outputs. The paper has also served to demonstrate how the current need for a deep learning-driven design process within practice and academia might be addressed via the proposed associative design synthesis co-creative framework. Future work will include a more coherently developed and finely articulated framework beyond the use of design research projects alone.

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Behind Algorithmic Geometric Patterns: A Framework for Facade Design Exploration

Inês Caetano and António Leitão

1 Introduction

Architecture has always explored the latest technological advances both in terms of building design and fabrication. Nowadays, digital tools and computation-based design approaches play a relevant role in the conception, analysis, and production of architecture. These include Algorithmic Design (AD), a formal method that creates designs through algorithms (Caetano et al., 2020a) and whose flexibility brings several advantages to the design practice, such as automating repetitive, time-consuming design tasks; facilitating design changes; increasing design freedom; and facilitating the search for better-performing solutions.

Among AD's potential applications, the design of building facades stands out due to (1) the esthetic and environmental relevance of this architectural element (ElGhazi, 2009; Schittich, 2006); (2) the complexity of its design (Dritsas, 2012), which involves dealing with multiple context-specific design constraints (Boswell, 2013); (3) the growing need to reduce the buildings' environmental impact (Boeck et al., 2015; Huang & Niu, 2015); and (4) its tectonic potential in providing comfortable and better-performing interior spaces. Nevertheless, and despite its advantages, AD is not yet widespread in the field, mainly due to its high level of abstraction and its need for programming skills (Castelo-Branco et al., 2022). To smooth its learning curve, several AD tools have been released in the last decades, but few successfully combine the architects' creative practice with the need to simultaneously respond to multiple requirements. Moreover, most do not sufficiently simplify the algorithmic task, forcing architects to build the necessary functionalities from scratch.

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To make AD more accessible to architects, it is therefore important to systematize the algorithmic generation of design solutions in an architectural-oriented theory considering the wide variety of possible design scenarios while responding to different esthetic, performance, and construction requirements. We address this problem by extending our previous research on mathematics-based strategies encompassing the variability, diversity of requirements, and context-specificity of facade design problems (Caetano & Leitão, 2021; Caetano et al., 2015, 2020b). More precisely, we add a set of strategies addressing a wider range of geometry-related principles, as well as their fabrication through different manufacturing means and materials. The aim is to support architects with some programming experience in the algorithmic development and realization of facade design solutions, decreasing the implementation time of new designs, while providing the flexibility needed to handle each design stage in a continuous workflow.

As in previous research (Caetano & Leitão, 2021; Caetano et al., 2015, 2020b), the mathematics-based strategies addressing the geometric exploration and fabrication of a wider range of facade elements are implemented in a framework of predefined algorithms that can be easily combined in the development of new facade design solutions. In this paper, we elaborate not only on their implementation in the AD framework but also on their application to generate, transform, and materialize nonstandard three-dimensional facade elements. To evaluate the flexibility and versatility of the extended AD framework, we apply it in the step-by-step development of a set of case studies of different volumetric compositions while addressing their subsequent materialization using different manufacturing strategies.

2 Methods

Inspired by modular programming and design patterns strategies (Chien, et al., 2015; Hudson, 2010; Qian, 2009; Su & Chien, 2016; Woodbury, et al., 2007), this investigation aims at systematizing facade design processes based on AD by:

1. reducing the time and effort spent on AD tasks, freeing the architect from having to write all algorithms from scratch and avoiding potential programming errors.
2. guiding the selection and combination of the best algorithms for a given scenario, making it easier to deal with the diversity and context-specificity of most design requirements.
3. smoothing the transition between design stages, solving the interoperability issues between their different specialized tools, and thus minimizing the accumulation of errors.
4. facilitating the conversion of the resulting AD models into physical ones by automatically adapting their structure according to the fabrication means.

To that end, we adopt a mathematics-based perspective to structure a theory handling the complexity, variability, and diversity of facade design problems, implementing it in an AD framework containing different categories of algorithms. The preference for a text-based algorithmic implementation over a visual-based one lies on its greater expressiveness and scalability, which is critical to deal with the complexity and scale of architectural design problems. In this research, we extend previous theories (Caetano & Leitão, 2021; Caetano et al., 2015, 2020b) by placing particular emphasis on the geometric exploration and concretization of three-dimensional unconventional shapes, resulting in a six-stage methodology encompassing the following tasks:

1. identification of the most relevant facade design problems;
2. solution of the collected problems using mathematical formalism;
3. integration of the latter into the overall theory;
4. elaboration of algorithmic strategies addressing their materialization;
5. implementation of both (3) and (4) into the AD framework;
6. practical application.

The results of tasks 1–3 are briefly described in Sect. 3, and those of tasks 4–6 are presented in Sect. 4. Section 5 discusses the previous findings, concluding the proposal has enough flexibility to adapt to the ever-changing nature of architectural practice and its diversity of design scenarios and requirements.

3 Mastering Unpredictability

Architectural design problems are unique by nature as they are the natural product of multiple design requirements and constraints that can be global or context-specific, straightforward or abstract, and fixed or evolving. When combined with the variability of the design brief and the architects' creative nature, their complexity becomes further accentuated, making it difficult to use the same strategy in different scenarios. Moreover, given the projects' tight deadlines and the lack of flexibility of most design tools, the need to quickly explore a wide range of possible solutions is often unfeasible, hindering the creative potential of the architect. As a result, only a limited set of solutions is often considered, leaving many design scenarios unexplored.

This becomes especially evident in the design of building facades, due to the need to consider their multiple functions and requirements (ElGhazi, 2009; Schittich, 2006). Given the potential of AD approaches to improve design processes, we propose their use in current practices. To address their technical complexity and abstractness, we propose a mathematics-based theory and framework to support the algorithmic development of building facades, containing several AD strategies organized into a multidimensional classification.

We expect to overcome some of the limitations found in facade design processes by guiding architects towards the most suitable algorithms for (1) generating the idealized solution; (2) analyzing and optimizing it regarding one or more performance criteria; (3) making it feasible in terms of cost and resources; and (4) facilitating its manufacturing. Nevertheless, given the diversity and context-specificity of most design problems, we do not expect this matching process to yield a complete algorithmic solution and, thus, we assume that architects are still responsible for (1) dividing the design into smaller parts, (2) identifying and establishing dependencies between them, (3) combining the different algorithms dealing with each part, (4) implementing additional algorithms that might be needed to handle the specific circumstances of the design brief, and (5) executing the algorithms and evaluating the results.

In the next section, we elaborate on the proposed formal methods together with their implementation and application in a set of case studies.

4 Mathematics-Based Implementation

As a starting point, consider the framework presented in Caetano and Leitão (2021), whose mathematical principles are organized by type and role in facade design processes in the following categories: *Geometry*, *Distribution*, *Pattern*, *Optimization*, and *Rationalization*.

The proposed formalism regards building facades as two-dimensional parametric surfaces described as $S(u, v)$, whose shape can be defined through algorithms from the *Geometry* category, such as $Straight$ and $Cylindrical$, which create planar and cylindrical parametric surfaces, respectively. Along this surface, we can distribute one or more geometric elements according to different configurations available in the *Distribution* category, such as the squared and hexagonal grids produced by the algorithms $grid_{\text{squares}}$ and $grid_{\text{hexagons}}$. Combining these two types of algorithms with those of the *Pattern* category originates several geometric patterns, whose levels of complexity and variability depend on the algorithms selected: these can either target the creation of different shapes (the *Shape* subcategory), e.g., the algorithms $shape_{star}$ and $shape_{\text{pyramid}}$, or their geometric manipulation (the *Transformation* subcategory), e.g., the algorithms T_{scale} and T_{rotate}. This means that the more algorithms are selected from the first subcategory, the more variety of shapes the design will have, whereas the more are selected from the second subcategory, the more diverse their geometric variation will be. To control the shapes' geometric characteristics to meet one or more performance requirements, we can use the algorithms available in the *Optimization* category, such as the algorithms $opt_{\text{structure}}$ and opt_{daylight}, and to make the shapes feasible for fabrication, we resort to the *Rationalization* category, which provides algorithms like $tallying$ and $rationalize$ to either count or reduce the number of different elements composing the final solution.

This research extends this classification by (1) adding more algorithms to both *Shape* and *Transformation* subcategories addressing the generation and manipulation of three-dimensional facade elements, accordingly; (2) adapting some of the existing ones in the *Transformation* subcategory to be able to deal with the manipulation of three-dimensional shapes; and (3) including an additional category, *Fabrication*, addressing the materialization of the resulting solutions.

4.1 Pattern

This category contains algorithms to create different facade patterns resulting from the repetition of one or more geometric elements that can be kept unchanged or changed according to one or more geometric transformations. In previous research (Caetano & Leitão, 2019a, 2021; Santos et al., 2021), we focused on the mathematical representation of one- and two-dimensional patterns, addressing their potential to generate a wide range of geometric patterns responding to different esthetic and performance requirements. In the current research, we focus on the formal methods driving the creation, manipulation, and materialization of three-dimensional patterns.

As described in Caetano and Leitão (2021), all *Shape* algorithms receive a set of points (pts) and a set of additional parameters depending on the geometric characteristics of the shape to create: while a rectangular element receives the length and width of its edges (e_u, e_v) and an horizontal placement angle (α_u) (see Eq. 1), a cuboid element receives the previous parameters plus a height (e_z) and a vertical placement angle (α_v) (see Eq. 2). When combined with both *Geometry* and *Distribution* algorithms, these algorithms will extract different amounts of information depending on the received parameters: while the former requires the surface points and their normal vector to place each rectangular shape, the latter requires these points to center the cuboid element and both their normal and tangent vectors to correctly orientate it (Fig. 1).

$$shape_{rectangle}(pts, e_u, e_v, \alpha_u) \tag{1}$$

$$shape_{cuboid}\left(pts, e_x, e_y, e_z, \alpha_u, \alpha_v\right) \tag{2}$$

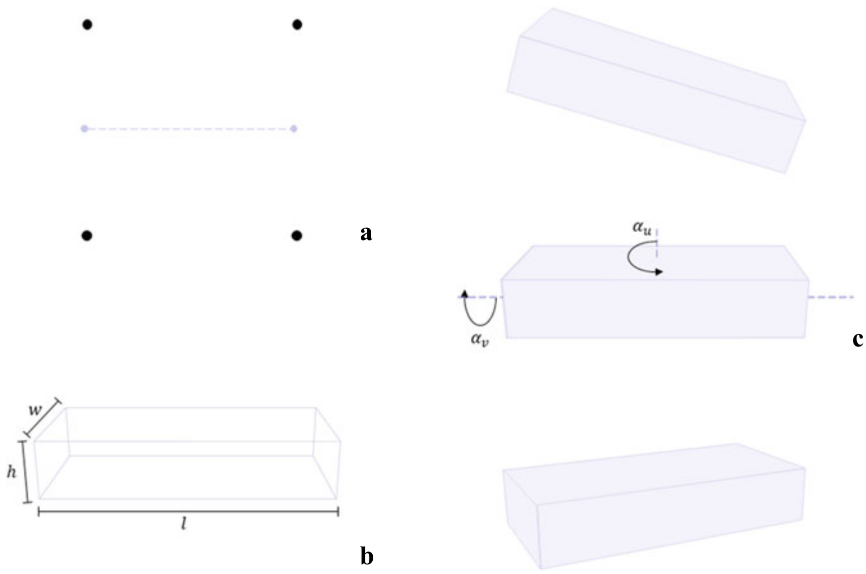

Fig. 1 Cuboid algorithm parameters: set of points centering its axis (**a**); its length, width, and height values (**b**) and its placement angles regarding the points' tangent and normal vectors (**c**)

Regarding more complex shapes resulting from constructive solid geometry operations, such as union, subtraction, intersection, or more complex modeling operations such as morphing, lofting, and bending, among others, the framework provides algorithms to create, for instance, irregular 3D tile shapes and panels (Caetano et al., 2018), complex truss-like structures (Caetano et al., 2020), and nonstandard brick elements (Caetano & Leitão, 2019b).

One such example is the algorithm producing a type of *cobogó* bricks (Eq. 3), which receives, in addition to the set of points (pts) defining its outer frame shape (Fig. 2a) and two placement angles (α_u and α_v) dictating its spatial orientation (Fig. 2b, c), a thickness and a width ($thick$ and $width$) controlling the corresponding frame dimensions (Fig. 2d). In this case, the resulting shape is achieved either through the union of several parallelepiped elements or the subtraction of a smaller three-dimensional element from a larger one of the same shape. Then, to create its inner elements, the algorithm receives their radius size (r_{bars}) and a rule guiding their spatial orientation ($rule$). The result is a geometric composition made of smaller regular elements whose spatial distribution can follow different rules (Fig. 3):

$$shape_{cobogo}(pts, \alpha_u, \alpha_v, thick, width, r_{bars}, rule) \tag{3}$$

Given the framework's flexible nature, we can now manipulate the previous algorithm's parameters in different and independent ways and apply, for instance, multiple geometric rules that result in different *cobogó* elements. To that end, we provide it with:

1. the set of positions where to create each *cobogó* shape ($ptss$), which we obtain by combining the algorithms $straight$ and $grid_{squares}$ from the *Geometry* and *Distribution* categories.
2. the dimensions characterizing those shapes ($thick$, $width$, r_{bars}), to which we assign a set of fixed values.
3. the geometric rules to apply ($rules$), which correspond to a set of functions.

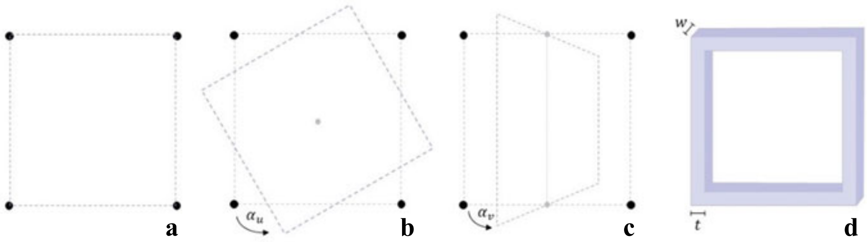

Fig. 2 *Cobogó* algorithm parameters: a set of points shaping the brick's frame (**a**); placement angles regarding the u (**b**) and v directions (**c**); and frame's width and thickness values (**d**)

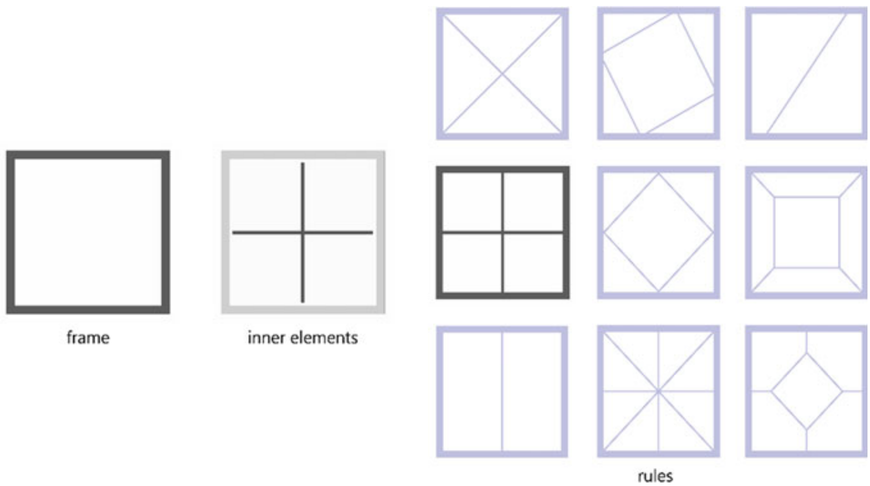

Fig. 3 *Cobogó* algorithm geometric evolution: creation of the outer frame and its inner elements according to different rules

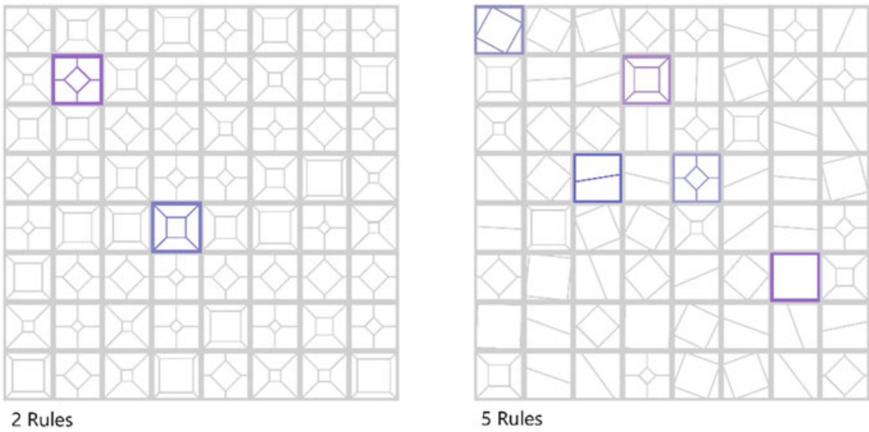

Fig. 4 Two patterns resulting from the same algorithmic composition but different sets of rules: on the left, the random selection is between two rules and, on the right, it is between five rules

To deal with the different number of dimensions of the received arguments, we benefit from *broadcasting* (Caetano & Leitão, 2021), i.e., the mapping of a function across multidimensional data structures, allowing us to apply the *Shape* algorithm $shape_{cobogo}$ to an array of elements with a higher number of dimensions than expected, as it happens with its parameter pts, which is expecting a one-dimensional array but receives a two-dimensional one ($ptss$) resulting from the combination $grid_{squares}(straight(w, h))$; or with a higher number of dimensions than the other received arguments, e.g., while $ptss$ is a two-dimensional array, $rules$ is a one-dimensional one, and the remaining arguments are independent numeric values. Using broadcasting, each one-dimensional array (pts) of the two-dimensional one ($ptss$) is independently assigned to the algorithm $shape_{cobogo}$, as also is each independent function of the one-dimensional array $rules$. This allows us, for instance, to make the latter selection random by simply combining it with the *Transformation* algorithm T_{random}, which returns randomly chosen values (Eq. 4). Figure 4 illustrates the results with two examples resulting from randomly alternating between two and five possible rules.

$$shape_{cobogo}.\begin{pmatrix} grid_{squares}(straight(w, h)), \\ \alpha_u, \alpha_v, thick, width, r_{bars}, \\ T_{random}(rules) \end{pmatrix} \tag{4}$$

As another example, we can make the equally sized *cobogó* elements irregular by simply transforming the set of surface positions shaping them, making their uniform distribution randomly vary in both u and v directions. To that end, we select the *Transformation* algorithm $T_{translate}$, which translates a set of surface points ($ptss$) according to a given translation factor (k), combining it with the T_{random} in the following composition:

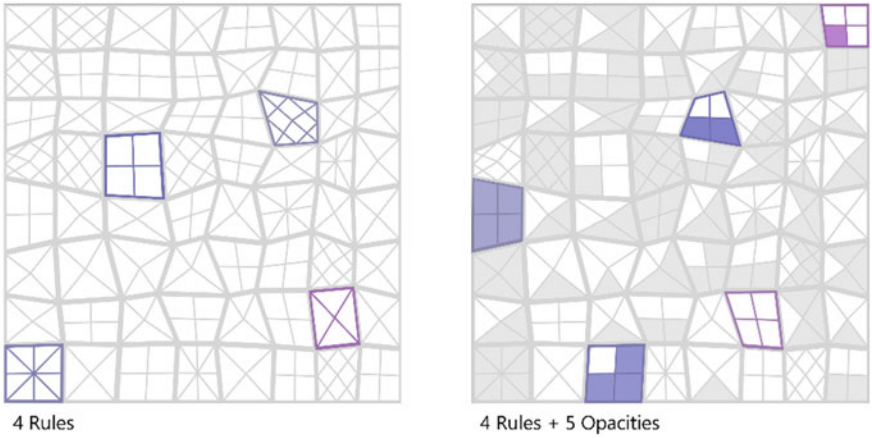

Fig. 5 Two patterns resulting from the same algorithm but different opacity levels: the algorithm randomly selects between four rules with no opacity level, on the left, and five possible opacity levels, on the right

$$T_{translate}.\big(grid_{squares}(straight(w, h)), T_{random}\big) \tag{5}$$

By adding the *cobogó* algorithm to the previous composition (Eq. 5), we obtain bricks of varying shapes and sizes as those illustrated in Fig. 5, which result from randomly selecting between four possible rules ($rules$) with either fixed (left) or random (right) opacity levels (see Eq. 6).

$$shape_{cobogo}.\begin{pmatrix} T_{translate}.\big(grid_{squares}(straight(w, h)), T_{random}\big), \\ \alpha_u, \alpha_v, thick, width, r_{bars}, \\ T_{random}(rules) \end{pmatrix} \tag{6}$$

As another example, to create a pictorial visual effect resulting from horizontally rotating standard bricks in different ways, we combine the previous algorithm $shape_{cuboid}$ with the *Transformation* one T_{rotate}, making the latter control the former's horizontal placement angle in the following composition (Eq. 7):

$$shape_{brick}(pts, lenght, width, height, \alpha_u \times T_{rotate}, \alpha_v) \tag{7}$$

To control the rotation angle so as to create the desired visual effect, we select the *Transformation* algorithm $T_{pictorial}$, which receives (1) the surface points where to create the pattern ($ptss$); (2) a matrix containing the transformation algorithm(s) to apply ($M_{transfs}$); and (3) another matrix with the intended pictorial effect ($M_{pattern}$). Based on the latter information ($M_{pattern}$), it then maps the algorithms of $M_{transfs}$ along the positions ($ptss$), affecting the shapes assigned to them. As, in this case, $M_{transfs} = [T_{rotate}]$, only this algorithm is applied to the bricks, while using the rotation angles set in $M_{pattern}$.

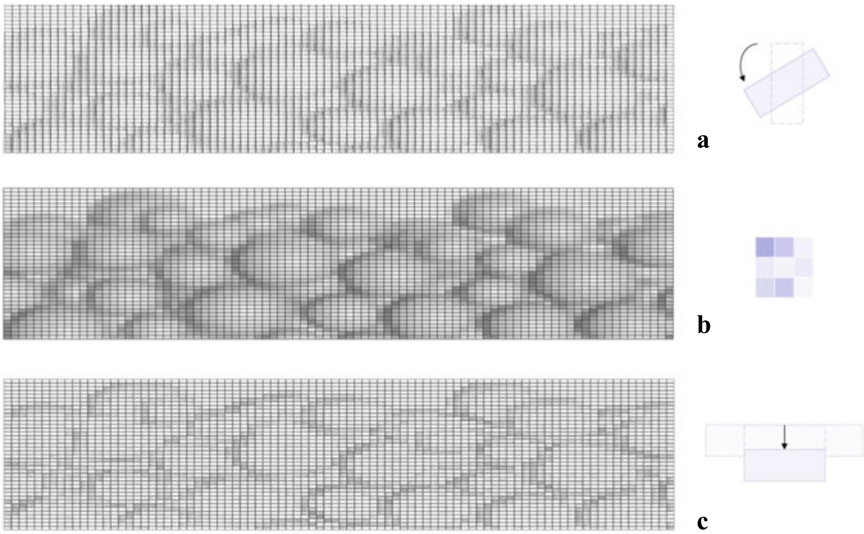

Fig. 6 Three examples resulting from the *pictorial* algorithm: creating a spheres-inspired pattern by strategically rotating (**a**), coloring (**b**), and protruding (**c**) the bricks

To translate the desired pictorial effect into rotation angles, we select the algorithm $pixelmap_{image}$, which, based on an image ($image$) and its domain of application ($ptss$), collects the RGB values of the former's pixels, while storing them in a matrix with the size of the given domain. When provided to the algorithm $T_{pictorial}$, the collected RGB values are automatically converted into factors that consider, for instance, the type of transformation(s) to perform and the intensity of the pictorial effect to create. Figure 6a illustrates the result of the following composition (Eq. 8):

$$T_{pictorial}\left(\begin{matrix} itera_{rhombus}(straight(w,h)), \\ [T_{rotate}], \\ pixelmap_{image}\left(\right. \end{matrix}\right.$$

$$\left. \left. , straight(w,h) \right) \right) \quad (8)$$

Having this composition, we can simply replace T_{rotate} with other transformation algorithms, such as $T_{colours}$ or $T_{translate}$, and obtain the same visual effect through differently colored or protruded bricks, accordingly (Fig. 6b, c).

4.2 Fabrication

This category contains algorithms to materialize the developed solutions through different manufacturing techniques and materials. When combined with the previous algorithms, the *Fabrication* algorithms (1) suggest different fabrication strategies by considering the designs' geometric and material characteristics, while (2) automating the production of the technical documentation needed for each one (see Fig. 7), e.g., two-dimensional drawings with different line types delimiting the areas to cut, engrave, or fold by laser-cutting, or 3D models containing the printer-head paths for 3D printing. They also provide (3) a high-level control over the solutions' manufacturing, contributing to the latter's increased efficiency, accuracy, and viability: e.g., adjusting the printing path planning, i.e., the trajectory of the 3D printer head, to obtain either the desired structural integrity or surface quality or manipulating the profiles' thickness of sectioning strategies to meet the desired visual effect, among others.

In the former case, by receiving the set of shapes to produce, the available functionalities analyze their geometric characteristics to understand the suitability of different manufacturing scenarios to fabricate them, which in turn require different representation schemes and methods. As an example, while the *sectioning* strategy is based on the use of a series of profiles to create either a surface or a structure, *cutting* involves the extraction of two-dimensional planar elements from surfaces or solids, and *forming* uses molds to mass-produce elements. Therefore, when the elements to produce are, for instance, differently patterned panels, the first two strategies will probably be suggested, whereas when they are customized, three-dimensional tiles with, for instance, a round shape, it is the last one that will eventually be proposed.

In the latter cases, they allow controlling the manufacturing process by adjusting its related parameters, while evaluating the impact each strategy has on the solution's mathematical description, changing its structure accordingly. The result is a new algorithm representing the solution according to the specifications of the selected manufacturing strategy, from where all the information and technical documentation needed for the actual fabrication can be automatically extracted.

As an example, consider a pattern similar to that of Fig. 5 (left) and suppose that we intend to manufacture it using 3D printing. We therefore combine the *3D printing* algorithm ($fab_{3Dprint}$) with those producing the *cobogó* elements, automatically converting the latter's three-dimensional shapes into paths for the printer head. When planning these paths, the algorithm considers different printing specificities, such as the printer resolution ($head_{mm}$), the material layer thickness ($layer_{mm}$),

Fig. 7 Automatic production of technical documentation for the same shape according to the selected manufacturing technique: 3D printing, sectioning, casting, and laser cutting

and the printing strategy ($path_{plan}$), which in turn result in different numbers of printing paths and distances between them and different trajectories. Accordingly, the resulting machining time, surface finishing, geometric accuracy, and material use also change (Jiang & Ma, 2020). Figure 8 illustrates the result of this combination with the conversion of a set of *cobogó* bricks into their corresponding printing paths, where $head_{mm} = 3$, $layer_{mm} = 1.5$, and the planning type is based on alternated paths by level.

To convert the *cobogó* elements' volumetric model into one prescribing the printer head paths, its algorithmic representation has also to change, the originally used geometric solid primitives being replaced by path operations (Eq. 9), whose distribution along the generated volume is controlled by the previous parameters.

$$fab_{3Dprint}\left(shape_{cobogo}\right) \rightarrow shape_{3Dpaths} \tag{9}$$

On the other hand, if we want to produce the previous elements through casting strategies, we select the *forming* algorithm ($fab_{forming}$), automatically obtaining the 3D models of their negative shapes (Eq. 10), together with cost-related information, such as the number of different molds and material quantities (see Fig. 9). As, in this case, both the original and translated models correspond to three-dimensional, albeit inverse, shapes, the converted algorithm will apply the same primitives as the original one with only slight differences.

$$fab_{forming}\left(shape_{cobogo}\right) \rightarrow shape_{negative} \tag{10}$$

Having the molds' 3D models, the possibilities for their production are the same as for the *cobogó* bricks, making it possible to proceed with the combination of the resulting algorithm with those available in the *Fabrication* category and, for instance, planning the paths for their 3D printing, if we select $fab_{3Dprint}$ (Eq. 11), or setting the instructions for their CNC milling, if we opt for the $fab_{milling}$ (Eq. 12).

$$fab_{3Dprint}\left(shape_{negative}\right) \rightarrow shape_{3Dpaths} \tag{11}$$

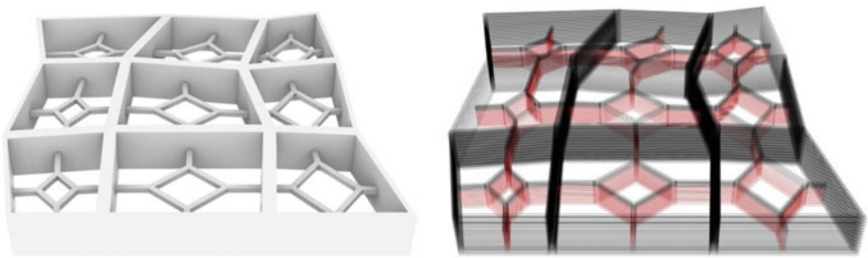

Fig. 8 A perspective view of the design's 3D model on the left, and the resulting printing paths (black lines) and support structures (red lines) on the right

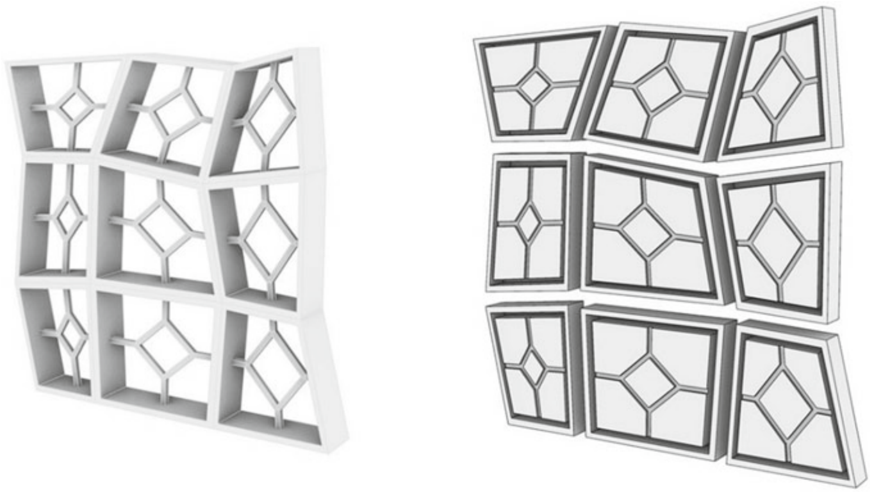

Fig. 9 A perspective view of the design's 3D model (left) and the resulting molds with each element's negative shape (right)

$$fab_{milling}\left(shape_{negative}\right) \rightarrow shape_{millingOperations} \tag{12}$$

As a last example, if we adopt a sectioning strategy, we combine the algorithm $fab_{section}$ with those producing the *cobogó* elements, automatically obtaining a set of profiles, whose number is controlled by the $n_{profiles}$ parameter and whose superposition creates the intended shapes (Fig. 10 middle). When setting the previous parameter ($n_{profiles}$), it must be considered that, first, it depends on the thickness of the selected material and, second, its division by the element's total thickness does not always result in a whole number of sections. As, in this case, the material and element thicknesses are 10 mm and 90 mm, correspondingly, we set $n_{profiles} = 9$. Given the

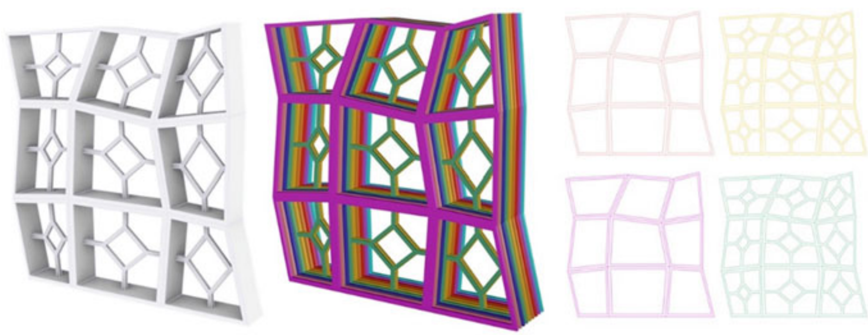

Fig. 10 A perspective view of both the design's 3D model (left) and sectioned model (middle) together with some of the profiles' two-dimensional drawings for laser cutting (right)

profiles' relatively small thickness (i.e., 10 mm), the use of laser cutting techniques is therefore suggested, requiring the production of two-dimensional drawings with paths representing the areas to cut. Finally, to obtain this technical documentation, we add the algorithm $fab_{lasercut}$ to the previous combination, the results being illustrated in Fig. 10 (right).

Regarding the resulting mathematical structures, while the combination of $shape_{cobogo}$ with $fab_{section}$ originates a new algorithm using the same geometric solid primitives but in different ways (Eq. 13), its combination with $fab_{lasercut}$ causes more radical changes as the latter are replaced with line primitives defining the elements' contour shape (Eq. 14).

$$fab_{section}\left(shape_{cobogo}\right) \rightarrow \left\{shape_{layer01}, \cdots, shape_{layern}\right\} \tag{13}$$

$$fab_{lasercut}.\left(shape_{cobogo}\right) \rightarrow shape_{contours} \tag{14}$$

Having the ability to test and visualize multiple manufacturing possibilities allows us to assess their different advantages and disadvantages, not only in terms of their production times, material waste, and overall costs but also regarding the esthetic quality, geometric precision, and physical properties of the resulting solutions.

5 Evaluation

The mathematical nature of our proposal makes its principles easy to implement in any AD tool for architectural design, either using the visual or the textual programming paradigm. In this research, we focused on the latter due to having the scalability and expressiveness needed to solve large-scale, complex design problems. To evaluate the proposal, we implemented it in the AD tool *Khepri* (Sammer et al., 2019), the result being a text-based AD framework supporting the algorithmic development and manufacturing of facade design solutions. In the next sections, we compare the results of its application with other state-of-the-art AD tools in terms of (1) geometric exploration and (2) fabrication.

5.1 Algorithmic-Based Exploration

Within the scope of building facades, there are already some AD tools supporting the algorithmic development of facade design solutions, which include (1) ParaCloud Gem, which provides features to map 3D elements on a mesh, subdivide and edit surfaces, integrate fitness requirements, and 3D print the resulting solutions; (2) Dynamo's addons Quads from Rectangular Grid, Ampersand, Clockwork, LunchBox, MapToSurface, Pattern Toolkit, and LynnPkg, which contain features for surface paneling, mapping elements on a surface, and creating and manipulating geometric patterns; and (3) Grasshopper's plugins PanelingTools, LunchBox, Weaverbird, Parakeet, and SkinDesigner, which integrate surface paneling and pattern generation functionalities, rationalization, and mesh subdivision techniques for analysis and fabrication, mechanisms to produce facade geometries from buildings massing surfaces repeating panels, among others.

Despite facilitating the typical modeling procedures of facade design processes, these tools present several limitations, such as (1) requiring frequent manual-based interactions and thus favoring iterative user-driven processes that are potentially tiresome and error-prone; (2) suffering from the scalability and performance limitations of visual programming languages, particularly, when dealing with larger AD solutions (Janssen, 2014; Janssen, et al., 2016; Leitão et al., 2012, 2014; Nezamaldin, 2019; Wortmann & Tunçer, 2017; Zboinska, 2015); (3) having limited ability to directly address relevant concepts like materiality and tectonic relation between facade elements, being often restricted to generic panelization, subdivision, and population of surfaces problems; and (4) providing a limited set of predefined operators that are difficult to adapt to respond to more specific problems (Zboinska, 2015).

Our proposal addresses most of these limitations, providing users with higher levels of design freedom by (1) automating repetitive and error-prone design tasks, minimizing manual intervention; (2) facilitating programming tasks, reducing the time and effort spent in them; (3) smoothing the transition between designs stages, facilitating the coordination between their specific requirements; and (4) addressing the solutions' materiality and concretization, making it easier to consider different manufacturing scenarios.

By reducing the time and effort spent on each of the previous tasks, the user is left with more time available for creative exploration, potentially increasing the explored design space and the probability of finding better solutions, whether in terms of esthetic, performance, or feasibility. Moreover, as our proposal supports flexible design workflows merging the different design stages' information, it also eliminates most interoperability issues resulting from their transition process while solving the latter's tendency to accumulate errors.

These advantages are visible in the examples of the previous sections, where we used the framework to facilitate, first, the exploration of multiple geometric compositions responding to different esthetic requirements and then, the transition between design exploration and materialization stages, not only increasing the variety of construction scenarios considered but also improving our perception of their impact on the solutions' esthetic quality.

5.2 Algorithmic-Based Manufacturing

Regarding AD tools for manufacturing, relevant examples include the plugins (1) FabTools, Bowerbird, Xylinus, Droid, Kuka Prc, RoboDK, OpenNest, and Ivy for

Grasshopper; (2) DynaFabrication, Fabrication API, 3BMLabs.DigiFab, and ParametricMonkey for Dynamo; and (3) Laser Slicer Addon for Blender. However, these are mostly (1) based on visual programming languages, whose limitations hinder the manufacturing of more complex solutions (Janssen, 2014; Janssen et al., 2016; Leitão et al., 2012, 2014; Nezamaldin, 2019; Wortmann & Tunçer, 2017; Zboinska, 2015); (2) tool specific, forcing architects to use multiple AD tools to assess different construction schemes; (3) limited in terms of modeling freedom; and (4) dependent on laborious, time-consuming, and error-prone manual- or script-based interventions, not fully automating the design-to-fabrication conversion and the extraction of technical documentation. Given the uniqueness of architectural design problems, these interventions are, however, hardly reused in different projects without major modifications, thus hindering the testing of different manufacturing scenarios and construction schemes.

In the case of our framework, besides smoothing the design-to-manufacturing transition process by automating most of its related tasks, it provides control over the manufacturing process and its different parameters, allowing higher levels of production quality, accuracy, and viability (Jiang & Ma, 2020; Petunin et al., 2019). Moreover, by adapting the designs' algorithmic descriptions according to the specificities of the selected fabrication technology, the framework ensures that the available functionalities are portable between design and manufacturing tools, overcoming the latter's typical interoperability issues and allowing the use of the same algorithm to obtain both the design's geometric and construction models containing the required information. This is illustrated in Figs. 8, 9, and 10, where we experimented with different construction schemes and manufacturing strategies for the same solution, making it easier to assess their different advantages and disadvantages.

There are, nevertheless, several aspects that need to be further developed and integrated into the proposed framework, particularly in what regards the specificity of each manufacturing technique and its sensibility to different requirements and parameters. As an example, while in 3D printing and CNC cutting the printing path planning, i.e., the specification of the tool movement, is critical for achieving higher levels of surface quality (Ezair et al., 2018; Jensen et al., 2019) and shape accuracy (Ding et al., 2014; Jin et al., 2014) and reducing time and material expenditure (Bui et al., 2019; Coupek et al., 2018; Shembekar et al., 2018), in cutting strategies, it is important to optimize the machines' cutting paths by considering parameters such as cutting speed, material thickness, laser cutting type, and material used, among others (Dewil, 2014; Dewil et al., 2014, 2015; Makarovskikh & Panyukov, 2021; Petunin et al., 2019; Sherif et al., 2014). In contrast, casting strategies need to address the molds' production cost and material and geometric properties, as well as their impact on the geometric complexity, surface quality, and molding speed of the produced elements (Almaghariz et al., 2016; Chhabra & Singh, 2012, 2015; Estrada et al., 2018; Gill & Kaplas, 2011; Pagone et al., 2020; Ramakrishnan et al., 2014; Salonitis et al., 2016; Singh, 2011; Snelling et al., 2013; Thiel et al., 2017; Upadhyay et al., 2017; Zhao et al., 2018).

We are currently extending our proposal with guiding strategies supporting the iterative refinement of the solutions' manufacturing process by also considering the elements' geometric properties, materiality, and desired finished quality and precision. We also intend to integrate functionalities for cost and machining time control, as well as for comparing the trade-offs resulting from the previous requirements in different manufacturing scenarios.

6 Conclusion

The field of architecture is always evolving to accommodate the latest technological advances in terms of design exploration and fabrication. One such advance is Algorithmic Design (AD), a design approach based on algorithms that has the potential to flexibly coordinate conceptual, performance, and construction requirements. Besides automating repetitive and time-consuming design tasks, AD facilitates design changes and increases design freedom. By reducing the time and effort needed to explore new designs, it allows architects to explore wider design spaces, promoting the search for improved solutions. AD is particularly apt to solve intricate design problems involving multiple esthetic, performance, and construction requirements.

Nevertheless, AD is a complex and abstract approach that requires programming skills, which most architects do not have. Despite the release of several AD tools in the last decades aiming at smoothing its learning curve, few successfully combine the architect's creative process with the need to meet multiple design requirements. This paper addressed this problem by systematizing the formal methods behind the algorithmic generation of facade design solutions in a mathematics-based theory considering the wide variety of existing design scenarios and strategies, as well as the variability and context-specificity of architectural problems. The aim is to make AD more accessible to architects by not only reducing the time and effort spent on algorithmic-related tasks, but also guiding the search for improved solutions in terms of esthetics, performance, and constructability.

To evaluate the proposal, we implemented it in an AD framework specialized in facade design processes, placing particular emphasis on the geometric exploration and materialization of three-dimensional unconventional elements. Based on the results, the proposed formal approach has enough flexibility to coordinate the geometric exploration of facade design solutions of different volumetric compositions and their concretization using different manufacturing means and strategies.

As a still ongoing investigation, current efforts have been placed on the improvement of the available functionalities and their extension with more advanced features, such as providing higher levels of control over the different manufacturing strategies; extending the range of shapes supported; adding cost and machining time control strategies; and including a recommender system comparing the trade-offs resulting from different requirements and manufacturing scenarios.

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Formal Studies on the Parts and Wholes of Historical Bricklay Designs

Sevgi Altun and Mine Özkar

1 Introduction

The artistry and the knowledge of geometry have been interlaced in Islamic architecture. In the era preceding the Anatolian Seljuk architecture of the eleventh–thirteenth centuries, master builders and mathematicians in the Islamic world were known to be in contact with one another and in correspondence over problems of practical geometry (Özdural, 2000). The outcomes of this interaction are most observed in the geometric ornamentations of architectural surfaces. Although these patterns have been the subject of many studies for decades, more recent investigations from the perspective of computational design provide insightful analyses of the geometric approach behind them and offer projections for novel designs based on the know-how. These include a generative system for the two-dimensional Islamic patterns via the application of a visual grammar (Cenani & Cagdas, 2006), a geometric analysis and mathematical calculation of common surface adornment motifs from historical architecture in Iran (Cromwell & Beltrami, 2011), and investigation of the star-shaped motifs and their patterns in three-dimensional interlocking layers for creating sculptural polyhedral forms (Kaplan, 2017).

More recently, some computational investigations focus on the design and construction process of these patterns as a whole, either by focusing on stone carvings (Hamzaoğlu & Özkar, 2018) or the glazed tiles unique to the region (Özgan &

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Özkar, 2017). Additional to the patterns, the muqarnas, a three-dimensional organization of geometric units that forms an ornamental and structural architectural element characteristic of Islamic architecture, has also been a popular area of research in computational design (Alaçam et al., 2017; Gökmen et al., 2021; Yaghan, 2010). Similarly, various combinations of brick units that form patterns adorning the structures of the Seljuk Period in Iran (Panahi, 2012) in comparison with those in Iranian architecture (Kharazmi & Excellence, 2016) are explored for their underlying geometry of circles and polygons deeply rooted in the effects of mathematics and geometry on Islamic Architecture. The existing literature, however, leaves out the particular ways in which the units are combined by manual labor and how this particular constructional know-how is shaped by, and perhaps shapes in return the pattern design.

Alongside of limited computational analyses of the unit relations in bricklaying of that era (Altun & Özkar, 2021; Özen Yavuz & Sağıroğlu, 2016) are general studies that focus on contemporary bricklaying via parametric models (Afsari et al., 2014; Imbern, 2014). Even if the latter set does not specifically look into historical examples, architectural heritage reconstruction often makes use of parametric modeling. Such applications are usually at the building scale and with regard to style. Examples include the parametric reconstruction of Indian pavilions based on the descriptions from the Mayamatam text (Garg & Das, 2013), the parametric rule set for ancient Chinese buildings based on the Chinese design rule book named Yingzao Fashi and the data collected from existing historical structures (Li et al., 2013), the parametric models of the American Second Empire architecture (Kramer & Akleman, 2020), and the regeneration of New Zealand's nineteenth-century timber churches based on parametric definitions derived from architectural heritage studies (McLennan & Brown, 2021). Apart from a few distinctive studies, such as the implementation of parametric shape rules to generate different bricklaying patterns and brick arrangements (Vazquez et al., 2020), there is limited application of parametric shape rules for the design problems at the level of construction units. From a more technical point of view, parametric shape rules as tools vital to understanding and exposing the three-dimensional relations between units and the development of its generative system have been a research problem for the design of interpreters (Grasl & Economou, 2018; Yue et al., 2009).

In our research, we analyze brick structures from the Anatolian Seljuk period using parametric shapes rules to extract unit relations and underlying geometric patterns. Existing architecture and construction history literature on the brick structures of the period provide inferences about the types of brick bonds, brick sizes, shapes, and their surface finishings. In a previous study, we have analyzed a singular example of the particularly unique brick panels from the Anatolian Seljuk period, a panel from the northern side of the entrance iwan of Konya Sırçalı Madrasah (thirteenth century) composed of both plain and glazed bricks of different colors and shapes. In the way that they are placed vertically and horizontally, bricks form abstract geometric patterns. In works of this genre, visual reasoning, with flexibility in perceiving different parts and wholes, delivers the constructional relations between individual bricks and the geometric patterns formed by groups of bricks. In our current study, we expand the breadth and variety of the examples for more in-depth analysis.

2 Methodology

The study presented here consists of site surveys, geometric analysis based on historical knowledge, and a model proposal. Defining a computational relation between the pattern designs and the construction of historical brick wall panels, we integrate their geometric and constructional aspects in a generative system. We devise and utilize parametric shape rules as the means for exposing the three-dimensional relations between the parts of material constructions.

Prior research which established a starting point for this study was an analysis of a single brick period panel that contains both naked and differently colored glazed bricks in a vertical–horizontal bond (Altun & Özkar, 2021). We developed a grammar with the least number of rules that enables the making of the panel, using Andrew Li's Interpreter (2018) in Rhinoceros 3D. Taking into consideration the flexibility of the eye and the mind in the perception of parts and wholes, we had then devised a rule set to represent the constructional relations between individual bricks and the various spatial relations of the abstract geometric patterns formed by groups of bricks. In this current study, we improve the definitions of the rules by adding parameters to contain more aspects of bricklaying and to expose the generative system behind many more designs including examples of the vertical–horizontal bond. We use the Sortal GI interpreter developed by Rudi Stouffs (2018) in the Grasshopper environment of Rhinoceros 3D to test and validate the syntactic accuracy of the rules and the grammar.

3 Setting Up a Generative System

The analysis phase comprises the defining of the parameters of bricklaying and the sequential and spatial procedures that are followed in manual building of a brick panel. Studying photographs, photogrammetry-based models, and survey drawings, we identify the parameters of Anatolian Seljuk bricklaying and define the smallest number of spatial relations between bricks required for recreating the panels.

3.1 Characteristics of Bricks

The cases studied embody particular types of bricks. We identify these types and make inferences on the relations between them according to construction history literature for the relevant era and region. There are two types of bricks in the Anatolian Seljuk period based on their application on the construction site and these are, respectively, called unit bricks and cut bricks (Bakırer, 1981a, 1981b). Unit bricks are premade and laid on the construction site as they are, while cut bricks are generally produced as large elements and shaped on-site according to the applied pattern. Unit bricks are divided into four groups based on their shapes and into two based on the surface finishes. Shape-based categories are whole bricks, half bricks, quarter bricks, and minaret bricks whereas surface-based categories are naked and glazed bricks. There are three types of brick bonds in the Anatolian Seljuk period: horizontal bond, vertical–horizontal bond, and herringbone bond (Bakırer, 1981a). There are also additional classifications based on the horizontal and vertical mortar thickness, stride, and the use of additional elements between bricks such as tiles and plaster (Aktaş Yasa, 2016). It is known that measures based on human body parts like the hand and fingers were used in construction sites (McClary, 2017).

3.2 Parameters of Bricklaying

We divide the parameters of bricklaying into three groups. These are the parameters of individual bricks, of the relation between two bricks, and of the pattern. The parameters are defined by the directives in the rules or outcomes of the application of multiple directives.

The parameters of the bricks are related to the shape and size of the bricks. The typical dimensions for the brick types in Anatolian Seljuk architecture are the determinants of these parameters which are the width, the height, and the depth for whole, half, and quarter bricks. The width of a whole brick is equal to the width of a half-brick, but while the whole brick is a low square prism with equal depth, the half brick is a smaller rectangular prism. In the horizontal position, the total height of three bricks on top of each other and the mortars between them, likewise, the total of a short side of one half brick and the height of one brick with the mortar between them is equal to the long side of one whole brick or a half brick. The depth of a half brick equals the total height of two bricks lying on top of each other in the horizontal position and the mortar between them. In comparison, the quarter brick is a much smaller cube with dimensions equal to the heights of the whole and half bricks. In most of the vertical–horizontal bonds, half bricks with different orientations and quarter bricks are used.

The parameters of the relations between bricks are crucial for defining the three-dimensional spatial relations between two consecutive bricks. There are many possible relations between the half bricks of different orientations and the quarter bricks. The position of the bricks, the stride, and the mortar spacings are the parameters of the brick relations. In a vertical–horizontal bond, the stride is generally constant and equals a horizontal dimension of a brick and a vertical mortar spacing (Bakırer, 1981a, 1981b). Based on the proportion of the height to the long side of a brick, the vertical mortal spacing is 1/3, 1/4, or 1/5 rising.

What we refer to as the pattern units in the scope of this analysis are squares rotated 45 degrees, nested, translated or interlocking. These are not exclusively the only pattern system perceivable on this panel. However, they are general enough to match the shapes that horizontal and vertical bricklay is used to achieve in this genre. Pattern parameters are closely related to brick parameters since the patterns consist of multiple bricks laid together to define a whole. The offset distance between horizontally aligned corners of nested squares or the stride between two squares equals the width or the depth of a half brick, depending on the bricklaying pattern.

3.3 Rules of Bricklaying

We define the least number of rules required for the recreation of the analyzed panels. There are two types of bricklaying rules, namely, the brick rules and the pattern rules. Brick rules define the three-dimensional relation between two adjacent bricks and the dimensions of the bricks through the use of parameters. Pattern rules define the geometrical order of the emerging pattern due to bricklaying.

In some cases, such as the panel from Sırçalı Madrasah, visually, there are three different brick dimensions, but two of them are half bricks with different orientations, and the other is quarter brick. Generally, the long side of the half bricks is used horizontally, while the short side is used vertically. The short sides of the front-facing half bricks are generally glazed in different colors (turquoise and navy-blue) to emphasize the pattern, while the long sides can be both glazed or naked. The quarter bricks define the corners and rotation points of the square-based patterns and can be glazed or naked.

In brickbonds, the rising of vertical mortar spacings defines intersecting inclined lines parallel to or mirroring each other. The inclination is related to the stride of bricklaying, and the distance between the lines is related to the dimensions of bricks. Their intersections define equilateral quadrangles of different sizes that are nested and intersecting. In the complex vertical–horizontal bond examples, the stride is strictly related with the brick dimensions, thus the inclination is constant and alike for different examples. We can interpret the complex patterns as squares rotated 45 degrees around their centers.

4 The Generative System for Historical Brick Wall Panels

Based on the spatial and constructional relations identified above, shape rules are defined either as pattern rules or brick rules. These rules, respectively, correspond to the design and construction of existing structures, to serve the purpose of integrating cultural-historical knowledge and the making from a computational approach.

4.1 Brick Rules

There are 11 spatial relations between any two bricks (Fig. 1) while bricks come together in the order of laying. For each brick relation, there are two possible reciprocal shape rules except the first three that are spatially symmetric. The rules are named based on the relation they define and the order of the bricks added to the right-hand side. For instance, Rule 4.1 and Rule 4.2 represent two alternatives to achieve Relation 4. In rules, we use labels to indicate the front-facing borders with colors of the bricks, and tags in relation to labels to indicate their dimensions and distances between bricks.

The first three rules define the relation of bricks placed with the same orientation in the XY-axis are the most commonly used ones. These rules do not require variations based on the order of the left-hand brick and the brick added in the right-hand side since both cases would be the same with Euclidean transformations. They show the addition of bricks in a row, the laying of additional rows with a stride. The second and third rules also show the definition of the borders of square pattern units. Horizontal bonds without quarter bricks can be reconstructed with these three rules. In the fourth rule, the long faces of the bricks are facing to the front but one of them is rotated around the XZ-plane. The following four rules include bricks laid

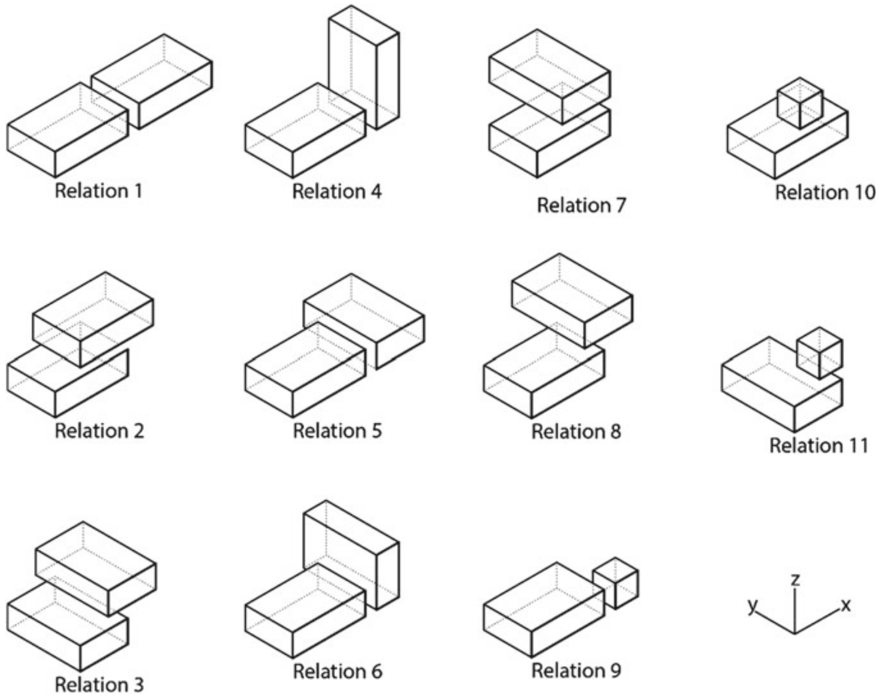

Fig. 1 Spatial relations of brick pairs

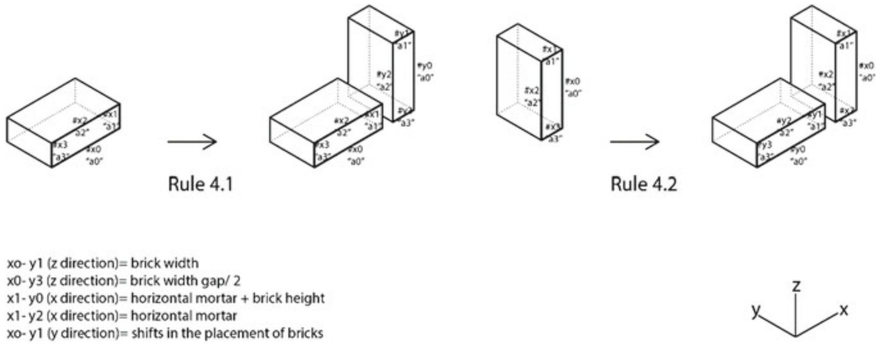

Fig. 2 An illustration and the list of parameters for two brick rules

in different orientations on the XY-plane. Rules 9, 10, and 11 are for relationships between quarter bricks and larger bricks.

We specify the color of the bricks with the letters a, b, and c in labels which correspond to naked brick, turquoise-colored glazed brick, and navy-blue-colored glazed brick, respectively. The rules can be applied for bricks of the same color or for transition, in which case the color of the brick on the left is the same as the newly added brick on the right. They can also be used for the transition between bricks of different colors. The labels of bricks are constant and do not change during application.

The parameters that express the distances between the front-facing borders of bricks define the brick dimensions, shapes, subtle shifts in the placement of bricks in Y-direction due to craftsmanship, and mortar spacings for both directions (Fig. 2). In Sortal GI, we use tags related to the labels to calculate and parametrically restrict the distances between labeled curves with distance directives. The labels and tags are not removed after the application of a rule since the same brick could be the left-hand shape for two different applications. To define the settlement of bricks in the mortar after the bricklaying, a post-processing brick rule can be defined showing the rotation of prisms representing bricks around their centers. This rule would require a change in the labels to select and rotate the bricks without a direction restriction.

4.2 Pattern Rules

In wall panel designs where the bricklaying is a combination of horizontal and vertical bonds, glazed bricks are utilized to overlay additional layers of patterning. The groups of glazed bricks form certain shapes, i.e., rotated squarish ones, and the geometrical arrangement of these shapes form a pattern, i.e., one with interlocking rotated squares. The panels of vertical–horizontal bonds are fundamentally based on an arrangement of squares. There are interlocking squares of different sizes for each panel. The arrangement of squares in the panel can be repeated with three rules

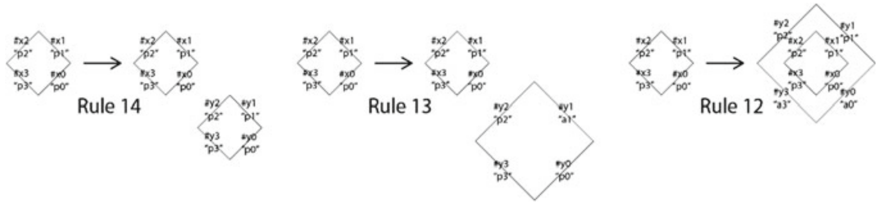

Fig. 3 Pattern rules

(Fig. 3). The relationship of the inner squares defines the overall arrangement of the model as well as the intersections between the other squares. With these rules, the squares that form the basis of the geometric layout of the panel turn into a bricklaying pattern with the brick rules. The first pattern rule shows the translation of the same-sized squares while the second shows the relation between two different-sized squares. These two rules can be used to set up the layout. The third rule is for the placement of nested squares. The distance between the squares is directly related with the dimension, count, and orientation of the bricks that fill them as well as the mortar spacings. Squares and the areas between nested squares are filled with different bricklaying rules (Fig. 4). For all pattern rules, the format on the left side of the rule is the same, regardless of the size. With the rule set, the bricklaying and pattern on different panels can be produced in relation to one another.

5 Results of the Generative System

For validating the grammar on other designs of the same genre, we apply the parametric rules to recreate existing panels from the same period and geography. We have reconstructed simple horizontal and vertical–horizontal brick panels from the period implementing brick rules (Fig. 5) and more complex patterns with both brick and pattern rules. For the latter, we have recreated panels from the Konya Sırçalı Madrasah, Çay Taş Madrasah, Amasya Gök Madrasah Mosque, and Akşehir Güdük Madrasah (Fig. 6). The resource for the first is site surveys and the latter three are re-modeled from the descriptions and drawings by Bakırer (1980).

We define the bricks with the borders in Sortal GI, labeled the front-facing borders, and used distance directives to set specific constraints. The directives define the range of the distances between the edges of the left-side brick and the brick added on the right side using tags, thus the dimensions and the spatial placement of added brick with the mortar spacings. The labels indicate the different edges of the bricks and the define type of the bricks. We define the target and the reference edges between which the distances will be calculated. To set the distance range, we refer to the existing literature. We use the random tuple function in Sortal GI to get a distance value in the range. The application requires a direction vector as an input. Since we cannot change the input in relation to the orientation of the left-side shape, the

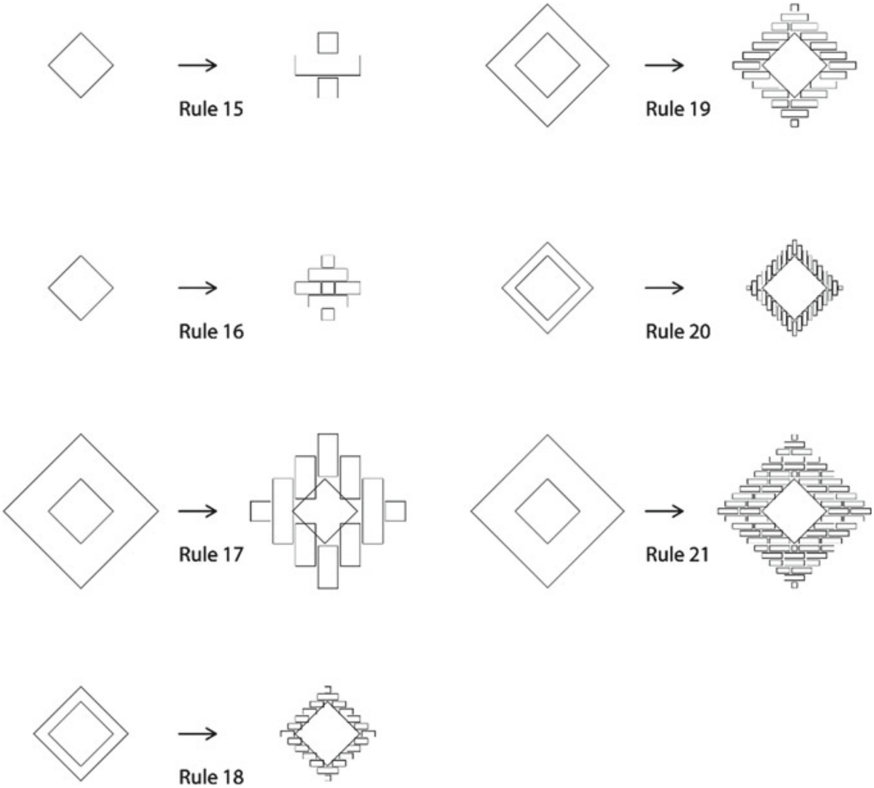

Fig. 4 The rules to integrate the bricks and the square motifs of the pattern

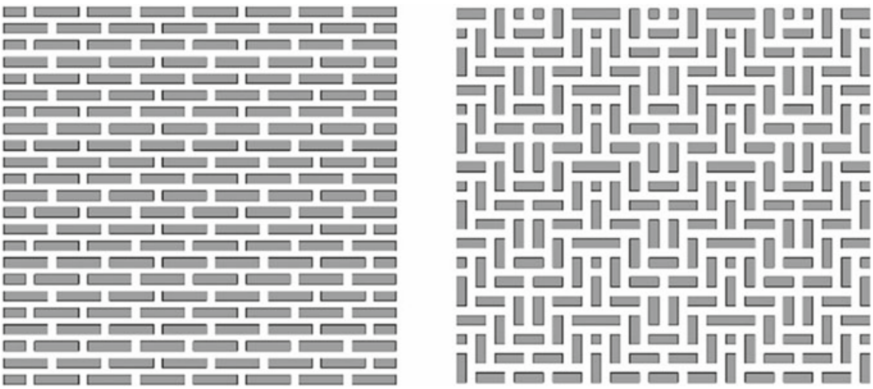

Fig. 5 Simple bricklaying patterns from the period

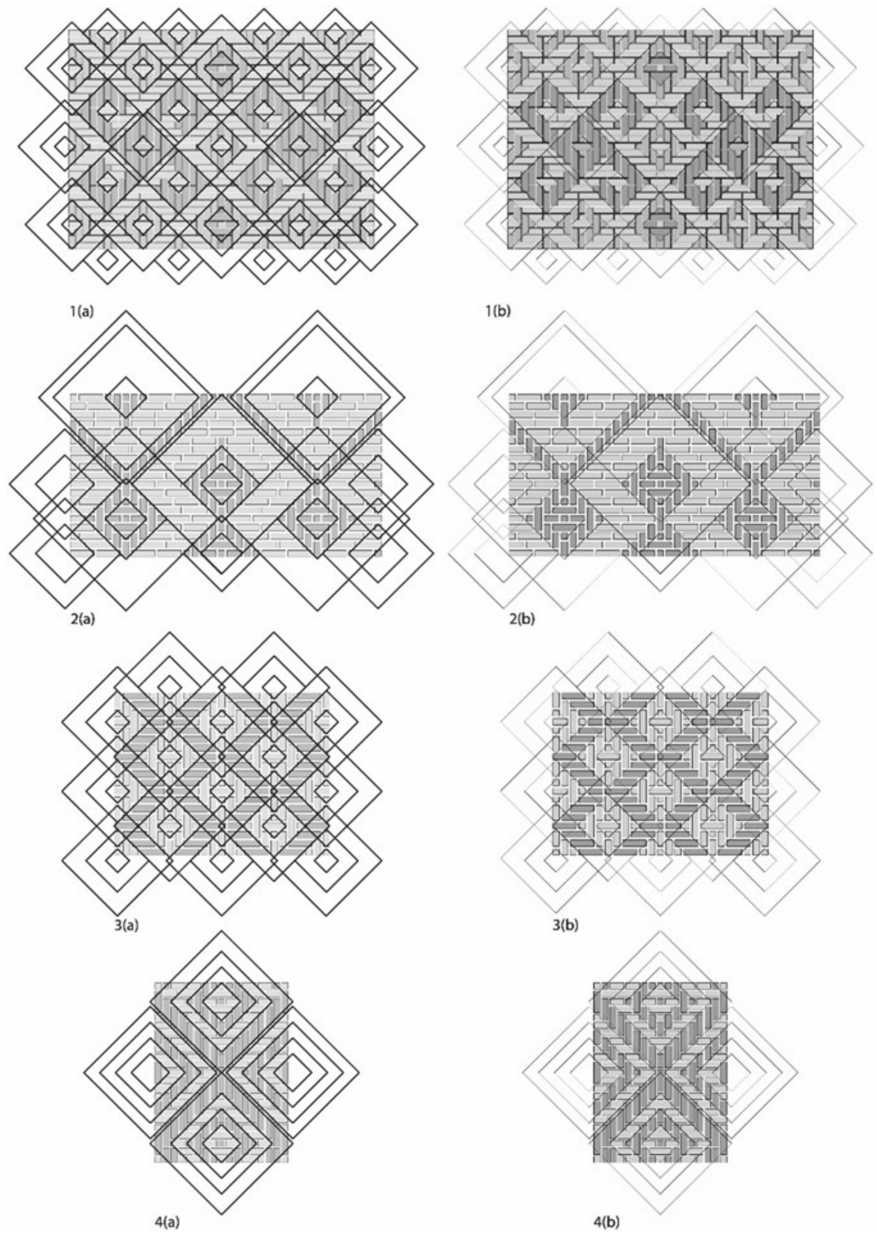

Fig. 6 Panels from the Anatolian Seljuk Period (1) Konya Sırçalı Madrasah, (2) Çay Taş Madrasah, (3) Amasya Gök Madrasah Mosque, (4) Akşehir Güdük Madrasah. Overlain representation highlights the patterns in the left (**a**) and the bricklaying in the right (**b**)

application of rules in different directions requires the definition of additional rules with appropriate vectors. This issue could have been solved if we were able to define the direction vector using the labels of the left-hand shape of the rule.

6 Conclusion

The visual patterns in the brick wall panels from the Anatolian Seljuk monumental architecture are results of both the spatial relations of individual bricks and their constructional logic. Shape rules can represent the procedures of manually assembling the bricks but are not enough to simultaneously generate the additional layers of patterns that come about. The geometrical organization behind the various spatial relations of these multiple overlapping patterns is represented in complementary shape rules. We define the relationships between the units, i.e., bricks, at different scales with a small number of parametric rules to reconstruct different panels from the period. Exploring the formal design of the pattern and the sequential assembly of individual bricks during the making process, the application of parametric rules for various structures reveals the commonality in the construction knowledge of the patterns. The study of the generative system displays that the basic building units are not sufficient to understand or reconstruct the bricklaying.

The proposed approach is to analyze and document a common element of architectural heritage such as a brick wall beyond its overall structure. With consideration of the spatial relations between different parts and their combinations in a historical context, it helps to understand the know-how behind the design and making processes. Applying pattern rules together with the brick rules also increases the possibility of variation in the results. Changes in the brick colors, application orders, and the parameters will change the overall layout. As a limitation, the shape rules hereby shown do not represent the material interactions and the manual construction, measurement, and alignment processes which are essential factors in the formation of the geometric shapes of the panel. With the inclusion of such parameters and the parameters of movements of a robotic arm, the grammar has the potential to be applied for physical constructions with numeric control in future studies. Other future plans involve the inclusion of the curvature of the surface as a parameter to the rules to transfer the relations of bricklaying patterns to curved surfaces of vaults, arches, or minarets.

A generative system that integrates the design and its construction provides a ground for more comprehensive architectural heritage studies since transferring knowledge of making and knowledge of form is essential to develop a holistic understanding of the analysis, preservation, and application of knowledge. The overlapping patterns of visual design and bricklaying, i.e., different parts and wholes, shed light on the multilayered nature of a sequential procedure such as wall construction. The paper relies on the limited historical research on the Anatolian Seljuk bricklaying and on-site documentation. At the same time, it taps a potential to expand this literature and survey methods by yielding to new understandings of products taken for granted.

As an approach to transfer the knowledge, the method can be applied to other cases in other domains where units and repeating relations between them define the whole.

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Experiences in Dissemination AND Teaching of Formal Methods in the Architectural Domain

A Data Workflow Approach for Pedagogical Sensitization to the BIM Concept

Mohamed-Anis Gallas, Gregorio Saura Lorente, and Etienne Godimus

1 Introduction

The evolution of BIM in recent years has been very rapid. This accelerated progress in the industry is pushing the academic sector to create discrete initiatives to try to fill the training gaps needed in the professional world. However, this type of training requires the prior acquisition of skills that are not integrated into the university curricula and which should be integrated in a transversal way from the first years of study (Andersson, 2013; Boton et al., 2018; Huang, 2018; Zaed et al., 2021).

The core of the BIM methodology is the creation, manipulation, and exchange of building data (de Boissieu, 2020, 2022). This means that the entire building sector is undergoing a systemic transformation. However, the training of new professionals is oriented toward the use and handling of software to produce physical deliverables. It is important to consider that the objectives of BIM training for professional practice differ from training within an academic framework. Indeed, in the latter, the objectives are the acquisition of competences that can form an analytical and critical capacity of the methodology and its tools (Adamu & Thorpe, 2016; Ibrahim Mahmoud, 2014; Kovacic et al., 2015; Nakapan, 2015).

There are many articles and survey studies that reference how many universities are teaching BIM (Adamu & Thorpe, 2016), how many students know about BIM (López Zaldívar et al., 2017), and how BIM courses should be structured during the

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5 years of study (Zaed et al., 2021). However, no articles have been found where pedagogical content is proposed regarding the source of the methodology: the data.

The digital tools used in the construction industry evolve every year, every quarter, or even every month. The concept of BIM is more about how information is structured and how it is transmitted. This is independent of the software used. Students must understand the importance of semantics in architectural models, as all uses of these models will be dependent on it.

The presented pedagogical experiments were evaluated from student feedback. This was collected from different sources. We analyzed the exchanges with students from collaborative tools, such as Teams (messages, forum). We also analyzed recordings of online meetings carried out by student groups during teamwork. The university organized a student survey for every course. The students gave an appreciation of the course quality (organization, outcomes) and comments. The comments were evaluated and used as feedback resources. The last source was the professor's notes taken during the live meetings with students.

2 Semantic Modeling Abstraction

The history of modeling is organized in three steps: 2D drawings by geometrical representation tools, 3D models by geometrical 3D modeling tools, and finally the generation of more linked and automotive 3D models. This process is the result of the evolution of CAD tools through the last decades. This process is appreciated by students who can make their practices progress from representation to 3D "smart" models. They make reference representations, better known as sections and plans. The generation of "smart" 3D models is considered as a faster method to make modeling activities more precise, more evolutive (fast modification), and to generate 3D models from 2D representation. The semantic features of the semantic (what we called "smart") are not well known by students and most practitioners because they are not visible or easily represented (Ambrose, 2012). At the same time, the links that also characterize the semantic ("smart") models are not known and visible for most users of modeling tools, such as Archicad and Revit. Our practice of 3D semantic modeling allows us to make some observations:

- Most uses of structure semantic modeling activities are from 2D representations.
- The constructive roles during 3D semantic modeling activities are considered but not the different families or features structuring the models.
- Modeling activities are considered as complex (even for BIM Level 1) and not really adapted to design practice (compared to conventional 2D/3D representation tools) (Hochscheid & Halin, 2019).

These observations show the need for a high level of abstraction to understand the nature and features of semantic models (more common named BIM models). The abstraction concept is used as a first representation tool of reality. It should evolve to generate new representation conventions of the complex semantic structures of

BIM models (Halin & Gallas, 2016). In this context, we propose a pedagogical experiment of semantic modeling activities. The activities focused on model structure analysis using a graph representation conventions. The graphs were proposed to first-level Bachelor's students studying architecture, enrolled on the Introduction to Digital Architecture course. Graphs were considered as a simplified representation of a data workflow of geometric and semantic models of commercial tools; SketchUp, Archicad, and Revit. We identified the elements, classifications (tags, categories, families, types, instances), database, and deliverable of every analyzed model. We also identified the links between all the models' components. The representation used was inspired by data models able to describe model objects and data exchanges between them. We chose to use a non-conventional data model to simplify the understanding and the creation process of the graphs. A simplified online dashboard tool (Miro) was used to visualize and to create the graphs. A template was given to the students to help them to adopt and integrate this new representation practice (Fig. 1).

We believe that data model representations (materialized by graphs) should be considered as major pedagogical outcomes, like mastering conventional architectural representations (elevation, section, and plan). The use of graphs, from the first step of the architectural learning process, helps students to think about the data that characterize (or are linked to) architectural models. This first outcome could be considered as a first step to assimilate BIM concepts.

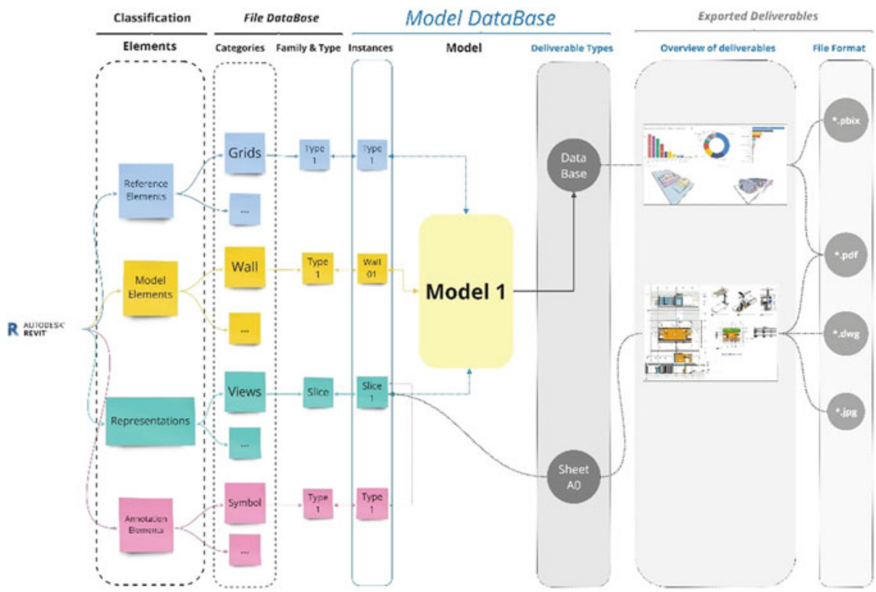

Fig. 1 Graph of a Revit global data model (simplified)

3 Assimilation of Semantic Model Structure for Modeling Activities

The assimilation of semantic model structure is seen during the Introduction to Digital Architecture course. The course outcomes are:

- To create global knowledge about the evolution of the use of data in design practice and the birth of digital design tools.
- To understand the differentiation of model types involved in digital design activities.
- To explore a methodology to analyze and integrate semantic model structure into modeling activities.

We will focus on the third outcome materialized by way of an educational experiment organized in two steps. The first step is a semantic analysis of a Revit/Archicad model structure as a simplified mapping activity. The flow that is intended to be taught to the students is to start with the reference elements, creating boundaries and references in space, then to explain how the model elements are positioned there, and then to explain the representation elements, which are completed with the annotation elements. This sequence is based on BIM modeling software. The classification of all elements differs from open formats, such as Industry Foundation Classes (IFC).

We propose a graph template that describes a Revit/Archicad model of a simple project (wall, slab, door). We also give a Revit model of an architectural configuration (Two side roof, window, wall, and slab). Students are asked to fill in the graph and integrate information that they should identify and discover from the Revit model. They are asked to identify the elements of the model and classify it in the correct data structure. They are also asked to give the specific information and proprieties associated to these objects (Fig. 2).

The exercise was proposed at the end of the second course. We collected some reactions and many questions from students about the exercise expectations. This reaction is explained by the lack of an analytical exercise during the first level of bachelor's studies. Students are used to producing objects (or models) but not to remap or analyze existing ones.

We chose this method to help students to be more interested in the structure of manipulated models. It was also a solution to develop the continuity between a model structure and tool interface. It was a simple way to reduce the feeling of complexity associated with the exploration of semantic models. The complexity is also associated to the hierarchical links characterizing elements of the models, elements of reference, representations, and annotations. These links are invisible and not tangible directly from the Revit (or Archicad) model but only through representations, such as graphs.

The evaluation with delivered graphs shows that most students can identify elements, categories, families, types, and instances. They are also able to notice differences between views and schedules/annotations and dimensions. The identification of the link between the elements seems to be more difficult for students. This statement is explained by the difficulty in noting the difference between a model

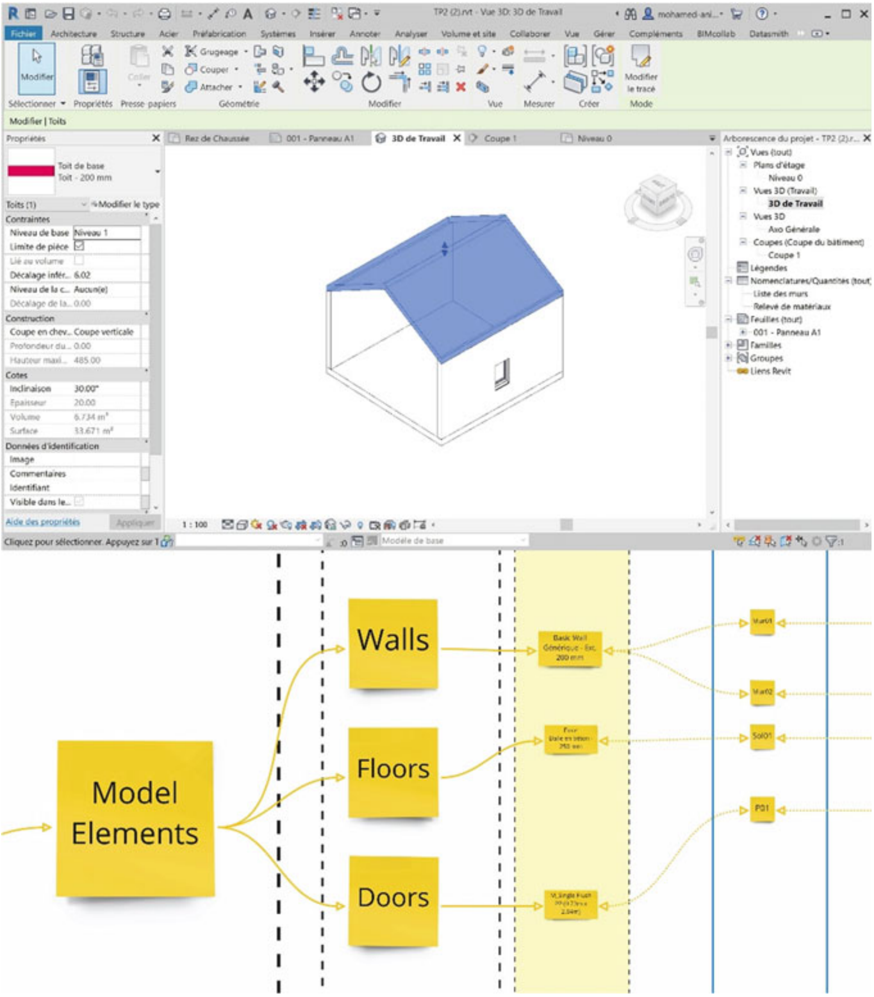

Fig. 2 Revit model and graph template

and representation, particularly for first-level bachelor's students. We had predicted these difficulties so we proposed the mapping exercise. We tried to explain that one model could generate different representations without being modified or impacted.

During the second step, we reversed the process and proposed a data model graph that would be used to generate a Revit/Archicad model. The graph integrated elements, categories, families, types, and instances of objects. It also specified the information and features associated with the objects. This task tended to enhance the outcomes of the first exercise. Students not only tried to identify objects in the tool interface but created it and integrated properties following a clear semantic scheme. For this second phase, it was necessary to go a little more into certain aspects of the

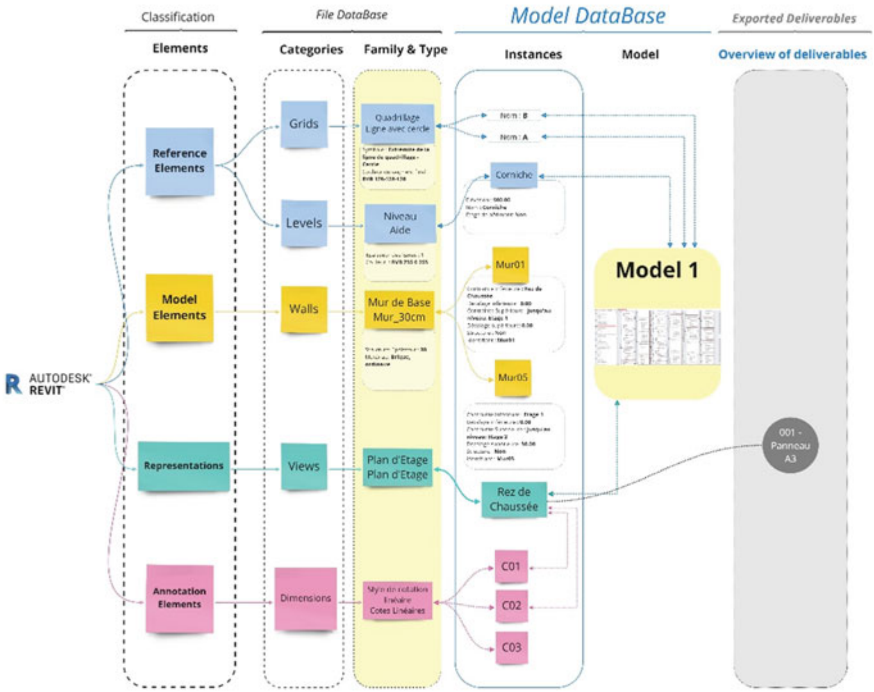

Fig. 3 Revit model structure and features

modeling software. Students needed to know where certain basic tools were located, as well as basic notions of object parameterization. The notions of practical use focused on the simplest elements of reference, modeling, and representation.

The proposed exercise was to start from the semantic schema of a simple model. The student should not focus on building something architecturally coherent, but to translate the information model into the modeling software (Fig. 3).

The model graph has the following elements:

– Reference elements: grids and levels.
– Model elements: walls, floors, doors, rooms.
– Representations: views and schedules.
– Annotation elements: dimensions and annotation symbol.

The main goal was to achieve a coherent semantic model, instead of focusing on conceptual, architectural and technical constraints. Although the elements of the model were of great simplicity, the students wanted to give a sense to a 3D space. Many of the questions raised during the practice of the exercise in class stemmed from the desire to create a correct connection between walls and floors, as well as the graphical representation of the sectioned walls. All these questions arose because the students, even if they were encouraged to ignore the architectural character of the exercise, were inclined to abstract the representation of the architectural object in 2D (Ambrose, 2012).

A strong emphasis was placed on the abstract aspect of the work during the exercises. The objectives were clearly stated at the beginning of the sessions: to identify the origin and destination of data within a semantic model. The problem with this pedagogical approach is that it remains rather isolated, and should be integrated by complementing other courses, both design studio and more technical courses. This approach needs to show its potential throughout the architecture curriculum.

In the second year, the pedagogical proposal for digital modeling is based on the abstract model, in order to gradually define an architectural model where all the semantic components of the model are organized in such a way that the classic deliverables that are usually worked on in the design studio can be extracted (Fig. 4).

This way of coming to conceive and model a project, while being aware of the semantic structure of the information it contains, prepares students for the implementation phase of the third year. This course aims to move from the study of the data itself within the models to its manipulation and creation with visual programming tools (Tedjosaputro, 2020).

At the end of these courses, one of the main shortcomings is the lack of collaborative practice. This is a pedagogical approach that should also be implemented in the early stages of abstract learning of model semantics. This causes students many problems in the development of the design study projects, as they have not been taught to devise modeling strategies aimed at creating and exchanging information. Interoperability is also a question of data schema mappings.

4 Assimilation of Semantic Model Structure for Collaborative Modeling Process

4.1 General Context for This Experiment

The BIM and collaborative design introduction module had been taught for two years, with a theoretical base focused on BIM protocols and conventions from different countries, and processes. This course was completed with a brief introduction to IFC schema. The final objective of the course was a team modeling of a building, where the teams had to define objectives and a BIM Execution Plan (BEP).

From the surveys we conducted with the students, one of the predominant comments was that in the collaborative work, the student who chose the role of BIM coordinator learned more about BIM than their partner, who, for example, had to concentrate on the modeling, writing the BEP or other less attractive BIM tasks. This made us rethink the course, opting for an exercise game, where everyone had to follow a set of rules, acting as modelers, coordinators, and managers at the same time: BIMTown. In general, there was a lack of understanding of all the processes, especially the structuring and transmission of information during the realization of

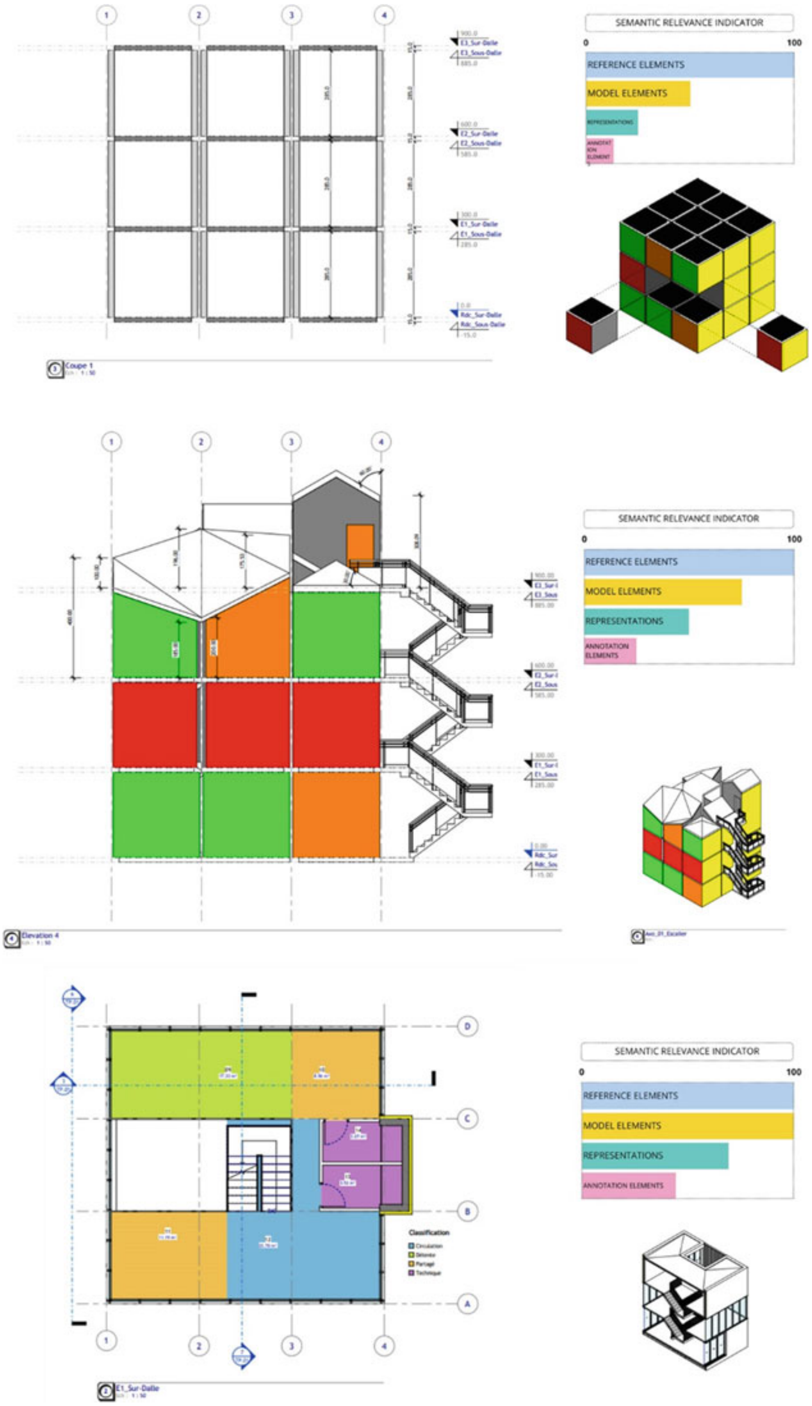

Fig. 4 Semantic model features (modeling activities)

the project. The students understood that the aim of BIM was to model and make "clash detections".

The model used for BIMTown was simple (Wall and Slab) without any formal or structural complexity. We chose to use a simple (abstract) model to relieve students of any cognitive overload related to architectural or structural constraints. We used it as a solution to make the students focus on data and not on objects. We were entirely convinced that the treatment of objects and their constraints would be easier if the data were mastered.

4.2 Objectives and Basic Assumptions

The aim of BIMTown is to enable all students to assume the most common roles in a BIM process, such as Modeler, Coordinator, and Information Manager. At the end of the game, students should know why the rules of the game are necessary for a collaborative digital modeling process. These rules should be translated into BIM Execution Plans in their future projects.

Students should:

- Understand the semantics of IFC models in order to exchange with other students.
- Be able to read embedded information within the models.
- Understand the need to establish protocols for the exchange of information (Fig. 5).

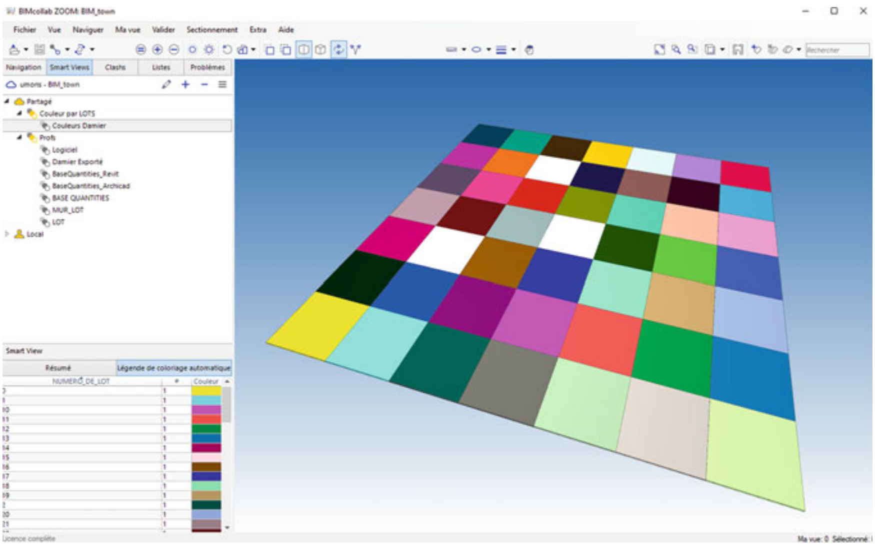

Fig. 5 BIMTown common IFC model

4.3 Description of the Experiment and Tools Used for BIMTown

This new pedagogical approach succeeded in democratizing the experience for all the students within the framework of a game. This game consisted of assigning each participant a random plot of land within a board of 49 plots. Every student had to find their plot within a common IFC model. The number of the plot was indicated in a parameter within each plot. The student had to reference their own IFC model within their authoring software and model a wall that had to be aligned with the wall of their plot neighbor. Depending on the position of the plot the student had to model three or four walls. Each wall modeled by the student had to be perfectly aligned with the wall modeled by their neighbor, with whom they had to agree, as well as contain a parameter with an identical code to be generated from the number of neighboring plots and the axis that separates them (Fig. 6).

The tools used in this work were Revit and Archicad, for the creation of the models, and bimcollabZOOM for the model controls and visualization of the files and IFC. The students were invited to use the BIM Collaboration Format (BCF) exchange platform of Bimcollab to communicate the incidents with their neighbors. In addition, all the students had to work in a common data environment where the personally validated IFC files were placed in a common folder so that all the components of the work could be visualized on the whole board. In this way, the students were also encouraged to create controls with Smart views to detect possible inconsistencies in the parameters of the objects (Fig. 7).

One of the main aspects was raising students' awareness of the notion of "exploitable data". For the model to be exploitable, it must contain all the data as requested. This means that the students had to verify that the model complied with the objectives of the game, by previously executing quality controls of the model to confirm that the model contained the parameters/attributes requested by the rules of the game. If it did not, it could not be compared with the rest of their neighbors. This exercise triggers a process of data validation, from the self-assessment of the structure of its model to the integration with other models. All these exercises of self-evaluation and model control were worked on with the help of SmartViews, which presents an interface of logical rules that the student can handle despite not having experience in this type of approach.

4.4 Analysis of Students' Results

The students spent a lot of time managing the creation and export of parameters and property sets to the IFC format. All these issues caused the first phase of the work to be very slow and caused some discouragement in the students. We explain this outcome by the changes in the students' habits. The proposed activities were considered as being in opposition to classical modeling activities and their goals.

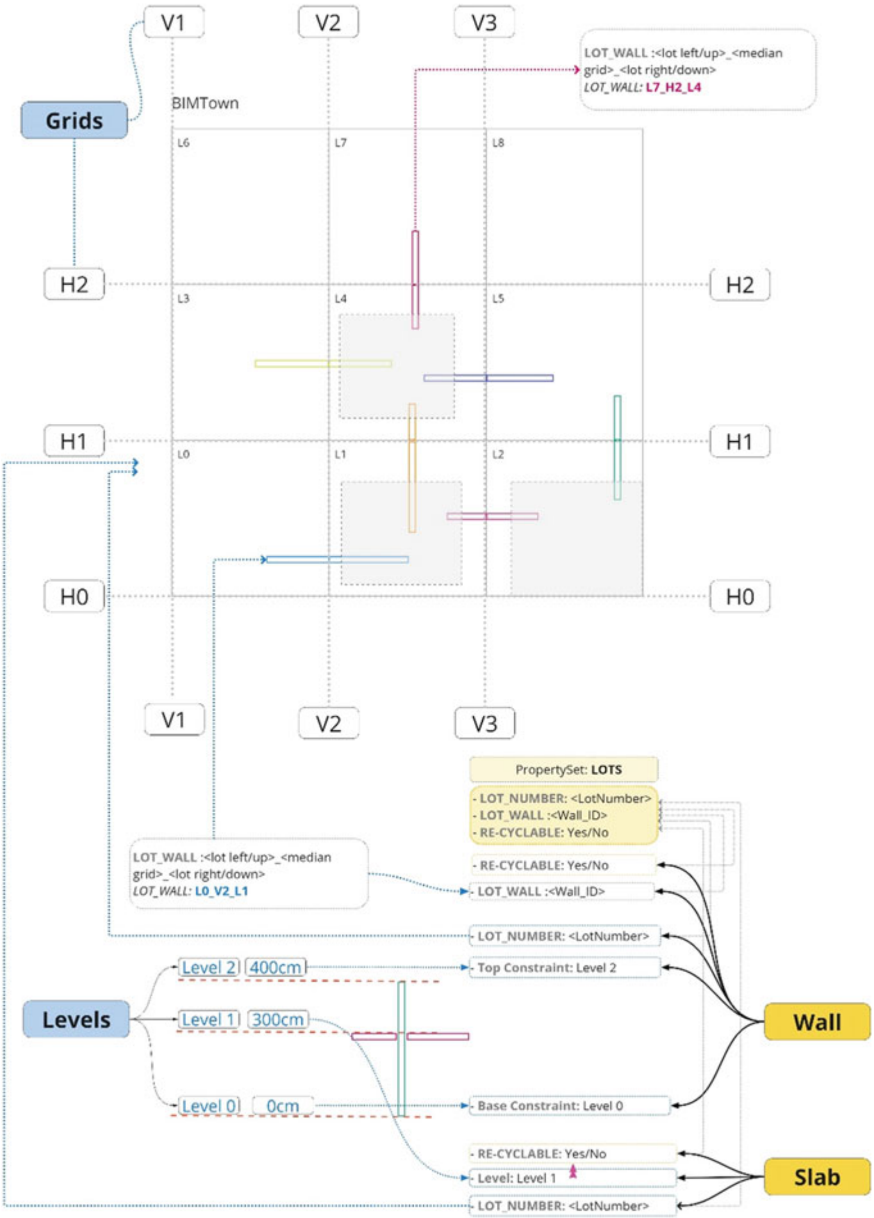

Fig. 6 BIMTown game parameters

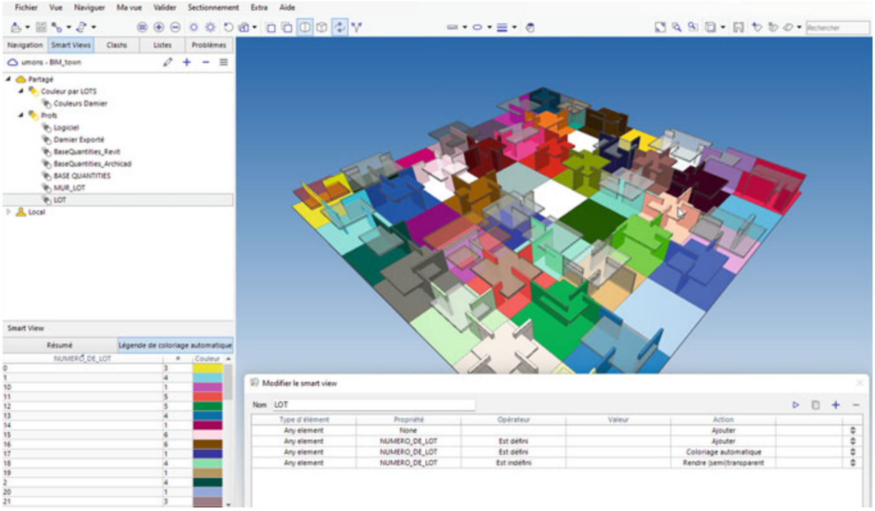

Fig. 7 Shared IFC model of the BIMTown game (BIMCOLLAB ZOOM smart view)

Once this phase was overcome, and all the students understood the methodology and the result, being a minimalist modeling, they were able to iterate and work with Smart views more freely.

The final result was quite satisfactory since all students faced the final work of the course having gone through the same experience of semantic moderation, model control, and collaboration.

4.5 Barriers or Problems Identified During the Experiment + Improvement

The following points were found to be barriers or problems for the development of the exercise:

- the limited knowledge of BIM software led us to drastically simplify the exercise.
- much of the time was spent on mapping problems or exporting to IFC (Archicad and Revit).
- getting started and handling visualization and sharing exported models with IFC viewers.

The improvements to the exercise, apart from being able to dedicate more time to the theoretical introductions that were necessary for the practical exercises, can be summarized in these points:

- More gamification (create different levels, challenges, bonuses, etc.).
- Enhance game rules communication and visualization.

– Better automatic control and feedback using solutions as shared smart views.
– Targeted tutorials for mapping and export tasks.

5 Global Outcomes

In the curricular framework of the architect's training, it has been perceived that there is a gap in the understanding of architectural models, such as semantic objects containing information. The attempts at theoretical training on aspects of BIM methodology and its collaborative approaches make the training gap evident. In another pre-digital era, it was understood that graphics had a specific weight in the architect's training, since the abstractions of the models were represented graphically in 2-dimensional deliverables. Nowadays, this graphic awareness should be learned from the point of view of the digital model, from which the deliverables are extracted (Ambrose, 2012).

The three experiments proposed in this paper try to fill this gap and respond to these new challenges. They update representation concepts in order to integrate the semantic dimension. They allow students to develop practices of representation and assimilation of the semantic complexity of models associated with BIM practices. These experiments demonstrate the impact of mastering the semantic dimension on the development of collaborative BIM practices.

The feedback from the experiments identified limitations and weaknesses, some of which have already been improved. Other points have been identified and will be improved during the next sessions. We are aware of weaknesses in the collection processing and analysis of feedback, and we are working on streamlining processes to make them more objective.

6 Conclusions

BIM project practices require a good understanding of concepts related to the differentiation of model types involved in this technology. The educational experiment mentioned above follows three steps: the first addresses semantic modeling activities for architectural project representation purposes; the second focuses on semantic model data structuring and exploitation; and the third concerns the assimilation of data structures in a collaborative BIM process. The mixing of these courses offers an educational work on the differentiation of model types handled in a simplified work of shared design, similar to what could be a collective practice with a BIM tool. The purpose of this outreach is to offer students a better understanding of issues on practices needed to collaborate in both the design (production) and operation (management) phases.

Today, we need future professionals to be able to create, read and understand the structure of the data contained in semantic models. The only way to face current challenges, such as energy management, circular economy, carbon footprint reduction, etc., is to digitize both existing and future assets.

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Massing and Skin: A Pedagogical Experiment with Physical and Digital Design Media

Ioanna Symeonidou, Giorgos Kalaouzis, and Alexandros Efstathiadis

1 Introduction

Architectural education in most universities comprises design studios, theory classes, architectural history, and a series of courses targeted on design tools and methodologies. The above are scattered across the curriculum in a way that courses cross-inform each other, and students obtain a global overview of the architectural discipline, getting prepared for their future career as architects. More specifically, digital design media and computer-aided design (CAD) in most universities are taught in the form of seminars with the aim to equip the students with tools not only for architectural representation, but also for design thinking. Geometric modeling is closely associated to the design process, as 3D models are crucial for the design development and decision-making. However, in the last two decades that computer-aided design was introduced in the academic curriculum of architecture, it has been observed that the creativity and formal experimentation of students in early years of their studies were heavily constrained by their knowledge of the respective design tools, comprising mainly of "easy" shapes, simple geometric volumes, and 3D objects that they could handle with basic knowledge of CAD tools. With the aim to expand the formal repertoire and leave space for more creative formal experimentation, we designed a foundation course for computer-aided design. The course titled "Introduction to the Use of Computers in Architecture" is a course with 4ECTS taught during the first semester of architecture studies at the University of Thessaly. The aim of the course is to prepare students for their subsequent studies, introducing them to the use of computers in architecture, addressing a relatively wide spectrum of technologies, covering tools for image editing, video editing, digital presentations, and setting the foundations for computer-aided design that follows in the second semester of

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their studies. The semester-long project is purposely combining analog and digital media, in order to introduce students to architectural representations while triggering artistic reasoning and creativity. Among the objectives is to familiarize students with the expressive practice of sculpture, to offer technical knowledge about nondestructive image editing with masks, transparency, and layers, and to challenge the students' imagination and creativity through an experimental and unconventional but well-prescribed design process. The challenges of 3D spatial representation that are addressed during the design process act as a stepping stone for 3D modeling software which will be introduced during the following semester. The idea of combining subtractive and additive construction strategies (3D sculpture) and layering of visual information (2D collage), along with physical and digital models and tools not only adheres to the learning objectives of this introductory course, but further expands the students' formal vocabulary beyond established building types and fuels their creativity and design thinking.

2 Controversies in First-Year Studio Teaching in Architecture

Digital technologies and computer-aided design (CAD) software has significantly transformed the professional practice of the architectural discipline over the last two decades. In consequence, architectural education institutes have strived to keep up with these changes by incorporating courses of digital tools into their curriculum. However, there is still an open debate on how and when architecture students should be introduced to digital technologies (Kara, 2015). Literature research reveals a great wealth of teaching protocols for first-year architecture students. One approach is to introduce digital tools early in the curriculum through mandatory or selective courses. An advantage of this approach is that students acquire digital soft and hard skill sets early on in their educational process and become familiar with the software and hardware that they will use throughout their professional career (Doyle & Senske, 2017). One could also argue that such approach is more attuned with contemporary architecture practice and the demands of the industry (Guney, 2015). Another advantage is that CAD tools are free of any physical constraints (like gravity), thus they provide first-year students with the compositional freedom to explore spatial forms and structures without having to worry about the limitations of the tangible medium used in traditional studio practices like drawing, sketching, and model making (Song et al., 2007). Furthermore, digital courses enable effortless, long-distance communication and sharing of the subject between students and academic staff (Guney, 2015). This was especially useful during the COVID-19 pandemic, where in situ studio courses were prohibitive and online classes were the only available form of teaching and will continue to find use in the post-pandemic world as the demand for remote-working remains strong.

However, opposing pedagogical approaches criticize the infusion of curriculums with CAD courses from the beginning of undergraduate programs. Digital technologies are accused of constraining the creativity and spatial exploration of first-year students due to their knowledge gap and software limitations (Song et al., 2007). As a result, the students' work is restricted to simple geometric operations with the use of a few basic CAD tools that ultimately leads to low-quality design, often wrapped under flashy renders and visualizations (Guney, 2015). Another point of criticism is that the barrier of the screen and the dependency on CAD software hinders understanding of internal scale and relations compromising the ability of the students to comprehend and design a living architectural space. It is proposed, instead, that first-year students should participate in intensive experimentation with hands-on projects with an emphasis on drawing, sketching, and physical model making, before being acquainted with CAD software. In this way, they can build a solid perception of space, scale, hierarchy, and internal relations (Kara, 2015), while they develop better comprehension of the materiality and constructability of physical objects (Song et al., 2007). Once these fundamental skills are acquired, more complex architectural projects can be assigned to the students, where they will tackle for the first time, the issues of habitable structures and lived environment. Digital technologies should only be introduced to the students at this point of the educational process as a tool to assist their efforts for realizing complex design solutions based on the spatial and synthetic skills they have already honed. Another benefit of this educational strategy is that students develop the ability to transition effortlessly between physical and digital tools and between different CAD software during their architecture design practice (Kara, 2015). Ultimately, architectural education should not simply aspire to teach software and programs but instead aim for an integrated digital design (Doyle & Senske, 2017).

Within this line of thought, the introductory studio course aims to combine analog and digital media targeting a broader understanding of tridimensional form, while introducing digital design tools in discrete phases across the curriculum, over three semesters, and building up the knowledge from 2D to 3D methods.

3 Learning Through Formal and Material Experimentation

Architectural practice has been associated with skillful knowledge of drawing and sculpture since the Renaissance. With the establishment of formal architectural education in the eighteenth century, architects were required to master drawing and sculpting as an integral part of their academic training (Białkiewicz, 2019). Sculpture and architecture have generally been considered to be interlinked as designed three-dimensional structures with indistinct dividing lines (Saliklis, 2007). Both practices share similar goals at a technical, societal, and symbolic level. Architectural along with sculptural forms must have structural integrity in order to withstand physical forces like gravity and weather effects. They must also be integrated in the cultural, political, and socioeconomical environment they are built in. At the symbolic level, both forms have to deal with aesthetic and expressional issues. Despite all the resemblances, architecture is characterized by more constraints compared to sculpture like cliental and contractor demands, or spatial and movement considerations (Billington, 1985). However, a successful architectural practice is considered to be one that manages to overcome these technical limitations and materialize the aesthetic intentions of the designer (Howard, 1966). Having to deal with this manifold objective of aesthetic quality and technical integrity, architectural education needs to address the challenging task of equipping students with both tacit knowledge and technical skills. It is easily understood that experiential learning can be of great value for architectural education, and this has been manifested through a series of successful studio curriculums across the globe. Already since the BAUHAUS years, experiential pedagogies have always formed the core of architectural education. In the BAUHAUS teaching tradition during "Vorkurs", the legendary introductory design class, Josef Albers' decided to teach design through paper *models "because it is an abstract exercise that allows students to focus only on the design and the paper, not on pragmatic or functional requirements"* (Demaine et al., 2011). Albers supported the doctrine that *"experimenting surpasses studying"*; he affirmed that *"playing"* with materials encourages inventiveness and real-time discovery of form. His pedagogical approach was to provide materials to the students for creative experimentation, restricting at the same time the use of machinery and other tools so that the students develop a *"feeling for materials"*. According to Albers such an approach *"forces us to begin thinking and doing on our own without a theoretical introduction, without method and without tools"* (Albers, 2013).

The above is in line with the ideas of Montessori about acquiring knowledge, *"he does it with his hands, by experience […] the hands are the instruments of man's intelligence"* (Montessori & Chattin-McNichols, 1995). Learning by doing has also been largely praised by Papert (Harel & Papert, 1991) and formed one of the core concepts of Constructionism, a student-centered learning theory that encourages project-based and experiential learning. Up to date, the above learning theories have had an enormous impact on architectural education, due to the nature of the discipline, and due to the need for transfer of tacit knowledge as well as the need for creative and artistic reasoning. This necessity is also explained by the theory of the Reflective Practitioner developed by Donald Schön (1990) where he discusses the Knowledge-in-Action, defined by the "routinized responses that skilful practitioners bring to their practice" as well as the Reflection-in-Action "a critical function, questioning and challenging the assumptional basis of action", a form of problem-solving on-the-spot, coupled with the construction of theory, or re-appreciation of the situation. Our methodology aimed to address the above, by combining media and teaching strategies, creating the circumstances for formal and material experimentation and documenting the process. The following section describes the procedural studio development and methodology.

4 Design Studio Methodology

The studio brief is based on the doctrines of constructionism (Ackermann, 2001; Harel & Papert, 1991) requiring the students' active involvement with physical models and digital tools for image processing. The initial stage of the project relies on pure design principles and artistic criteria. Students work with extruded polystyrene, a material they can easily cut, carve, sculpt, and employ a variety of additive or subtractive processes (Fig. 1). Polystyrene is a lightweight material that can be easily cut by novices in architectural model making, with the use of hot wire cutter or hand cutter. It is a cheap and easy to source material, therefore allowing for several iterations of design modifications, trial and error, and experimentation. This manual practice of wire-cutting and material subtraction will be revisited in later semesters when students learn about solid editing in CAD, namely, wire-cutting commands and Boolean operations.

The idea is to prepare the students for future CAD courses while giving them opportunities to expand their creativity toward artistic practice, without considering constraints for building design. They are prompted to work intuitively, without preconceived ideas. The aim is to widen their understanding of form and take distance from archetypical building forms. The moto is that the physical model *"Should not look like a building"* but it has to display certain hollow areas, to create interior spaces and thresholds, that will be conceptualized during the subsequent stages of the project.

Fig. 1 Students working on the polystyrene models at the university studio

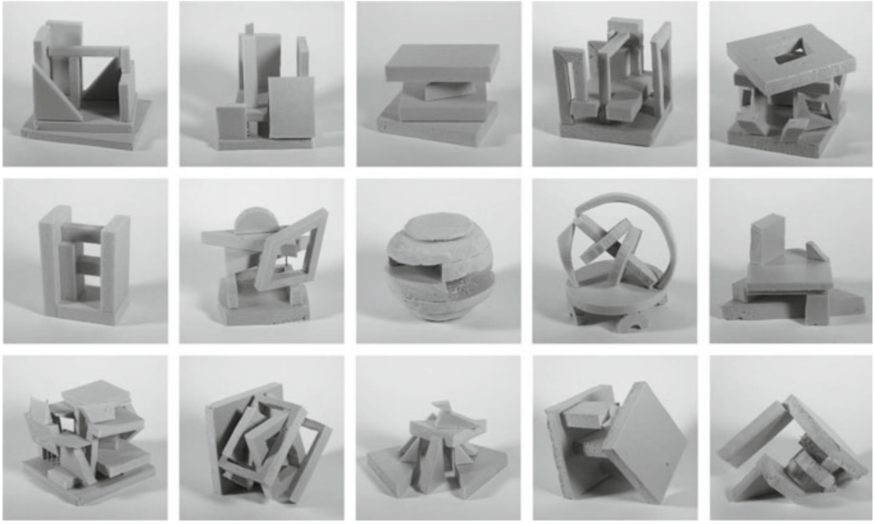


Fig. 2 Compilation of polystyrene models produced during the first stage of the exercise

The model making comprises mainly of subtractive and additive techniques with great affinity to creative processes of sculpture and very often also employs aggregations and staggered volumes. This initial formal exploration evolves as an intuitive artistic practice where students reflect in action (Schön, 1990) giving shape to a sculptural piece. The main requirement for this stage is to experiment with geometry and topological transformations so that the models display a clear tridimensional character with convex and concave areas which will later evolve into external and internal spaces. The models are photographed from various viewpoints, often leading to real-time discovery of counterintuitive spatial configurations by turning the model upside down, further expanding the understanding of the volumes and spaces. A series of these formal explorations can be seen in the following image (Fig. 2).

The students are also asked to document the process of their model making, presenting the sequence of processes that lead to the final object. This is done in the form of pseudocode (Fig. 3) that describes the design and construction sequence. They are therefore introduced to algorithmic processes and analog parametrics, by understanding the procedural material manipulation, the internal rules that govern the design, and the discrete steps one may follow to construct the form.

Practices of physical model making are intrinsic to analog sculpting and forming practices, in addition to this intuitive process, the documentation of design thinking, and composition helps first-year students understand and articulate their workflow and the constraints and variables that dictate their design outcomes. As a result, emphasis is placed on the design praxis itself, which can ultimately transcend technical, material, hardware, and software limitations.

This first stage of the project unveiled physical models with architectural qualities. We could observe a balance of open and closed spaces, a play of light and shadow,

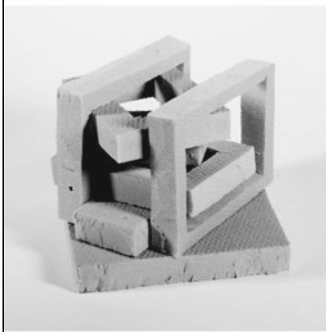
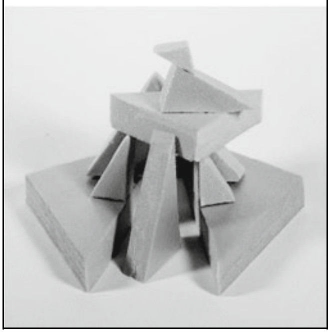
PHYSICAL MODEL	PSEUDOCODE
	• Create a flat rectangular solid volume • Create a copy of this volume • Randomly reduce or increase its area • Move the volume upwards • Randomly rotate the volume in z axis • Iterate the process 7 times
	• Create a flat rectangular solid volume • Create several copies of the volume • Randomly reduce or increase their area • Offset the perimeter of the rectangles and remove material to create rectangular frames • Solid volumes and frames can be placed horizontally or vertically ensuring a minimum of two contact points with the rest
	• Create 15 triangular volumes with a predetermined thickness • Randomly scale the volumes in 2D • Create a layered composition where volumes are placed horizontally or vertically • Each triangular volume has to connect to the upper and lower layer of triangles

Fig. 3 Examples of polystyrene models with accompanying pseudocode

and a well-thought equilibrium of smaller and bigger volumes, that led to models which combined structural stability with architectural design affordances. The exercise introduced students to procedural design thinking and modeling which is to be addressed during the following semesters with coding and visual programming.

The last stage of this design process involves the editing of the model images to create architectural collages of their envisioned spaces. This is the most challenging stage of the design process, as the students will need to source different textures,

Fig. 4 An example of "Massing and Skin", with polystyrene model (left) and textured model (right)

either from online databases or through photography of real-scale building materials and proceed to *"reskin"* the photographed model with new textures (Fig. 4).

Particular emphasis is to be placed on the correction of perspective, either through tools that are inherent to image editing software (such as Photoshop or Photopea) as well as more sophisticated strategies to combine images with the same point of view (Maestre López-Salazar & Juan Gutiérrez, 2018). The physical model will dictate the "massing" of the building while the digital collage will mainly focus on the building "skin". This is not always a straightforward task, as very often parts of the geometry are cylindrical or spherical, therefore a rectangular texture map may require a series of more complex manipulations (free transform, distort, skew, warp) to adjust to the underlying geometry.

In correlation to the previous stage, this is also to be revisited with 3D software during future semesters, when students learn about texture mapping and UV coordinates. The aim is that the students are acquainted with the functionalities of digital tools, before they actually implement them, and that they are aware of the manual process before they put it in practice in a digital environment. However, within this exploratory set-up, there is no evident process protocol, and often students will have to think out of the box, and resort to their creativity, they need to "hack" a 2D image to represent a 3D form. New design questions arise: How can we constrain a new design to a given massing option? How do the volume and skin counter inform each other? Eventually, how do we convert a sculptural volume to architecture? The notions of lived space and scale become of crucial importance. Eventually, how do we convert a sculptural volume to architecture? The notion of scale becomes of crucial importance. Images are often enriched with the use of human figures, building elements of known shape and size, such as doors and windows, as well as other objects that add to the understanding of architectural scale, internal relations, and movement.

Through this additive process with different layers of visual information, the volumes obtain texture, materiality, transparency, and depth (Gómez Zepeda, 2019). At this stage of their studies, due to the lack of familiarization with 3D software, among the objectives of this design experiment is to correct the perspective of the collage elements, adjust their color tone, light, and shadow to create a 3D image through 2D methods. The students will have to instrumentalize their previous knowledge from perspective drawing, free hand sketching, and painting to create a visual

Fig. 5 Community Center Concept by Avraam D. (Left), Art Gallery by the Lake Concept by Karagianni E. (Top Right), Bookstore Concept by Chasioti E. (Bottom Right)

composition of architectural scale. The process of transformation from the volumetric physical model to the representation of built form is per se challenging, not all formal explorations are suitable to be transformed into habitable space. This initial difficulty is compensated by the fact that for this second stage the students have a total freedom of choice with regard to the programmatic scenario. The more extravagant the form, the more sophisticated the design decisions. Students came up with novel scenarios such as art galleries, museums, ski resorts, beach bars, and bus stations. These were dictated by the form so as to match the geometry to a potential architectural concept. The images (Figs. 5, 6, 7) depict some of the projects. It is interesting to highlight here that the prescribed design strategy enables students to express tridimensional ideas without strictly relying on 3D software, this is in line with contemporary post-digital architectural visualizations which rely on sketches and collages and are defining a new stylistic trend among architectural offices (Gomes & Bae, 2009; Maestre López-Salazar & Juan Gutiérrez, 2018; Symeonidou & Papapanagiotou, 2021).

5 Results and Conclusions

The design studio revealed that first-year students were more capable to "think with their hands" to create 3D forms than to use orthographic drawings to represent a tridimensional idea, their creativity was not constrained by their knowledge of representational techniques, perspective drawings, axonometrics, or CAD.

Among the most common observations during introductory courses is the fact that students are limited by the design medium and only adhere to geometric forms that they can easily handle with regard to representation, they tend to replicate known architectural typologies, confining their imagination and creativity. The initial stage

Fig. 6 Bookshop Concept by Filippitzi E. (Left), “Boats in the air” by Kouskouridis I. (Top Right), Info Center Concept by Samalidou M. (Bottom Right)

Fig. 7 Museum Concept by Chasiotis G. (Left), “The Writer’s Retreat” by Alexandropoulou D. (Right)

of intuitive artistic practice appeared to expand the boundaries of conventional architectural form and enrich their formal repertoire with non-standard and even extravagant design projects. The idea to introduce physical model making which would be later processed digitally achieved exactly that, not to constrain the students’ creativity to known types and geometries. Frank Gehry has been among the pioneers that highlighted the importance of physical model making as a tool for form generation and design thinking, by working with big scale models which he later converted to digital files with a 3D scanner or digitizer, to further process them in 3D software. As William

Mitchell explained in the book about Frank Gehry, *"architects tend to draw what they can build and build what they can draw"* (Mitchell, 2001).

The pedagogical approach employed in the first-year design studio had a similar starting line, but instead of leading to the final editing of the volumes in 3D software, it skipped the phase of 3D modeling and editing, to jump directly to the representational stage of the projects. Students worked with textures and collages, with the aim to digitally wrap the volumes with a textured skin, to define areas of solid material, transparent or semitransparent elements, to distinguish internal and external spaces. This studio acts as a general introduction to computation and as a stepping stone to courses that follow in subsequent semesters and introduce students to actual 3D modeling and photorealistic rendering. Following this propaedeutic course on digital media, students were more prepared to comprehend geometry in CAD environments, they could easily understand solid editing, perspective and axonometric representations, and also a series of concepts relating to rendering, such as the scale of a texture map, light, shadow, reflection, and other attributes. When each of these topics emerged, students could easily refer to their previous experience with analog media.

The experimental teaching protocol discussed in this chapter proved to be a valuable experience for both students and educators. It confirmed the initial hypothesis that architecture students in the early stages of their studies can be more creative with their hands than with established architectural representation media like technical drawings or CAD, yet they were building up the necessary knowledge to seamlessly proceed to digital tools and tridimensional modeling in the semesters to follow. Students were not limited by their computer skills or programmatic requirements, and we witnessed an unprecedented formal repertoire which frequently tends to rationalize in the following years of their studies when they have to deal with floor plans and sections.

During the model making stage, among the hard constraints was the structural stability of the object, the material and fabrication limitations and the subjective yet necessary quest to create visually interesting volumes. Polystyrene proved to be a great material choice, as the students could very easily cut it or sculpt it. It was easy and cheap to source and thus permitted experimentation and several iterations of trial and error. This direct, hands-on approach fosters the first-year students' sense of materiality and manufacturability, stripped from 2D drawing limitations or preconceived notions of architecture and space. The ingenuity and originality of the initial models proved to be very motivational for the second stage of the exercise, which required to explore various techniques and develop new skills in image editing. The students were able to learn from their mistakes, understand the geometric rules of perspective representations, and adjust the "skin" accordingly so as to adhere to the intention of a realistic architectural representation.

Through this process students studied the importance of light and shadow, the notion of internal relations, movement and scale, and the overall atmosphere of an architectural visualization, before even being introduced to rendering techniques. Among the benefits of this exploratory approach is that students explore the rules that define their creative workflow and learn to train their aesthetic criteria and design standards before they actually learn the digital tools to implement them, therefore leading to the quest for high design quality and ambition once they master digital skills. Additionally, they learn to mix design methods, and freely experiment even if they don't know the end result, facilitating open-ended design processes and emergent results. By writing pseudocode or keeping a visual log of their construction strategy, they learn about the importance of algorithms, procedural design methodologies, and analog parametrics, before they even learn to write code. This can be considered as the meeting point of analog sculpting practices and digital design workflow, suggesting a new methodological teaching protocol for the introduction digital design processes that utilize mathematical reasoning and principles of computer sciences.

It is understood from the above that the greatest advantage of this preparatory course is the fact that in subsequent semesters, when students expand their digital skills and learn about solid editing, subtraction or aggregation, rendering and texture mapping, or coding, they always have some previous experience to relate to, draw formal and conceptual connections and expand upon their existing formal repertoire. During the two subsequent semesters, when students are introduced to digital media and advanced geometry, it is much easier for them to grasp a new concept when they had previously familiarized themselves through manual processes and abstract computational processes could be comprehended more easily when linked to an embodied experience about form and material.

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An Experience Around the Rationalization of Architectural Analysis

Plácido Lizancos Mora and Vicente López-Chao

1 Introduction

The images in this chapter are part of the 2015 course of the subject Architectural Analysis of the School of Architecture of the University of Coruña. At that time, there was a refugee crisis in Europe, with thousands of people fleeing the war in their homelands and forced to cross the Mediterranean to go into exile in Europe. This circumstance, which with other protagonists returns in 2022, led us to alter the teaching curriculum to address this unexpected situation. The supervening academic assignment to a group of 30 international students was to study a shelter response to this extreme situation, assuming that the city could accommodate 3,000 people according to the welfare authority.[1]

The students followed a research process on various scales. It included the recognition of the human group to be accommodated, the location of spaces within the city body with such capacity and with the maximum potential to achieve the integration of these people.

It is intended to reach the location and conceptualization of the appropriate place, in other words: a reception strategy. The outcomes were brilliant. A selection of some of the graphic documents produced showing these analytical capabilities is displayed in this manuscript.

[1] Provisional housing solutions were expressly rejected as an academic departure point on the understanding that the accommodation to be offered should to refugees must be aimed at facilitating a long stay and integration not just sheltering.

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These resources have been selected by the authors based on their scientific interest to explain:

- The use of an appropriate methodology of architectural analysis by architecture students in their process of discovering architecture.
- The formulation of a formal method that can accompany the performance of similar works.

2 Toward the Conceptualization of Architectural Analysis

The dictionary reports that analysis is 'the act of studying or examining something in detail, in order to discover or understand more about it, or your opinion and judgment after doing this',[2] that is, to separate the different qualities [of a body] by means of intellectual operations, split of the object of study to consider them in isolation in their pure essence.

Therefore, the architectural analysis looks for the ideas that define the so-referred "pure essence" of a piece of architecture.

To achieve this, analyzer methodically decomposes architectonic objects on its components. Secondly sorts its results, interprets the arrangement, and exhibits ideas through one of the rigorous languages and scientific communication. In short, this analytical process addresses issues as

- How the static and dynamic components of a building are articulated.
- What relationship exists between the characteristics of a certain space and its purpose.
- The architectural space as a setting for human activity.
- How structural and construction systems are related for their material, formal and aesthetic expression of architecture.
- How the use of such a certain building systems shape architecture.
- The role of the building skin as a technical, spatial, and semantic interface.
- The interpretation of the power of walls as physical boundaries setting the relationships between interior and exterior spaces.
- The way each physical enclosure manages human psychological well-being due to space perception, intimacy, and lighting.
- The relationships between the building and the environment as physical connections and all kinds of links.
- The relationship with its topography and its consequences as accessibility, sun and wind exposure, views, etc.
- Gestalt and morphological criteria as a basis of the shape of the building.

[2] "Analysis" meaning. Cambridge English Dictionary.

3 A Methodology for Architectural Analysis

3.1 How to Approach a Rigorous Analysis of Architecture?

Nowadays most of the scientific literature refers to architecture not as the final conclusion of a complex composition, but as the organization of a set of qualities in an artifact that admits very different outcomes. Following this analytical strategy, it makes sense to think that architectonic analysis must go above its mere visual aspect. The essence of architectural analysis is to identify deepening qualities inherent to the architectonic body. The developed analytical method identifies each of these components and how they participate in the characterization of the whole. So, once all secondary aspects are dropped, dominant concepts will be visible and logical rules behind the design will be unveiled.

3.2 Types of Architectural Analysis

The architectural designer must encompass simultaneously a number of various tasks not just the configuration of the field of human activity but the design of spaces, their technological resolution and the endowment of meaning and aesthetic values in a structured budget. These are some of the dimensions that are part of such a complex activity as architectonic design is. So, architectural analysis must be able to manage plural requirements, several and diverse research paths, and multiple analytical objectives within the framework of architectural knowledge. Above all, analysis will always have to answer two major objectives: to identify the ideas that ruled the design of the project and to explain the scope and characteristics of the architectural artifact as a whole. In general terms, the analytical method should be considered complete when it attends to the functional, spatial, technological, territorial, visual, and semantic sub-analytical categories.[3] The scope of each of these items is as developed below.

3.2.1 Spatial Analysis

Spatial as an analytical category addresses a sophisticated conceptual problem: the definition of architectural space. Its complexity comes from the non-rational but sensitive dimensions of space, connected with perception and other subjective

[3] A teaching methodology that develops this classification has been successfully used in the Architectural Analysis subject of the School of Architecture of the Universidade da Coruña since 1993. It is not a random fragmentation of the analytical fact but a rigorous and rational structuring that attends to the architectural fact as a whole. These are not existing classifications or stagnant categories, but rather dynamic and intertwined ones that are presented to students according to a logical sequence of increasing complexity.

constraints such as cultural or ideological background. From an architectural point of view space can be understood as a raw material shaped by enclosures, boundaries, color, light, and all kinds of signs managed under certain architectonic strategies. We will agree that spatial analysis refers to the characteristics of a space in a given architecture. Thus, we will approach the evaluation of space from notions such as compression and expansion, preponderance and dependence, isolation and permeability, transparency and opacity, intimacy and publicity, or extension and concentration. This approach encompasses venues, itineraries, limits, light (natural and artificial), textures, emotions, sensations….

3.2.2 Functional Analysis

This analytical category refers to the use of built spaces. Use and function should not be considered from a sociological point of view, but from the architectural expectation generated by the spaces as containers of functions. Should we identify what uses are required in the spaces studied, defining the relationship between the spatial configuration and human activities developed in identifying the kernel of that relationship. The final purpose of the exploration is not to bring to light different spaces linked to certain uses, nor even their mere classification. Functional analysis pursues to discover the rules and the order that underlie the spatial organization of an architecture. Functionality encompasses circulations, routes, accesses, scheduling, identifying users and activities, versatility, capacities, compatibilities, and even emergency situations analysis.

3.2.3 Site Analysis

Buildings rise in a physical location but also in an environment resulting from a cultural construction. It cannot be limited to the strict establishment of the built place and its borders, but it is necessary to find the relationships that make this particular arrangement peculiar. Relationships that will be subjected to the search for values such as permeability, preponderance, connection, privacy, or mimesis, without forgetting their connection with the applicable regulations in the area. The building-environment relationship has to do with *genius loci*, topography, urban or landscape regulations, climate, memory, social impact, public opinion, geology, archeology, skyline, and of course with the connections to all kinds of technical systems.

3.2.4 Technological Analysis

Architecture is at the end expressed through its material construction. Edifices must withstand natural demands such as climatological and gravitational ones and behave appropriately toward user requests as the efforts caused by the use or even by the misuse of the buildings. Technological analysis includes everything related to the hardware conformation of the building: structure and wrapper but also the facilities that make the operation of an architecture possible. From an elevator to a fire hydrant or a lighting point. This analytical category uncovers the erection and assembly procedure, crumbling the diverse hardware elements according to their significance and relevance, such as the structural grid, the wrapper, the dividing walls, or vertical connectors. Technical constituents that influence the conditions of use of architecture, such as artificial lighting, air conditioning, fire protection, and waste management, are also considered.

3.2.5 Visual and Semantic Analysis

Within this category, the analysis should address the study of architecture's visual shape or its accuracy to a given typology or model. The analysis must deepen on the internal rules that allow understanding of the composition order of such an architecture, not only the pure identification or description of the geometric rules. So we should be talking about prevalence, dominance, horizontality, sprawlness or compactness or heaviness, and the capacity to become a landmark or not.

4 Architectural Analysis Feasibilities

4.1 For Decision Makers and Participatory Processes

For decision-makers' analysis can be used as a guiding thread for project design, since it allows organizing issues such as the interpretations of the forces of the place, the management of a brief, or the explanation of how a building works. It also affects conceptual matters such as the big idea (also known as *parti*) of a project, the configuration of the image of the building or its role within the community.

Analysis can be deployed in all the phases of the project process: accompanying from the very first decisions to closing ones. Architectonic analysis allows the designer to choose between various alternatives, or to clarify and reinforce ideas. It also can be used by other people as users, developers, builders, etc. to escort designing procedures. Hence this is precisely in public participatory processes when analysis is especially brilliant.

4.1.1 For Training Future Professionals

When studying the utility of architectonic analysis for academic purposes we must refer to two different possibilities. Analysis as a tool to help students to achieve best outcomes when designing architecture during their learning processes or as a tool for trainers to rationalize a formal evaluation of the outcomes produced by apprentices.

Certainly, even in minor projects there are many ideas, but there is always one that is the matrix. For this reason, the future professional must be able to analyze-by-decomposition the buildings that he proposes.

5 The Communication Interface: Drawing

Producers of architecture have been historically addressing their processes of ideation, analysis, communication, and rising spaces under the use of a number of different devices and communication strategies, but above all the act of **drawing** is common. Both scientific literature and professional practice do not find another more appropriate resource in referred architecture creation stages. It is therefore conceivable that the output of any architectural analysis process can only be a graphic document, perhaps supplemented with alphanumeric data.

From the very beginning, creation process starts with a simple stoke or an ideogram. May be it is enough for setting an idea.[4] Perhaps it is nothing but a draft of a floor plan or a section that defines a space, a natural lighting strategy, or a constructive solution, acting as the origin of the communication of the architectural idea. Later, from the seminal ideas, these rough drawings mature through different iterations giving rise to a final definition of the project.

The design process involves a track of sketches. Thus, at the end of the process, all those representation techniques will be transformed into a codified graphic model capable of describing all kinds of responses as a score for building execution.

The approach to architecture through its graphic analysis needs to set some reference criteria in order to build it as a scientific field. Formalization of architectonic analysis must define a methodology involving procedures to obtain information, to select data, to classify it, and to produce a graphical outcome.

Determining the appropriate criteria for architectonic analysis depiction is not an immediate a priori. Scientific literature with a historical continuum of inconclusive debates corroborates that the graphic process beside architectural decisions is essentially hard to rationalize. Gregotti warned us in 1972 (Gregotti, 1972):

> Our journey through them [the different drawings that accompany architectural activity: sketches, notes, diagrams, graphs, notes…] is never rectilinear, but a patient and continuous re-elaboration, an attempt to solidify around some elements that can fall apart with the simple introduction of an unforeseen fact…

Such a complex process requires clear, concise, and intentional graphics. The analyzer person must choose the most appropriate representation system to explain each of the ideas. For this reason, diagrams and schemes, both of an austere and simple coding, seem to be the best devices when it comes to capturing the characteristic

[4] The very first place where the architectural project pops up is in the mind of the person who is in charge of the development of the idea. As stated by Marx in quotation by Boudon [3]:

The difference between the most incompetent of architects and the most perfect of bees is that the architect has put a cell in his head before he built it out of wax.

aspects of any architectural idea. However, complex it may be and whatever its level of definition and schemes, both austere and simple coding, seem to be the best devices when it comes to capturing the characteristic aspects of any architectural idea. The power of the diagram has never been as present on the architectural agenda as it is now. An increasing number of contemporary architects use diagrams for all kinds of purposes. As a matter of example, the leading Dutch architect Rem Koolhas supports the diagram as an essential device for architectural speculation at the dawn of the new millennium (Koolhass, 2004):

> Maybe, architecture does not have to be stupid after all. Liberated from the obligation to construct, it can become a way of thinking about anything—a discipline that represents relationships, proportions, connections, effects, the diagram of everything.

Certain expressive needs are only resolved through solutions that emulate three-dimensionality, such as axonometric or linear perspective. As we have said before, with reference to other kinds of graphic strategies also axonometric when simplified to the essential are also extremely effective in showing certain constituents of buildings as assembly procedures and perceptive dimensions of their spaces. Linear perspective representations are worth to emulate space perception. “However, should we advise that the large number of variables that come into play when producing a linear perspective, such as the location either of the point of view and that of the vanishing points or the choice of angle of view direction contribute to increase the level of subjectivism of the produced image.” On the other hand, axonometric offers greater objectivity as the number of people-oriented decisions is pretty reduced. So this quality, together with its capacity for abstraction and synthesis, recognizes it as the analytical representation system par excellence regardless of its type—cavalier, military or isometric—as it facilitates a perfect understanding of volumetric peculiarities and preserves dimensional accuracy.

The digital model and its 3d printed version have just arrived to multiply the set of devices available for producing architectonic analysis. s new device emerges as a complementary and powerful means of indisputable validity.

6 The Impact of Computer Science on the Representation and Performance of Architectural Analysis

6.1 New Outcomes Made Possible

The use of highly developed software running in machines with tremendous computing power has made it possible to solve graphic operations of unimaginable complexity in recent years. For example:

- Animations that simulate building processes.
- Simulations of people’s paths in unbuilt architectural spaces.
- Manipulation of light sources or weather conditions.

- Experience real-time alteration of the organoleptic characteristics of building materials.
- Simulation of the action within the space of all kinds of flows and transits (vehicles, people, fluids, data, energy, and any imaginable field).
- Revisions in real time of the physical dimensions of the architectural elements.

6.2 Arisen Problems Yet to Be Solved

The massive digitization of the materials with which the architectural fact is managed: numbers, codes, flows, costs, densities, coordinates… has transformed the modes of production and analysis, changing forever professional activities.

In other order of things, new activities made possible with digital tools have arisen and widely put in use without having built its new grammar. Many things are now pretty different from the past and some kind of reflection should be carried out. For example, yesterday the graphics produced were immutable over time. Interacting with them it only implied their decoding through reading. Today these materials are essentially unstable and permanently mutable. Consequently, whoever wants to learn about them should not read them but rather explore them.

For this reason, the new graphical interfaces surpass the traditional features of the diagram. Nowadays that old device must be considered dressed with a new potential. It is not only a form of expression but a tactic of thought and an operational interface (Puebla Pons & Martínez López, 2010)[5] stating the variable relationships that can be operated.

Another up-to-date innovation of the traditional mechanisms of representation of architectural ideas comes from the arrangement of the graphic information in layers. Overlaying as both an operational and communicative strategy has established a new and relevant role, which is evident in the increasing use of collages for communicating purposes. But also in new interfaces in which data and images emerge on demand in those places and circumstances in which the communication process requires it.

6.3 Risks of the Digital Tool

It cannot be ignored that the power of a digital tool can also become its weakness. It happens when the amount of information turns overwhelming so the objective for which the tool gets hidden. In addition, the features of the software to produce photo-realistic images have led to the confusion of understanding that the production of a striking (and subjective) image is the final objective of the architectural analysis.

[5] Diagram differs from the sketch on its capability of integrating heterogeneous data and in constantly rectifying itself as a cartography that shows the relational trajectories that generate architecture.

The scarce presence of axonometry in the graphic baggage of the youngest architects is not only due to the fact that the software directs the draftsman toward other kinds of documents.

7 Results

As indicated above, this methodology for Architectonic Analysis has been applied since 1993. From that date to today hundreds of buildings were analyzed by thousands of students, with varying levels of success. These learning experiences have led to methodological adjustments as for example to adjust technological, social, and cultural transformations related to the architectural fact.

Below are shown graphic examples made by students in the 2014–2015 academic year. That course academic activity was dedicated to the definition of a process for the accommodation of refugees in the city of A Coruña (Spain). The successful outcomes demonstrate the power of the graphic apparatus in its application to decision-making procedure in architectural and urban situations of enormous complexity. Tools have been able to support and manage a multitude of data and handle a complex amalgamation of variables. Also to clearly communicate the results to a very wide audience, both at an informative and professional level (Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12).

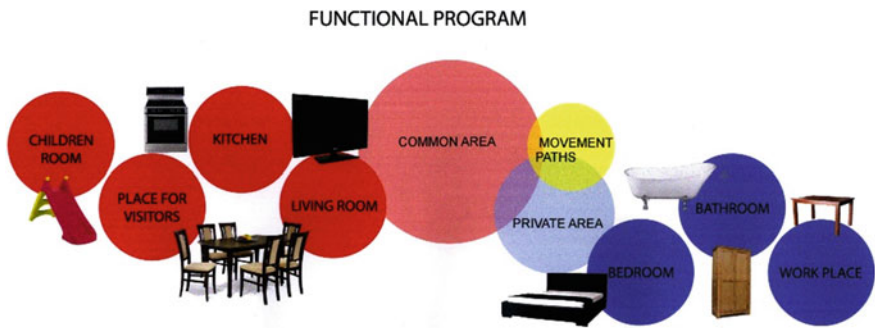

Fig. 1 Functional analysis. Needs brief

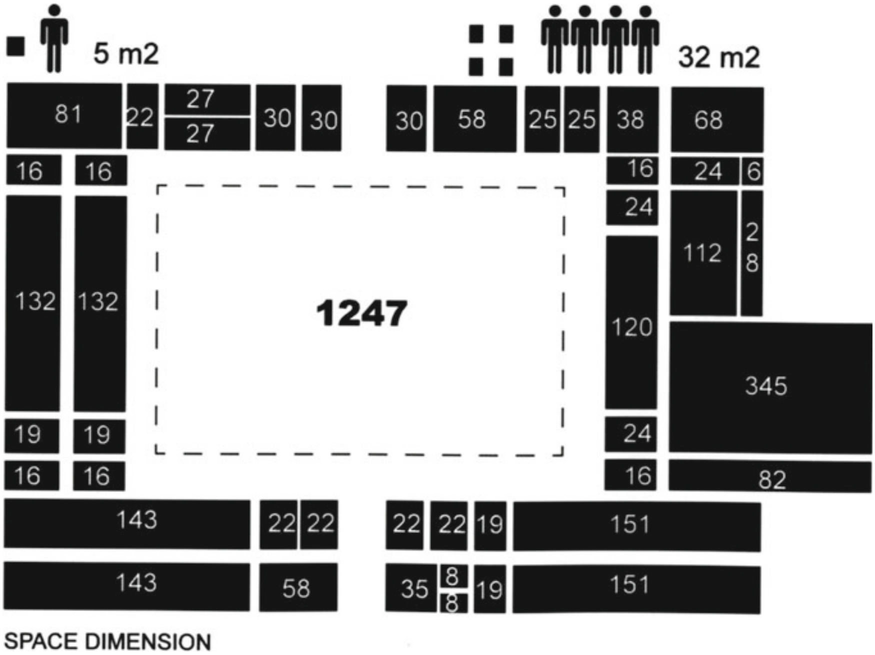

Fig. 2 Functional analysis. Dimensions

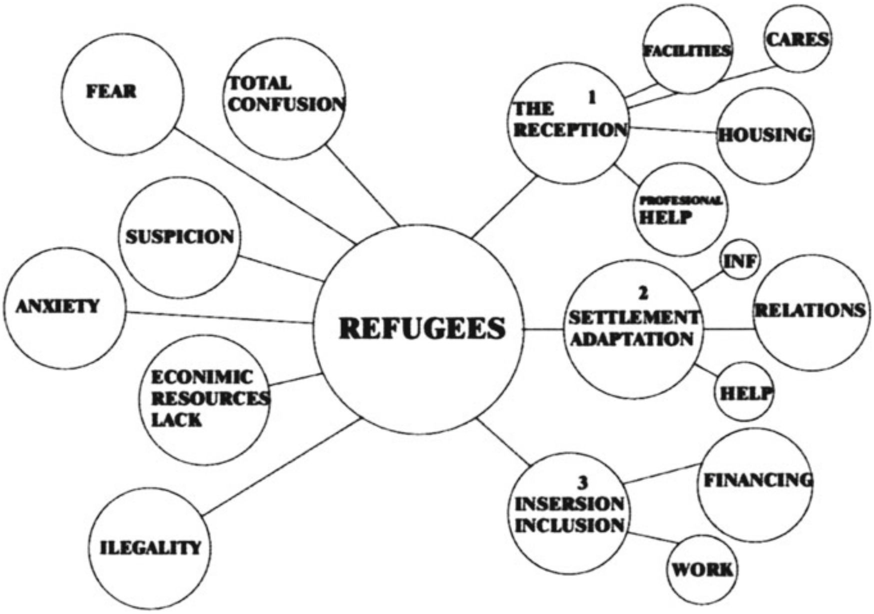

Fig. 3 Functional analysis. The users

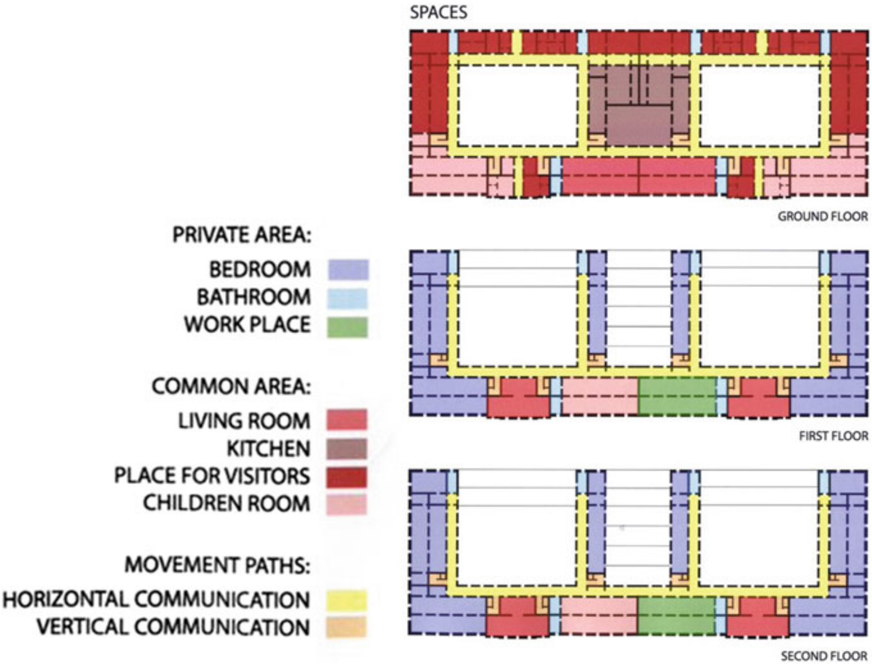

Fig. 4 Functional analysis. Layout

8 Discussion

8.1 In Search of the Automation of the Architectural Analysis Process

Once the conceptualization of the architectural analysis has been reached, other questions are left here:

– Can the architectural analysis be automated?
– Should it be possible to build a logical device to be used by any actor involved in architecture production for analyzing a given object and take the best decisions?

Our methodology for running an Architectural analysis as shown here provides the basis to program logical machines to afford some kind of automation. May be we could be quite close to solve the need that Christopher Alexander (1971) raised:

> My situation in 1958 was very simple. I wanted to be able to create beautiful buildings. I didn't know how and nothing I was learning in school was helping me. But I had a very clear sense of the difference: I knew what beautiful buildings were, and as far as I was concerned I was not only incapable of making them, but neither were most architects in the profession. What I wanted to do was create buildings with the same kind of beauty as traditional architecture. From there I began to define my task. This really meant getting to

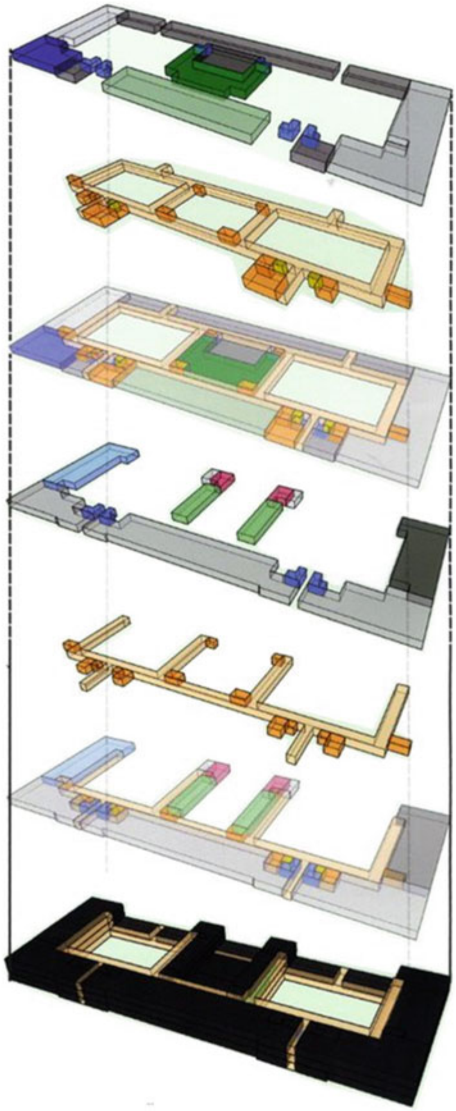

Fig. 5 Functional analysis. Functional structure

> the roots… What I learned, among other things, is that if you want to do something right, the only way is to develop a clearly defined step-by-step process. In this way anyone can carry out what is proposed.

The benefits of automating the architectural analysis would be numerous. On the one hand there are operational ones, such as those related to the management of existing buildings. On the other hand, as already mentioned, it would have educational applications such as objectively evaluating the training processes of students and improving their training. Between the two there is a non-minor utility: embracing a

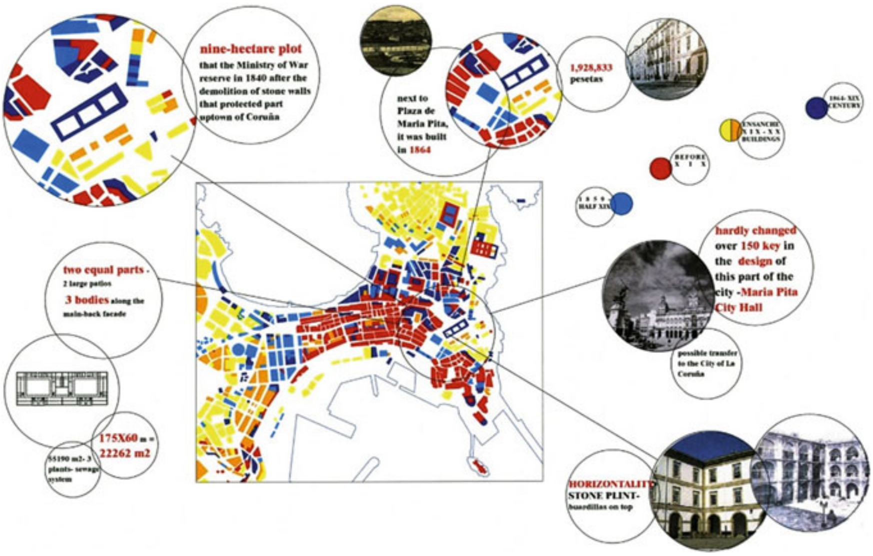

Fig. 6 Site analysis. Urban strategies

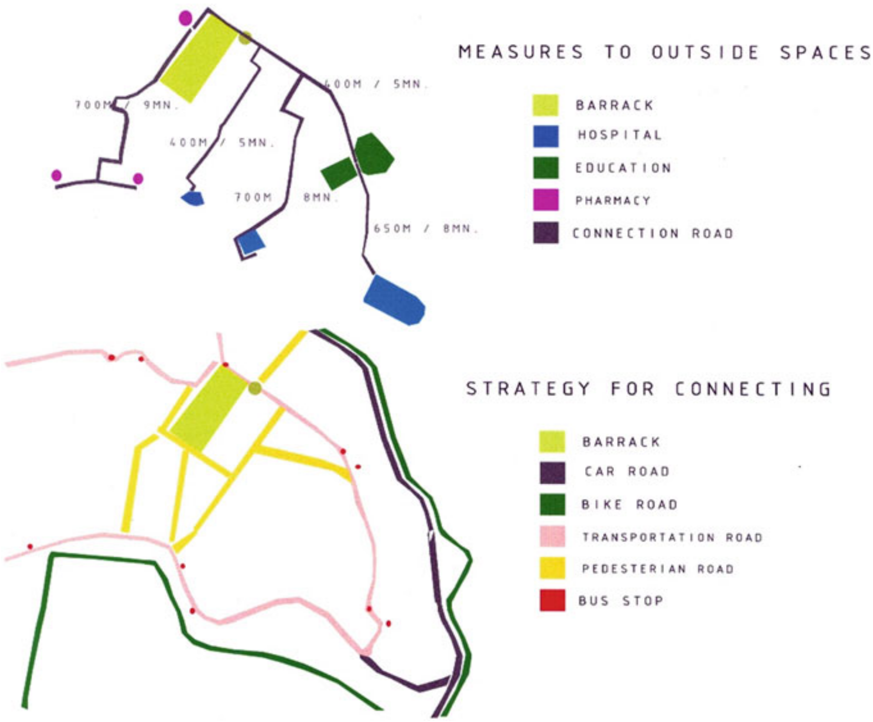

Fig. 7 Site analysis

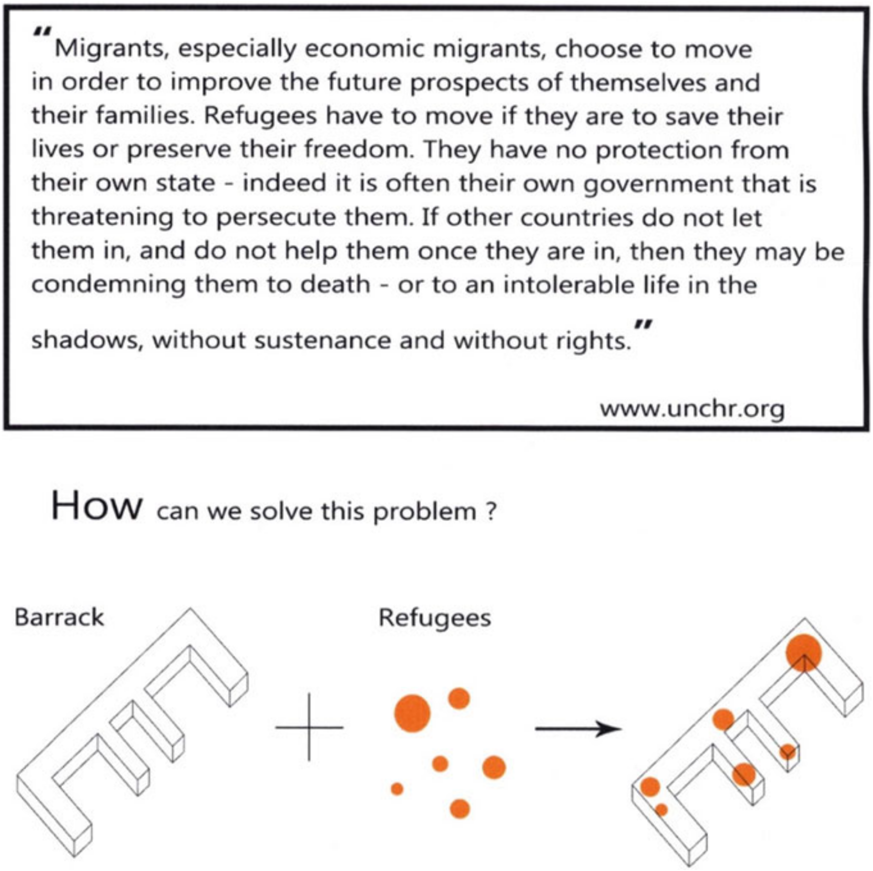

Fig. 8 Semantic analysis. The building as a social catalisator

logical process for architectural design. At the end the final objective is to produce the best architecture for society. Paraphrasing Alejandro de la Sota (1989).

> Without boasting, one could speak of methods to achieve a logical architecture today (…). The procedure for making Logical Architecture is good: a problem is presented in its entirety, all the data is ordered and made exhaustive, taking into account all the possible existing points of view. All possibilities of solving the problem in all possible ways are studied. All possibilities are studied. A result obtained: if it is serious and the path traveled is true, the result is Architecture.

8.2 Difficulties and Risks of Automation

The rationalization of the architectonic analysis and secondarily the formalization of the design process should not forget that designing it is always—with greater or lesser

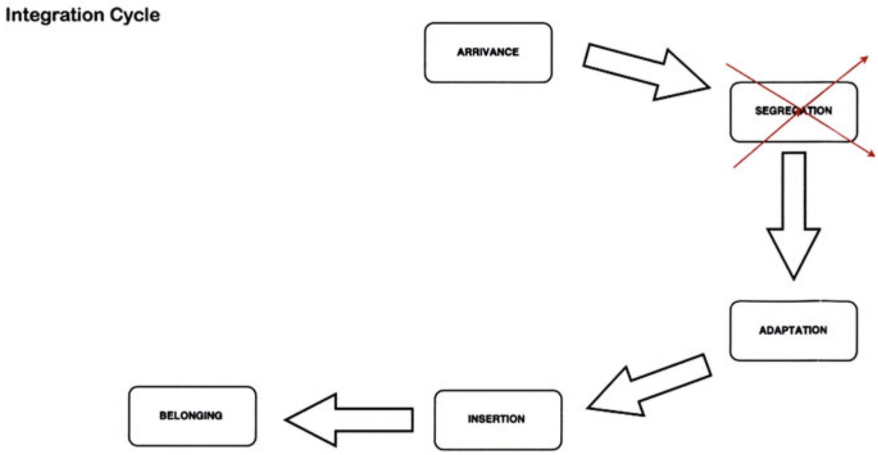

Fig. 9 Semantic analysis. The building as a social device

intensity—subject to the unfathomable fluctuations of intelligence and sensitivity. So any logical method must understand that the "uncontrollable" component of the design process must be allowed.

As Christopher Jones said (1971) "it is rational to believe that some of our actions are unconsciously controlled and it is irrational to expect that the design is susceptible to a fully rational explanation."

Thus, it must be assumed that some fraction of the architectural task can emerge from the most unfathomable places located down in the minds of people open to being surprised. And to surprise all of us.

> All buildings are predictions. All predictions are wrong (Brand, 1994).

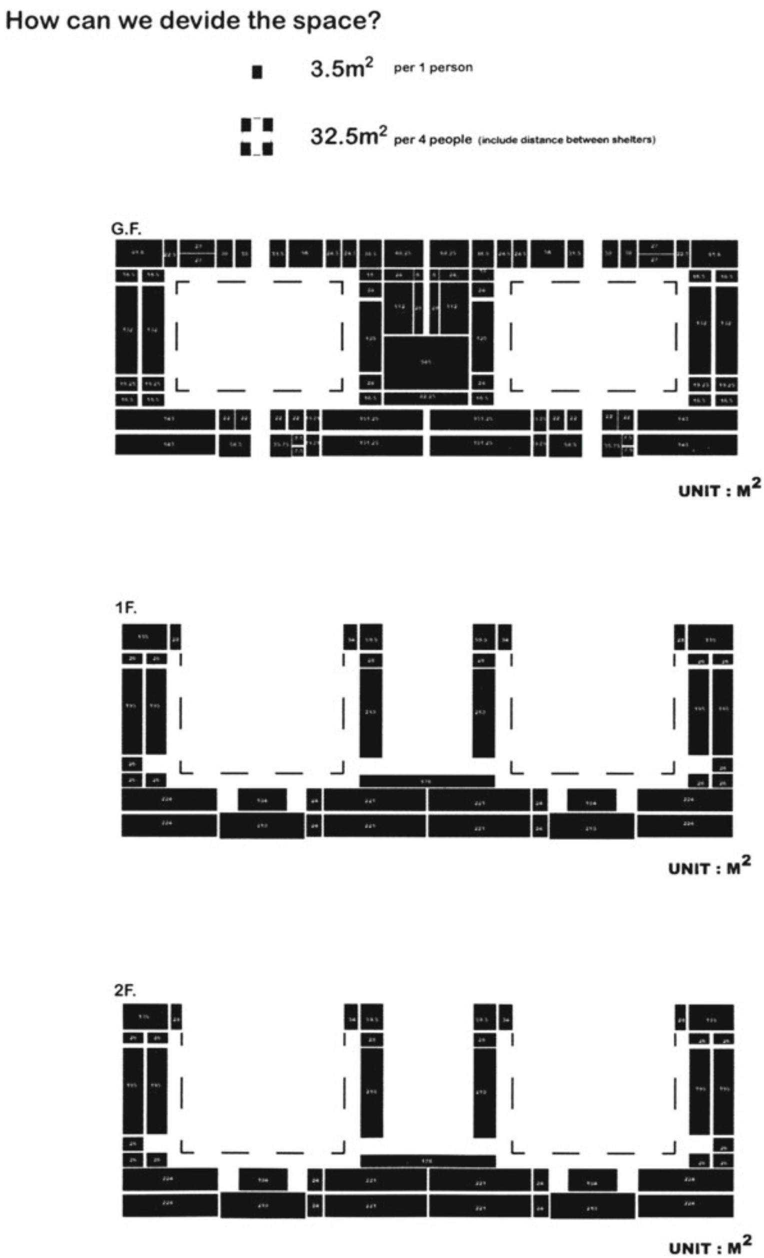

Fig. 10 Tech analysis. Structure and space

Fig. 11 Shape analysis. Building a hotspot

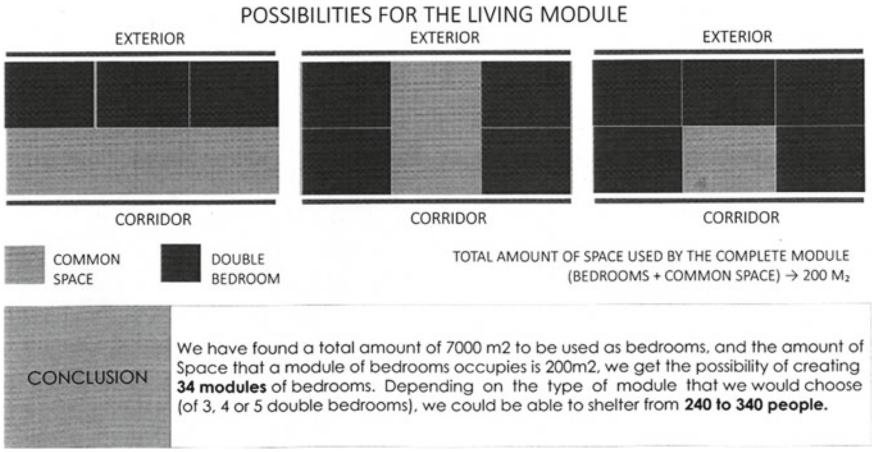

Fig. 12 Spatial analysis. Proposed organizations for sub-spaces

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Changing Methods in Teaching for Strengthening the Relation Between Research and Practice

Cláudia Monteiro and Vítor Oliveira

1 Research and Practice

Throughout the twentieth century, some crucial changes took place in the urban landscape. Street systems became increasingly fragmented and less adequate for the development of public transport systems, the size of street blocks steadily increased while the number of plots (and agents and urban strategies) per street block significantly decreased. Plot frontages and building façades got separated as buildings started to setback from the street, and street sections became increasingly opened (street width becoming significantly higher than buildings height), and the buildings' ground floor becomes devaluated (with a significant decrease in number of doors along the street). These physical transformations were promoted by a set of drivers, including the growing population, the use of private car, the emergence of real estate as a key agent of the urban space, and the proposal of new planning models, namely the modernist city and the garden city. The impact of these physical changes went well beyond the physical structure, including a decrease in socioeconomic diversity and in environmental sustainability (Oliveira, 2021a).

While evidence on the impact of these changes on everyday life started to be published since the early 1960s (Cullen, 1961; Jacobs, 1961; Lynch, 1960), the influence of these books and papers on practice has been surprisingly marginal, and the contents and processes of city building in the third decade of the twenty-first century are still very similar to those of the mid-twentieth century. One of the main reasons for this is the gap between scientific research and professional practice on the urban landscape. The gap is not very different from what happens in social, physical and life sciences (Oliveira, 2021b), and it prevents the main theories, concepts, and

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methods from urban morphology and other bodies of knowledge to be applied into day-to-day planning practice and development control, and to architecture. In urban morphology, the gap has been at the center of debate over the last two decades. Some scientific institutions have devoted significant attention to its causes, characteristics, and possible solutions, that is the case of the International Seminar on Urban Form (ISUF). Ten years ago, ISUF has established a task force on this theme (Samuels, 2013) and promoted the debate intensively in its journal 'Urban Morphology', not only through papers but also through editorials and viewpoints (Oliveira et al., 2014; Whitehand, 2013; Barke, 2015).

How can urban morphological research be characterized? At the beginning of the third decade of the twenty-first century, urban morphology is a consolidated body of knowledge with several theories, concepts, methods, and techniques to address the physical form of cities (Kropf, 2017; Oliveira, 2016). It can describe rigorously the elements of urban form—streets, squares and gardens, street blocks, plots, special and ordinary buildings—and their patterns of combination at distinct levels of resolution. It focuses on different urban landscapes, from historical kernels to peripheral areas, from planned to informal settlements. In addition, it can explain how these elements are shaped over time by different agents and processes of transformation. Finally, urban morphology can evaluate the impact of changes in urban form, framed not only by urban landscape criteria, but also by environmental, social, and economic criteria.

And how can practice on the urban landscape be characterized? Characterizing practice is more difficult than offering a picture of research, as it is more heterogeneous. There are major differences between planning and architectural practice. While planning takes place under legislative/political frameworks, addressing the fundamental dimensions of life in cities and aiming at prescribing the rules for their transformation, architecture occurs largely under a business framework, focusing specifically on the design of buildings. In architecture action on the urban landscape is more direct, while in planning action can be direct, mostly on the public spaces and public buildings, on indirect, defining the rules for the many private agents to act. Planning involves collective action and the permanent establishment of consensus, while architecture is more individual, involving the challenging of architectural styles. Urban design is somewhere between these two activities, but closer to planning. A major consideration is the legal systems framing practice—from mandatory to discretionary systems, from systems closer to the 'urbanism' French tradition to those closer to the 'town planning' British tradition. Nevertheless, practice in relation to the urban landscape is well established. It includes several processes and procedures aiming at producing policies, programs, plans, and projects for the transformation or conservation of the physical form of cities.

Over the two last decades, there have been many attempts to bridge the research-practice gap on the urban landscape. One of the most consistent has been the focus on tools, which in notably expressed under the label of planning support systems (Brail and Klosterman, 2001). Planning support systems are elements that systematically offer relevant spatial information to a specific process of related planning actions. Contrarily to other decision support systems, they are not highly structured models;

planning support systems are a set of techniques to aid planning agents to manage and overcome their problems (te Brömmelstroet and Scrijnen, 2010). These can include tools for the description and explanation of urban form, the evaluation of alternatives for transformation, and the subsequent design or prescription of rules for conservation and change, like Morpho (Oliveira, 2013) or MAP (Monteiro and Pinho, 2021).

Another relevant focus is on agents. Among these, one of the most promising lines is the emphasis on the researcher-practitioner, an academic who undertakes research and practice on the urban landscape. Oliveira gathers several examples of researcher-practitioners in different parts of the world working under different morphological approaches (Oliveira, 2021b). For example, Whitehand presents some planning experiences in Europe and Asia where he applies Conzenian research to analyze the historico-geographical structure of the urban landscape, divide the territory into different planning zones, and define the rules for change and conservation (Whitehand, 2021). Moving from planning to architecture, Strappa illustrates how he applies Muratorian research—notably ideas on the forming process and the urban fabric—in the design of a cemetery in Terni, Italy (Strappa, 2021). In another continent, South America, and framed by a different morphological approach, space syntax, Holanda illustrates how the main principles of this configurational theory and method can frame the design of a house (Holanda, 2021). Naturally, the focus on the researcher-practitioners can go back into the founding fathers of the field like Saverio Muratori or M.R.G. Conzen (see, for example, the relation between research and practice in the morphological approaches to Venice (Maretto, 2013) and Alnwick (Monteiro, 2021)).

This paper addresses the research-practice gap, not from the perspective on the tools or the agents but, from the point of view of the 'process'. In other words, it explores how the gap can be bridged through the realization of a sequence of coordinated events extended in time. Its focus is on an educational process. In an editorial published 22 years ago, Whitehand argued that research and practice were in largely separated realms. The mutual isolation was broken by the occasional guest lectures from across the divide or by the invitation for government planning officers to join the steering committees of research projects. Yet, as Whitehand states, these occurrences are too infrequent to have an impact on the urban landscape (Whitehand, 2000).

Looking at the gap between research and practice from an educational point of view, we can also see resistance in higher education to welcome alternative approaches to planning and architecture. For example, the poor applicability of urban morphology into planning practice is a direct reflection of a weak education in urban morphology, almost absent in high educational curricula (Oliveira, 2018). Education, like practice, must be based on scientific evidence, framed by an effective understanding of urban form and its dynamics of change. This cannot be found, especially in architecture schools, where the idea that 'to build a city' is just 'to build a collection of buildings' continues to be perpetuated and the success of the student intervention depends on the size and exceptionality of the building (Porta and Romice, 2010).

If practitioners are expected to adopt alternative views, academics must demonstrate the value of these and to develop new teaching methods in higher education to encourage new attitudes and interdisciplinarity (Dalton, 1986). In addition, the teaching and learning process should provide students with an understanding of the professional opportunities and entrepreneurial perspectives that might emerge from these alternative perspectives (Charalambous and Christou, 2016). Based on an on-going research project, the Knowledge Alliance for Evidence Based Urban Practices (KAEBUP), this paper proposes a process to effectively bridge the research-practice gap through education.

2 The KAEBUP Project

The Knowledge Alliance for Evidence Based Urban Practices (KAEBUP) is a 3-year on-going project (January 2021 to December 2023), founded by the Erasmus + programme, and involving eight partners including three universities, one research institution, one Non-Governmental Organization (NGO) and three enterprises in Croatia, Cyprus, Italy, and Portugal. These are as follows: University of Cyprus (coordinator), University of Porto, University of Parma, ISUF Italy, Social Fringe, Schiattarella Associates, ALA Planning Partnership, and André Dias Araújo Architecture and Design.

KAEBUP is built on the outcomes of a previous project, the Emerging Perspectives on Urban Morphology (EPUM) (Charalambous, 2020). The main objective of EPUM was to integrate different urban morphological approaches (the established historico-geographical, process typological and space syntax, and the emerging relational-material approach) through educational innovation, supported by information and communication technology. For that purpose, the project developed an open learning curriculum in urban morphology, involving teachers and students in multidisciplinary blended-learning activities to address some of the main issues faced by contemporary cities. The curriculum comprises a set of Open Educational Resources (OER) and an innovative collaborative online platform (Mettouris et al., 2021). KAEBUP draws on EPUM, both in institutional and substantive terms. It includes three of the five academic partners of the former project, and it explores and expands EPUM's experience of pedagogic techniques and OER, aiming at moving from morphological research to professional practice. More information about the EPUM project is available at http://epum.eu/.

KAEBUP's main goal is to create an educational and training process offering participants the opportunity to engage with professional environments, learning how research can be the basis for innovative professional practices, and what enterprises in planning, urban design and architecture require from academia. KAEBUP aims at achieving this goal, through three fundamental lines or paths: i. innovating learning and teaching through knowledge exchange and skills development, working on real-life urban projects; ii. understanding and developing business models for evidence-based urban practices; and iii. co-creating urban knowledge through multiple modes of exchange and involvement of students, teaching and company staff in teaching, research, and practice. This paper focuses specially on the third path, consisting of an innovative contribution: the design of an effective process made of multiple opportunities, to exchange ideas and facilitate interactions between academia and practitioners. The project is structured in nine work packages: i. project management; ii. preparation; iii. innovative learning and teaching through real-life urban projects; iv. business models for evidence-based urban practices; v. learners' professional skills; vi. co-creating urban knowledge; vii. quality assurance; viii. evaluation; and finally, ix. dissemination and exploitation.

This educational process aims at: i. promoting collaborations and knowledge exchange between research and practice; and ii. establishing continuous systematic interaction as a common practice in the teaching of planning, urban design, and architecture. By establishing a process that guarantees the continuity of joint events, KAEBUP aims at increasing the potential of a positive impact in urban development. It expects to recognize how teaching, learning, and research can benefit from the experience of evidence-based practice and vice-versa. The co-developed knowledge about what tools and research findings are needed by contemporary urban practices will be promoted by an online 'research-to-practice' platform (R2P).

One fundamental characteristic of this educational process is that is made of an unusual high number of events (as opposed to the usual weakness of isolated events identified by Whitehand 2000), aiming at strengthening the relationships between academic and professional partners, connecting students, researchers, and practitioners (Table 1). Two projects (for one new building and one building rehabilitation) and one masterplan currently developed by the three architectural and planning offices based in Porto, Rome, and Nicosia, offer the stage for the exploration of professional practice. These are as follows: the Ministry of Municipal and Rural Affairs (MoMRA) in Riyadh, Saudi Arabia (this project will be amplified in the next section); the Solar da Avenida in Porto, Portugal; and Verengaria, Cyprus. The next paragraphs briefly describe the main activities composing this teaching and learning process of KAEBUP (Table 2). These activities are strongly interrelated. Some are small-scale activities as presentations or dissemination sessions. Some are extended in time, and others are quite intensive.

KAEBUP includes a high number of Collaborative Learning Activities (CLA). These are joint learning activities using a blended-learning approach, combining online events (through the R2P platform referred above) with presential courses and seminars, taking place in the three universities involved in the project—Cyprus, Parma, and Porto. These activities can take the format of an event extended in time for a few months, including the development of different tasks over a sequence of time periods—for instance taking one of the two architectural projects or the plan referred above as the object of research and practice.

The project also includes Intensive Training Workshops (ITW). ITW are intensive activities focusing on one real project. KAEBUP includes only three ITW (Nicosia, Porto, and Parma), taking place in the first year of the project, contrary to the higher number of Collaborative Learning Activities. These three workshops, organized in a sequential way under the same framework, aim at exploring what research can offer

Table 1 A process made of multiple events

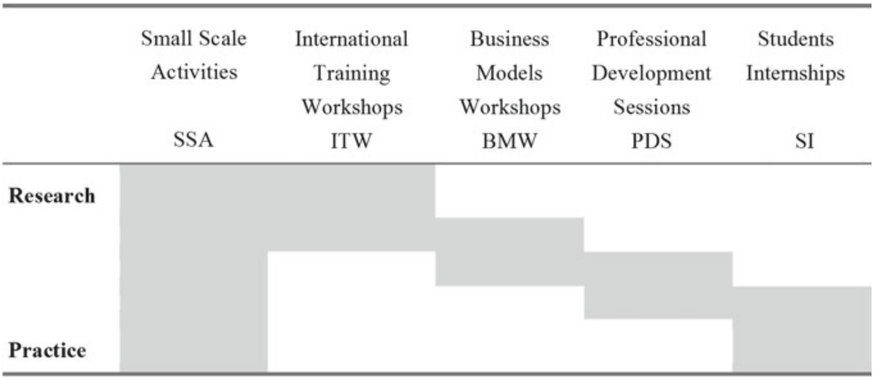

Table 2 KAEBUP main activities

	Participants	Activities		
		2021	2022	2023
Online/face to face	Staff, students, and participants from outside the project	Small-scale activities	Small-scale activities	Small-scale activities
R2P platform	Staff and students		Collaborative Learning Activities (CLA)	Collaborative Learning Activities (CLA)
Mobilities (face to face)	Staff and students	Intensive Training Workshops (ITW)		
	Staff and students	Business Models Workshop (BMW)	Business Models Workshop (BMW)	Business Models Workshop (BMW)
	Staff and participants from outside the project		Professional Development Session (PDS)	Professional Development Session (PDS)
	Students		Students Internships (SI)	Students Internships (SI)
	Staff, students, and participants from outside the project		Summer School	

Note Staff comprises members of KAEBUP's partner universities and enterprises to practice, in terms of tools and findings, and what research can learn from practice, in terms of potential application of research tools into project developments. This will be amplified in the next section focusing on one specific Intensive Training Workshop, taking place in Porto.

Business Model Workshops (BMW) are a third type of activity constituting this systematic process. The KAEBUP project includes three BMW, taking place at Nicosia, Parma, and Porto, over the three years of the project. The Business Model Workshops aim at developing a shared knowledge based on successful models for evidence-based urban practices and potential market and start-up opportunities, enhancing the learners' business knowledge and fostering entrepreneurial mind-sets. As the ITW, these are intense 1-week activities, led by recognized international experts in practice and business, attended mostly by students and teachers, but also by practitioners.

The fourth type of event included in KAEBUP project is a set of Professional Development Sessions (PDS). PDS take place throughout the second and third years of the project, under the coordination of one university and one research institution. Professional Development Sessions are international public events attracting participants from outside the project, both from academia and practice in architecture, urban design, and planning. These sessions aim at co-creating urban knowledge, and more specifically at enhancing and advancing the professional skills and knowledge, fostering innovation and entrepreneurship.

Another activity integrating this process is Students Internships (SI). Students Internships, lasting at least 60 days each, take place in the second and third years of the project, under the coordination of one of the enterprises. Two students from each of the three universities attend the internships each year in a foreign country. In other words, a student in the University of Porto develops his internship in Nicosia or Parma. The objective is for the students to develop their transversal and professional skills, including critical and innovative thinking, inter- and intra-personal skills, and global citizenship.

As stated before, the activities of the project are strongly interrelated to create a cohesive network. Two examples can be mentioned. The realization of the first Business Model Workshop, in Nicosia in April 2022, coincides with the development of a Collaborative Learning Activity on one of the three real case studies of the project, Verengaria (authored by ALA Planning Partnership), constituting an 'Introduction to Master Planning', an extended activity of two months mostly developed at the R2P platform. The realization of the first Professional Development Session, in Rome in June 2022, coincides with the realization of a Summer School on urban morphology—an event coordinated by ISUF Italy, together with ISUF and its regional networks, and with KAEBUP. The summer school is a center of excellence in urban form knowledge offering students the opportunity to learn urban morphological concepts and methods, and test the acquired knowledge in the interpretation of the urban landscape. The summer school hosts participants not only from partner institutions but elsewhere. Finally, additional information about the project is available at https://www.kaebup.eu/.

3 International Training Workshops: Porto

Framed by KAEBUP's strategy and goals, the Intensive Training Workshops (ITW), developed over the first year of the project in the three universities, aimed at promoting collective teaching and learning, based on discussion and interaction between researchers, students, and practitioners. The three intensive workshops focus on one real project, an exceptional building to accommodate the Ministry of Municipal and Rural Affairs (MoMRA) located in one of the most import avenues of Riyadh, Saudi Arabia. The building, currently under development, is designed by one of the project partners—Schiattarella Associates.

Throughout 2021, three ITWs were organized by three universities together with Schiattarella Associates. The main goal was to search in science for additional contributions to inform Schiattarella design approach. Each university contributed with one specific subject of expertise to a common framework, in close relation with the objectives and outcomes of the other two workshops. The University of Cyprus organized the first ITW focusing on public space (Nicosia, 14–18 June). The University of Porto (the authors of this paper) coordinated the second ITW centered on urban morphology and on the impact of urban form patterns on social diversity (Porto, 27 September–1 October 2021). Finally, the University of Parma organized the third ITW focusing on environmental analysis (Parma, 22–26 November). In this paper, special attention is given to ITW2, an intermediate workshop, building on the results of the first and informing the activities of the third workshop.

The fundamental goals of the second International Training Workshop were: i. understanding the difficult relationship between urban morphological research (theories, concepts, methods, and technics for description and explanation of urban form) and architectural practice; ii. exploring urban morphology as a scientific support for the establishment of an architectural view, alternative to mainstream architectural practice; and, finally, iii. recognizing the importance of the historical and geographical contexts in the design process (which was highlighted by the singular nature of the case study in Saudi Arabia, particularly in terms of climate, culture, and privacy needs).

ITW2 had the participation of 25 students, including researchers holding a PhD, as well as PhD and MSc students. Twelve of these students come from the three universities involved in KAEBUP and thirteen students were selected from an open call. It is important to mention that some of the students attending the Porto workshop have also attended the ITW1 and ITW3. The students' backgrounds included architecture, urban design, and spatial planning. Their geographical provenance comprises eleven countries in four different continents—Africa, America, Asia, and Europe. This diverse and rich cultural background was facilitated by the adoption of the online format due to the COVID-19 pandemic.

The theme of the ITW2 was 'Urban morphology and the assessment of physical change'. The workshop was developed in one week, although it has been preceded by pre-workshop activities over one month to create a dynamic of group. In the first day, several lectures on urban morphology—addressing the historico-geographical and process-typological approaches—and on the relationship between urban form research and architectural practice were offered by KAEBUP partners (coming both from the universities and enterprises) and other experts in the field. In the next days, students and tutors collectively worked on urban form at different scales—from the whole city to the urban tissue, and then to the single building—addressing time and change and reflecting on the relationships between the physical and social dimensions. Students were gathered into four groups, working in three different studios. The first studio, 'Time and change', in day 2, focused on the urban growth of Riyadh making evident the contrast between the piecemeal transformation occurred until the mid-twentieth century and the disruptive change that took place after the 1960s. The second studio, 'Urban tissues' (Fig. 1), in day 3, linked the different periods of growth of Riyadh to specific urban tissues constituting the city—from traditional tissues to the first transitional tissues and the imported tissues erected in the 1950s, and finally to the modernist tissues framed by the Doxiadis plan prepared in the early 1970s (Fig. 2). Finally, the third studio, 'The building and its tissue', addressed specifically the urban tissue of MoMRA building. Accordingly, the assessment of the MoMRA building was framed not by some of its architectural characteristics, but by the relation it establishes with its tissue and by how it responds to the main social needs and aspirations of the citizens of Riyadh.

The three studios and the collaborative work between researchers, students, and practitioners led to two main general results: i. the proposal for strengthening the role of the town-plan (including street systems, plot patterns, and building arrangements) and of a thorough understanding of the historical evolution of urban form and its social context with the design process; and ii. the recognition of the limited impact that one single building can have on the physical, social, and environmental dimensions of Riyadh, which reinforce the need for a more effective planning action on the city, supported by scientific evidence.

Fig. 1 Examples of Riyadh urban tissues: Al-Dira (traditional), Manfoha (1950s) and Al-Malazz (1957) (Al-Hussayen and Shuaibi, 1975)

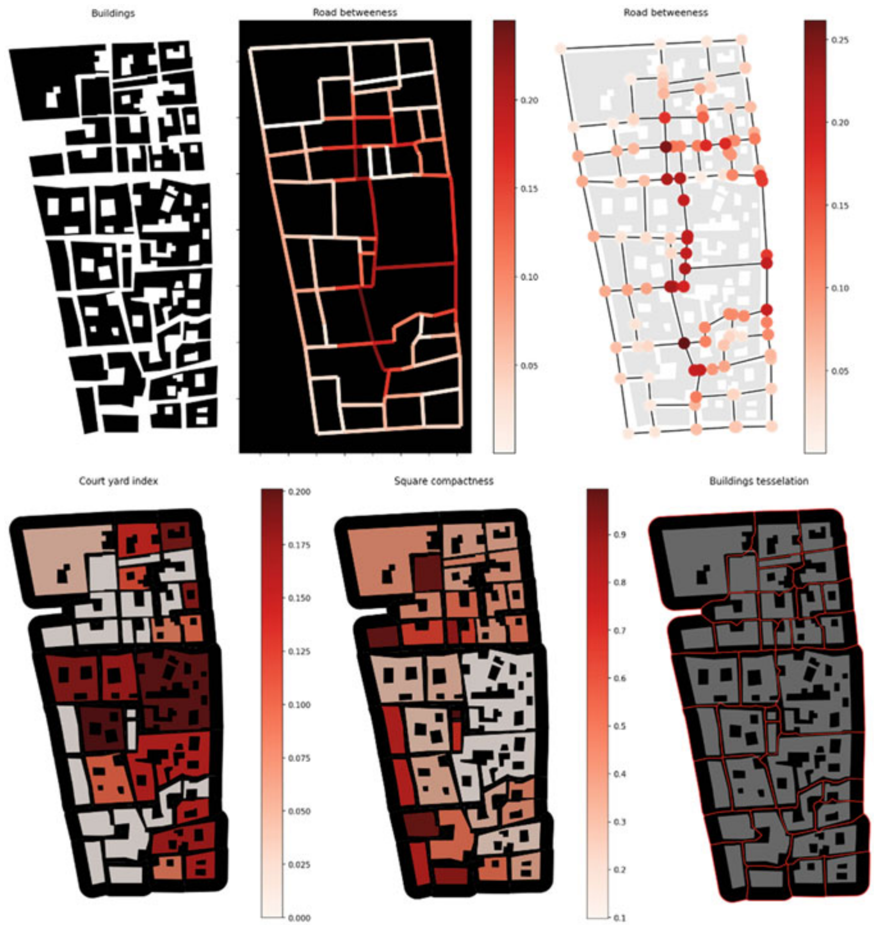

Fig. 2 Morphological analysis Al-Dira traditional tissue. Students work (Ahmed Rezk, Alice Monacelli, Chiara Finizza and Nuno Gomes)

4 Conclusions

Over the last years, the relation between research and practice on the physical form of cities has been at the center of international debate. While converging on the acknowledgment of the gap, and on its fundamental characteristics, some different perspectives on how to bridge it have been proposed. Some of these perspectives have focused on tools, while others have emphasized the role of agents. This paper focused on bridging the gap through the creation of a consistent process of relation between academia and professional practice extended in time and involving a sequence of different events.

Over 3 years, from early 2021 to late 2023, students and researchers from three universities and one research institution are invited into the daily practice of two architectural offices, one planning office and one NGO. This immersion into practice is prepared by a set of business model workshops and professional development sessions. The real integration of students and young researchers takes place through a set of internships. During these 36 months, the staff of the architectural and planning offices and of the NGO are exposed to several theories, concepts, methods, and techniques for describing and explaining the urban landscape and for assessing the impact of physical change on the socioeconomic and environmental dimensions. A set of intensive training workshops and an unusually high number of collaborative learning activities offer the stage for the practitioners' immersion into research. The whole set constitutes a robust process. The process is in clear contrast with the nature of the single event of collaboration, with no past and no future. It is argued that this process, this educational process, can contribute for strengthening the relation between morphological research and professional practice on planning, urban design and architecture. A stronger relationship between research and practice can be translated into significant improvements on the urban landscape: integrated street systems more adequate for public transports and active modes, smaller street blocks and more plots per street block, active building frontages contributing to the street life. It is argued that the impact of these physical changes can go well beyond the physical structure, including an increase in socioeconomic diversity and in environmental sustainability.

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Proposal and Application of a Graphic Method for the Definition of New Qualitative Indicators of Architectural Education

Luis Manuel Santalla Blanco

1 Introduction

Adding new indicators of the quality of teaching by using graphical methods is intention of this paper. These new indicators relate to students' opinions. In this work, students are placed in the position of interlocutors. They are the people to whom a message is sent with a content, previously structured by the curriculum, containing the knowledge necessary to become an architectural professional.

Their views on the functioning of this teaching structure are collected in a database that has been previously developed as part of a doctoral thesis in preparation. The importance of seeking their opinion is indicated in the White Paper of Architecture itself. After several visits to several architecture schools, having gained a solid database, the aim is to highlight the key points of interest in order to improve the different aspects of the training.

White Paper of Architecture[1] refers to the lack of information on students, stating that:

> The surveys provided by the network in all its aspects do not take into account the opinions of students, recent graduates or non-member graduates. The Commission considers this to be a major shortcoming of the study, as it has a negative impact on the quality of the response and, in particular, does not make it possible to ascertain and assess the impact and opinion of young architects on some of the key elements.

In this work in progress, 1,800 students and 220 graduates have been reached and have responded to questions related to the academic field. Their responses have

[1] A white paper is a report that informs readers concisely about a complex issue and presents the issuing body's philosophy on the matter. White Book of Architecture was published on 2005, coordinated by Juan Miguel Hernández León.

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resulted in 18 concepts that are proposed as indicators of the quality of teaching, exceeding existing indicators.

2 Target

2.1 *Main Objective: Detection of Indicators*

The main objective is to detect the indicators needed to improve the teaching of architecture, taking as a starting point the results of a process of surveys carried out with students and graduates. In order to find these indicators, a graphic method is proposed in which it is easy to identify the necessary key points. The starting point of this research is a database, which has been previously elaborated,[2] where the tabulated responses are collected.

2.2 *Secondary Objectives: Repository and Visualization Tool*

There are two secondary objectives. On the one hand, this system should be a time-varying tool that has the capacity to function as a repository of information and as a graphical tool for comparison between different schools. On the other hand, the visualization of the data will allow schools to fine-tune their curricula and the way in which they implement teaching, taking into account the opinions of the students.

The need to use new indicators and their reference values becomes more evident when using this graphical method. This database, previously enriched with verified results, provides the basis for the development of more fine-tuned algorithms allowing one to quickly identify the strengths and weaknesses of the system while showing evidence in a direct and visual way.

3 Methodology

3.1 *Time Diagram*

The aim is to make a comparison between the structure established for the implementation of the current curricula and the results obtained. This structure is represented in the form of a time diagram (Fig. 1), in which the following key moments are identified:

[2] Blanco and Manuel (2019).

Fig. 1 Xxxx

- Ideation of the study plan.
- Adaptation of the study plan by the school.
- Implementation (teaching).
- Graduate.
- Master.
- Professional life.

Using this line diagram, the aim is to identify where existing indicators are located and how to extend the diagram to include new quality indicators.

The current indicators[3] are limited to monitoring the volume of students. All of them could be included before starting the "graduate" section. None of the indicators refer to the quality of teaching or the competences provided to students and trained professionals. These indicators are

- Degrees offered.
- Places offered.
- Pre-registered:
- Admitted (in ordinary and extraordinary exams).
- Enrolled (ordinary and extraordinary).
- Preference rate: Percentage of places offered in the first year of a degree course that have been taken up by students who choose that degree course as their first option.
- Occupancy rate: Percentage of places offered in the first year of a degree course that have been taken up by new students from the pre-enrollment process.
- Suitability rate: Percentage of new students entering a degree from pre-registration who have chosen that degree as their first option.

On this timeline, more dimensions are added. Thus, on a second level, an ordinate line is added in which the professional competences grouped by professional profiles are included.

A linear diagram is used to represent the training process for students. If we take the reading from left to right as a reference, we have on our left the approach of the White Paper with the professional profiles it assigns to architecture professionals. These are five groups: "building", "urban planning", "real estate action", "technical specialization", and "drawing and design".

As we move in the direction of reading, we find a subdivision of these profiles into dozens of competences specific to the degree, which the syllabus subsequently assigns to the subjects taught. At this point, the graph corresponding to student

[3] These indicators have been extracted from the publication "Datos y cifras del sistema universitario español. Publicación 2020–2021" Ministerio de Universidades, 2021.

action begins. From this point onward, a period of time begins that spans 5 years and a qualifying master's degree. This period of time is divided into six parts, corresponding to six moments in which the competences of previous courses and those expected for the current course are accumulated.

The penultimate section of the graph relates to the expectations of trainees. These expectations may not materialize, but they show trends in the field of the profession the students are expecting to develop.

The final part of the graph, on the right, shows the point of view of professionals who have already graduated. In order to obtain reliable data on the opinion of architects, another parallel research has been carried out in which alumni assess themselves on the competences required in the current plan.

This graphical method provides a complete view of the training process. Each of its phases can be associated with a value in relation to its numerical indicators.

From this point on, the data obtained will enrich and enhance this diagram. One could envisage that with the incorporation of real data, it is envisaged that it will be possible to identify new indicators applied to the education system.

3.2 Vertical Structure of the Diagram—Competences

The diagram below shows the competences assigned to each subject. The intention is to complete it with competences that have been applied and showing to what extent they have been applied.

Each of the professional profiles assigned by ANECA[4] is divided into competences which in some cases are not complete. This might be due to the adaptations or conditions of the syllabus, lack of time of the teaching staff, the capacities of the students, or a combination of all of them.

The initial assumption is that the adjustment made by the schools leads to a tendency to skew the graph. This negative slope represents the realization of a theoretical concept, where for logistical, economic, and personal reasons teaching and training opportunities in some of the competences are lost (Fig. 2).

This negative slope represents the realization of a theoretical concept (not sure what you want to say here). Teaching and training opportunities, of some of the competences, are lost due to logistical, economical, and personal reasons.

The competences associated with each professional profile are represented in color. Those competences that have not been satisfactorily completed are shown in black (Fig. 3). Competences are represented with the same magnitude, as individual units, without giving more value or more graphical space to either.

[4] The National Agency for Quality Assessment and Accreditation of Spain, ANECA, is an Autonomous Body whose aim is to provide external quality assurance for the Spanish Higher Education System and to contribute to its constant improvement through evaluation, certification, and accreditation.

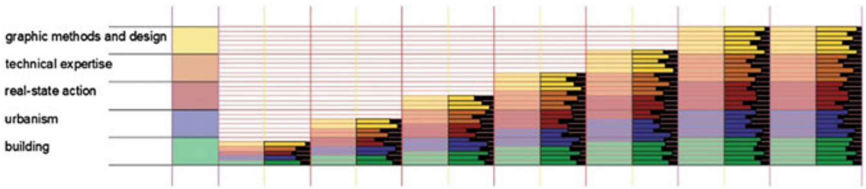


Fig. 2 Success in competences—Theoretical diagram (I)

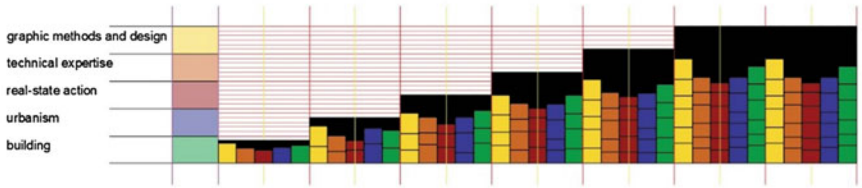


Fig. 3 Success in competences—Theoretical diagram (II)

Theoretically, it is proposed to graphically represent the evolution of the transmission capacity of the training message showing the evolution of the subject to be taught and its relative success. In this graph, the points where it is necessary to intervene, or at least to monitor them with an indicator, are indicated. This syntactic representation (Fig. 4) is not a result from the use of any data analysis program.

Four indicators can be detected in the graph:

– A: Adaptation of content by the school: the competences that are no longer taught due to the adaptation of the curriculum to the situation of the individual schools.
– B: Missed targets during training: skills that have not been delivered in a satisfactory condition (quality/manner) or have not been delivered at all.
– C: Training for professional qualification: students' efforts to achieve the objectives of the qualifying master's program.

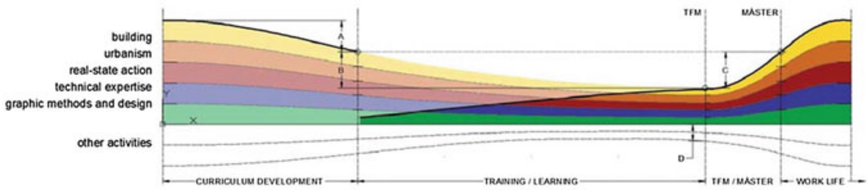


Fig. 4 Summary diagram

– D: Training outside the school, outside the academic field.

A self-evaluation mechanism for architecture schools will provide the indicators A, B, and C, and may be requested by control bodies such as ANECA. Section D is related to the students' own complementary training based on their interests.

3.3 Enrichment of the Diagram (I). The Student's Point of View

Student opinion is important according to the Bologna guidelines, but at the moment there is no method of consultation allowing for classification of mass results related to student opinions.

In order to study their opinions, a guided interview is designed and has been applied in schools of architecture. These interviews have a format similar to that of a survey, designed to allow students to provide as much data as possible related to the teaching structure in which they are an essential part. The process of developing this survey and its results are published in previous communications. The results provided in this article are directly extracted from the resulting database.

As a starting point of this database taken as a starting point is a table containing answers to 33 questions from students of seven schools on the Iberian Peninsula.[5] This series of questions addresses the four key concepts of teaching architecture: the school, teaching staff, student body, and curriculum.

The results of these surveys are included in a time diagram (Fig. 5) showing the evolution of teaching and the acquisition of competences by the student body. The student input can result in adding new dimensions and new indicator values to the base diagram.

– E. Personal profile of the student (creative, technical, or social).
– F. Student interest (numerical rating 1–5).
– G. Attitudes and skills of students (free response).
– H. Student competences and skills (free response).
– I. Objectives of the architectural professional (5 options to choose from).
– J. Objectives of the architecture (5 options to choose from).
– K. When an architectural professional is trained (5 options to choose from).
– L. Evaluation of school spaces: classrooms/library/assembly hall/cafeteria/outdoor areas/group work areas/library of materials/site visits (numerical rating from 1 to 5).
– M. Objectives of teaching architecture (free response).
– N. Knowledge of the curriculum (5 options).
– O. Dedication to subjects outside the classroom (numerical rating 1–10).
– P. Thematic of the TFG (9 options).

[5] Visited schools are: ETSA UDC (A Coruña), ETSA UPM (Madrid), ETSA UPC (Barcelona), ETSA US (Sevilla), ETSA URV (Reus), EAUM (Guimarães), and ESG (Vila Nova de Cerveira).

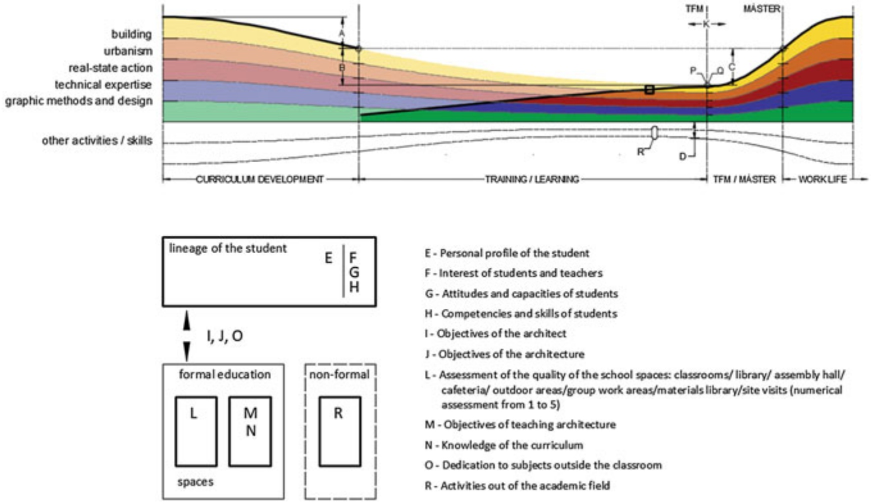


Fig. 5 Proposed indicators on the theoretical diagram

- Q. After the TFG (master's degree, master's degree in another discipline, not working as an architect, working for another professional).
- R. Activities outside academia (10 options).

The free-response questions (G, H, M) add a new dimension to the evaluation of architectural education as they represent the values and interests of the students. They are shown as relative indicators that can justify numerical percentage values. So far, there is no information on the control of the competences finally acquired by the students. Nor do we know about their state of mind and even their psychological state or other non-quantitative aspects.

3.4 Enrichment of the Diagram (II) the Professionals' Point of View

The aim of the training process is to create competent professionals. These competences are recognized by the award of a diploma. The final part of the graph shows the results of the self-assessment carried out by a universe of 220 architecture professionals who responded on a voluntary basis.[6]

The importance of this graph is that it clearly indicates the areas of the profession where the graduates are least aware of each of the competences they have been awarded.

[6] The questionnaire is available for professionals on the web: https://forms.gle/vtbbYk8gkxxbSW1i6.

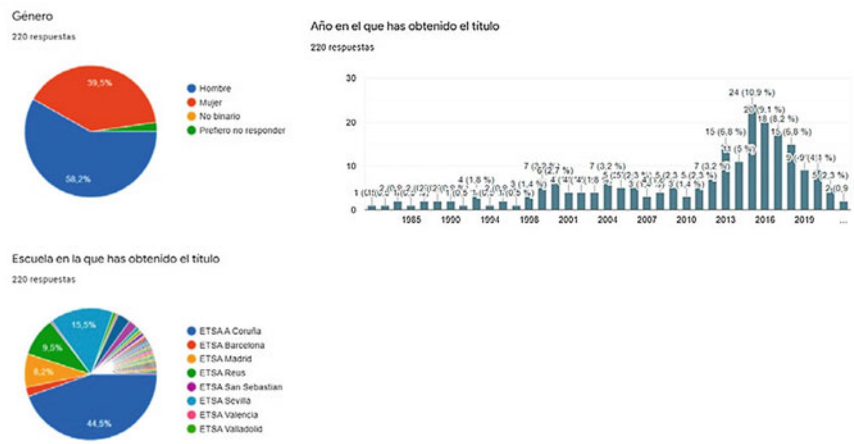


Fig. 6 Personal profile of volunteers

In order to carry out this exercise, an online call was made through social media, mentioning professional associations. A questionnaire was carried out using "Google Forms" and was answered by graduates from different schools in Spain. This form included three status questions, identifying the type of respondent (Fig. 6) (year of graduation, school of graduation, and gender). The second part of the questionnaire includes a list of general, specific, technical, and design competences and included in the curricula.

As a result of this survey, a database has been obtained allowing to make independent consultations which can be made according to the profile of each professional (school, year of qualification, and gender). The percentage values for the competences analyzed, and organized by professional category are shown in Fig. 7. Values below or equal to the overall average, in this case 56%, are highlighted.

4 Tools

Database visualization tools (mainly percentage, bar, and area graphs) can be used as the first graphical indicators of the results of the surveys conducted.

A tool has been sought that allows the direct entry of information by volunteer users, obtaining anonymous responses. The previous research work and search for results has been carried out through face-to-face visits and online calls.

A guided interview format with 33 slides was used to carry out the student surveys. The interaction tool is Mentimeter. Information on how to create the survey can be found in a previous publication. Students respond live to the questions projected in the presentation and the answers are automatically stored in a database.

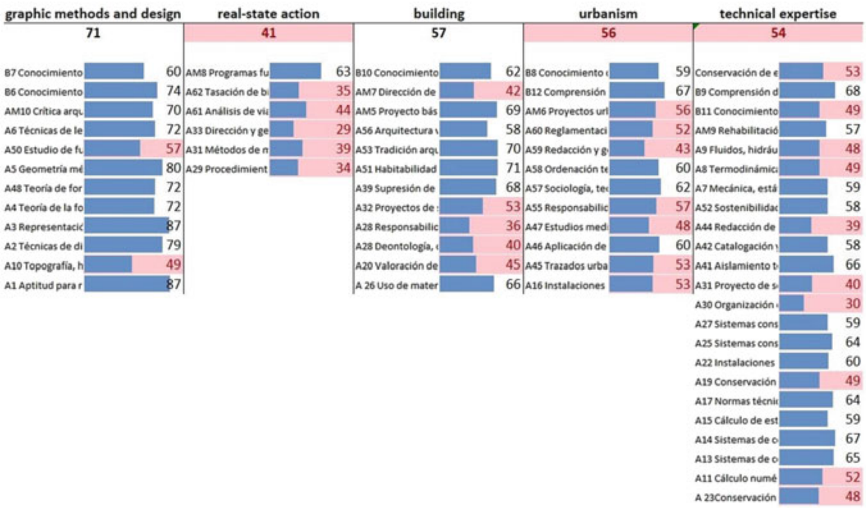


Fig. 7 Self-evaluation of competences acquired

In the case of the questions asked to professionals, the Google Forms tool was used, which is currently open to the public and has the capacity to expand the database. At the time of writing, there were responses from 220 professionals.

For both surveys, a common format for data processing is sought. In both cases, the data export format is .xls. For the elaboration of the partial graphs, Microsoft Excel and Powerbi[7] have been used. In both cases, the same pivot table is used for the queries.

The proposed theoretical graph can be programmed in such a way that it can be obtained using the data from the generated table. The computer development of the visualization tool requires the help of programmers, which was not possible in the preparation of this work. The theoretical graph and the graph with the actual applied results have been developed to show the synthesis capability of the state of architectural education.

5 Findings

In order to visualize the importance of the indicators set out in theory, the real case of the Escuela Técnica de Arquitectura de Madrid is shown below. In the surveys carried out, responses were obtained from 402 students of the ETSAM and 14 professionals who have graduated there.

[7] Power BI is Microsoft's data analytics service aimed at providing interactive visualizations and business intelligence capabilities with an interface simple enough for end users to create their own reports and dashboards.

The results of the questionnaires are displayed on the diagram, including the proposed indicators K, P, Q, R. These indices help to contextualize the students, and to show graphically how their training is progressing, as well as their future intentions.

First the indicators are presented individually, and at the end of this section you can see the combined result (Figure).

K—When is an architectural professional formed?

This indicator is a time variable. It establishes the moment at which students consider themselves to be an architectural professional. According to the students consulted, this variable K should not be placed at the time of completion of the degree. Based on the answers, it has been shown that at the end of the TFG, students think that they are not capable of developing a project on their own, and that they need to do a professional internship. The aim of better training is that this indicator K is completely reversed.

Responses to variable K:

P—Theme of the TFG:

This indicator shows the willingness of students to develop within one of the areas of architecture. In this situation, a choice is offered between the main subjects. They are then related to the structure proposed by the professional profiles.

Q—After the TFG:

This indicator shows the students' willingness to continue. This indicator causes gaps in the graph. This is due to the fact that there are students who are going to stop their training when they finish their degree, and do not wish to take the qualifying master's degree at the same school. The important values in the graph are those relating to those who want to continue doing the qualifying master's degree at the same school. The rest of the values justify the reasons for this percentage Q.

R—Activities out of the academic field.

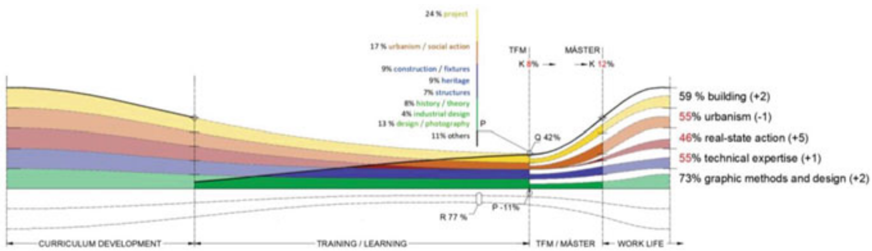
In order to have a complete picture of the students' education, this indicator is included to show their interests in other fields. This indicator also shows a representative value that measures the level of the students who participate in activities. This is a relevant figure that can indicate the level of stress of the students and be an indicator of their performance.

5.1 *Findings from Professionals*

The last part of the graph corresponds to the points of view of the professionals trained at the school. In the case of ETSA Madrid, it was possible to interview 14 professionals who gave their thoughts on the competences acquired. This is a relative value, which depends on people's perception and is therefore variable depending on the situation. For this reason, it has been decided to keep the questionnaire open and available, so that it can be completed over time. This will make it possible to accumulate results and have more reliable percentages.

The values represented correspond to a percentage of satisfaction with the training received at the ETSAM, if we classify the competences within the professional areas of the ANECA.

The summary graph is as follows:



Explanation of the data included in the graph:

- K: The first finding of this study of variables is that students consider that they are not trained as professionals after completing their Bachelor's and Master's degrees.
- P: The resulting values indicate that 24% of the students plan to carry out an architectural project, which in theory integrates different areas. There are 11% (equivalent to 44 students) who plan to work in other fields that are not included in the list of 8 options.
- Q: In the case of the ETSAM, 42% of the students interviewed (168 out of 402) intend to continue at the school, while 19% intend to change schools for their qualifying Master's. The percentage of 16% indicates that they will not continue their training and intend to work for another architect or studio. The relative percentage of 16% indicates that they will not continue their training and that they intend to work for another qualified architect.
- R: In the case of the ETSAM, 23% of students (92 people out of 402) say that they have no time for other activities outside their studies. The resulting indicator is 100–23 = 77%.

The comparison of the results with the national average is also shown in the graph. The percentage obtained for each professional area is indicated firstly, followed by and second value (+/− X) referring to its position with respect to the national average. In the case of the values shown in red, it indicates that it is below the absolute average for all areas.

5.2 Applications for the Diagram

Reading the indicators on the diagram allows one to see a temporal progression of trends in students' intentions and the success of the training from the practitioners' point of view.

This is a multidimensional diagram on which further indicators can be added. An annual study of individual schools is possible if the methods tested here are used. The accumulation of the data of the students feedback will make it possible to see the success of the different curricula. This ensures an easily accessible and searchable information base.

Mandatory indicators are currently not sufficient. It is proposed to complement the reading of the current rates with the reading of the graph. For example, the drop-out rate (one of the rates that schools are obliged to report to monitoring bodies) is clearer and more useful if the moment of drop-out is shown graphically on a time graph, which makes it possible to determine the problem more clearly.

The diagram can be used to its best advantage if it is carried out individually. If a student is tracked from the beginning of their graduation and their profile is maintained anonymously over time, they will have drawn a line showing their trajectory by the time they complete their graduation and the Master's degree.

The diagram of a school can be composed of superimposing different trajectories, which will make it possible to see and determine more clearly the profiles of the pupils.

In the curriculum, there is no space reserved for the lineage of students, which can help the teacher–student relationship. The graphical representation of the students' individual careers over time reflects, when the results are accumulated, the lineage of the school.

So far the reports of the monitoring bodies are tables of results from the different schools. The inclusion of the existing ANECA data into the database will increase the quality of the historical results, if combined with more professional surveys.

5.3 Detection of Key Points

The following quality criteria must be justified when a new curriculum is presented by the schools of architecture to the inspection bodies:

- RELEVANCE of the degree: With the proposed indicators it is possible to justify the interest of the student body (F), which in the case of the ETSAM is 7.1/10.

The principles of the students and the final satisfaction of the graduates are proof of the relevance of the degree.

- Relevance of general objectives and competences: Indicators A, B, and C relate to the number of competences that the school cannot satisfy. The assessment of these indicators should be made by curriculum planners.
- CLARITY and SUFFICIENCY of the systems regulating student access and admission: Indicator Q allows us to have a forecast for enrollments in subsequent years. Graphically, it seems logical that if the initial training of students is improved according to indicators G and H (conceptual, not numerical), training by competences will have a higher graph, and therefore a more complete teaching.
- COHERENCE of the planned planning: The system is coherent if the graph is as horizontal as possible and has no blank spaces. In this way, variables A and B should be close to 0, so that variable C is also as small as possible. This value C indicates a forecast of the effort that the student will have to make in order to be properly trained in the competences to be acquired.
- ADEQUACY of academic and support staff as well as the material resources provided: The assessment provided with indicator L on the quality of the school spaces is a result of the evaluation of the users of the school spaces themselves.
- Expected effectiveness in relation to expected results: The results that can be expected are those based on what the school can offer. This level is already lower than the expectations of a more generic and open plan. The adaptation of the school and the curriculum (indicators A and B) are the sign of the efficiency of the curriculum programming.
- Internal Quality Assurance System in charge of reviewing and improving the curriculum. With the proposed graphic system, based on a database that includes all aspects of the field of architectural education, it is possible to review and improve the curriculum with a repository of information on what has occurred in previous years.
- Adequacy of the planned implementation timetable. The position of indicator K is relevant in the sense that if low values are obtained (such as the 8% obtained at ETSAM), it is possible to think of a temporal adjustment of the graph and therefore of the reality of the syllabus. In syllabus reviews, the debate on the time adjustment always arises.

6 Conclusions

The graphical method has made it possible to reach the intended objective of visualizing the need for the implementation of new indicators. Based on existing data from previous research, it has been possible to establish the average values of these indicators and to situate the results of the schools visited. In the case of this communication, the results detailed are referred to the Escuela Técnica Superior de Arquitectura of Universidad Politécnica de Madrid (ETSAM).

Table 1 Database visualization tools

	Inquiry format	Tools	Results	Visualization
Students 1,800 people	Face-to-face visits	Mentimeter	.xls	Microsoft Excel PowerBi (dynamic-tables graphics)
Professionals 220 people	Online	Google Forms	.xls	

A list of 18 indicators has been identified, which have their situation within a general graph. The overlaying of these indicators results in a multidimensional graph, which is composed of numerical and conceptual values. The non-numerical results allow us to justify the variations of the numerical results. Specific treatment of indicators containing text will require the implementation of algorithms that allow the reading of large volumes of data, which is beyond the scope of this article.

The proposed secondary objectives are covered and justify the implementation of formal methods as an effective mechanism for monitoring indicators related to architectural education.

The proposed survey and results processing system is easily replicable. The previous results are placed within a database that allows graphic analysis. With the use of basic software it is possible to consult a repository of information that allows the comparison of results between the different schools of architecture.

The use of formal methods in the development of a metacognitive study is proposed, which will allow the schools analyzed to make adjustments and new proposals. The naming of possible indicators allows the development of pseudocodes for future algorithms that can help in decision-making in the face of common questions and debates such as the need for introductory courses, the recommended training time, the detection of those areas of the profession with the greatest problems, and their possible causes.

Reference

Blanco, S., & Manuel, L. (2019). En busca del cuestionario necesario para el estudio de la didáctica de la arquitectura. In: D. García Escudero & B. Bardí Milà (Eds.), *VII Jornadas sobre Innovación Docente en Arquitectura (JIDA'19), Escuela Técnica Superior de Arquitectura de Madrid, 14 y 15 de Noviembre de 2019* (pp. 190–203). UPC IDP, GILDA, 2019. ISBN: 978-84-9880-797-4.

Other Formal Methods

Encoding Social Values of Local Communities in Algorithmic-Driven Design Methods

Silvio Carta, Tommaso Turchi, Neil Spencer, and Miguel Vidal Calvet

1 Introduction

This study tackles one important but frequently ignored aspect of the housing crisis in the UK. Currently, designers, developers and policy-makers prioritise financial and legislative elements, including investment returns, national and local regulations, and health and safety measures. Focusing on such aspects ensures financially viable and regulation-proof new developments. However, in such cases the quality of living for resilient, net-zero and sustainable communities is almost entirely considered at later stages and with lower priority. This is compounded in the UK by the pressure to deliver a large number of new developments in the next years. The UK Government has committed to "*increase building output to 300,000 homes a year*" and "*deliver one million new homes by the end of this Parliament*", which is due in 2024 (UK Parliament, 2021).

From a sustainable community viewpoint, these new developments will suffer from social and sustainability issues in the mid/long term. Local values are often ignored or underrated, especially in communities with diverse social and cultural backgrounds. Major cities in the UK are actively devising ways in which social and cultural values could be embedded in future housing schemes (Greater London Authority, 2018). However, to date there is little progress on practical ways in which such values and aspirations of diverse communities can be considered systematically in design processes.

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In this work, we address the question: how resident aspirations, values and living qualities of local communities can be encoded in algorithmic-driven design methods to ensure that the future UK housing design and developments will address resilient, net-zero and sustainable communities?

We developed a novel design and development model that encodes the social and cultural values of diverse communities into a data-driven approach to ensure that future housing schemes strongly cater for resilient, net-zero and sustainable communities.

Working under the assumption that quality of life is highly influenced by urban form (i.e. spatial characteristics of housing and collective spaces), we developed a model that generates housing urban configurations using a combination of factors that encode (i) residents' social aspirations, (ii) housing regulations and policy-makers agendas and (iii) successful elements for resilient communities. We suggest a statistical linear method to inform the choice of inputs and suggest weights. The model combines these factors using a multi-objective optimisation strategy implemented through Non-dominated Sorting Genetic Algorithm II (NSGA-II) (Deb et al., 2002) to find the best trade-offs among competing factors.

We present our model with some testing and explain how the model can be used by city councils, developers and designers to include social aspects of local communities in the planning of new schemes and evaluation of existing ones.

2 Related Work

While the encoding of social aspects related to living is expensively considered in social and media studies (cf. Alaimo & Kallinikos, 2017; Beer, 2009; Cioffi-Revilla, 2014; Pitt et al., 2021, among many others), there is still relatively little work on embedding social values and aspirations into housing design through computational methods.

Recently, Preece et al. (2020) have been exploring the changes in housing aspirations for residents, using surveys and existing literature. Interestingly, their work links social aspirations to spatial elements of housing: "[…] *these dimensions encompass structural and dispositional, individual and social, and temporal and spatial factors*" (Peerce et al. 2020:101). The work of Preece et al. confirms that most aspirations relate to ownership and tenure, and that more work should be done to include political and social dimensions as well (Preece et al., 2020:99–100).

On the other hand, many scholars and designers have been using space syntax methods (Hillier et al., 1976) to explore social aspects of living (e.g. Marcus, 2015; Suonperä Liebst & Griffiths, 2020). Space syntax and Isovist models have been used, for example, by Ostwald (Ostwald & Dawes, 2018) to retrospectively analyse the social and cultural aspirations of Modern architecture.

In general, our research focuses on the encoding of human aspects in algorithmic-driven approaches. In particular, we have been developing methods to generate spatial configurations using social aspects in care homes with NeuroEvolution of

Augmenting Topologies (NEAT) (Carta et al., 2020) and nature-inspired methods (Jankovic & Carta, 2021). We apply these methods to measure the resilience of communities and suggest ways to improve it (Carta et al., 2021, 2022). We defined the extent to which automated processes based on Machine Learning (ML) have limitations in including human aspects (Carta, 2021).

With this work in particular, we want to use computational methods to intelligently produce housing configurations where the future aspirations of residents are included as criteria since the inception of the design process. Moreover, we want to combine social and cultural aspirations with housing regulations, policies and developers' and planners' drivers, as well as success factors for resilient communities. With this work, we explain how we started this ambitious plan by combining complex and diverse and often competing factors into a reliable design model where each factor has a clear (and parametrised) impact on the overall quality of future housing developments.

3 Methods

3.1 Workflow

With this work, we developed a model to encode 3 types of data into a generative process for housing configuration accounting for social and cultural aspirations at the community level, mediated by developers' and councils' drivers, and successful features for resilience. In particular, we followed this workflow:

1. Identify 3 datasets (as specified below);
2. Cluster the sets into a comprehensive list and indicate features, design criteria and measures;
3. Reduce list (2) for which data are currently available into 6 criteria;
4. For each criterion, establish an appropriate weight;
5. Input the weighted criteria into a multi-objective optimisation generative model for housing configuration;
6. Generate multiple scenarios rioritizing different combinations of criteria;
7. Assess the results of the model.

3.2 Datasets and Design Criteria

For this project, we used the combination of 3 different datasets. Each set has been named with a numeration system with sub-sections (e.g. 1.2.3 identifies set 1, subset 2, criterion number 3). This numbering is helpful to keep track of the merging of criteria across different sets.

Dataset 1: social aspirations of communities

The first set includes data about social behaviour (habits), values, expectations and aspirations of urban communities. Data comes from several UK governmental reports and published studies, including the Community Life Survey—London summary (City Intelligence Unit, GLA 2021), Equality, Diversity and Inclusion Evidence Base for London (City Intelligence Unit, GLA 2019), and the 2007–08 Citizenship Survey Identity and Values Topic Report (and Ministry of Housing, Department for Communities and Local Government 2014).

The GLA's Community Life Survey includes a base of adults aged 16 + with, for example, London: 2,933; West Midlands: 1,062; North West: 1,144; North East: 358; Yorkshire and The Humber: 895; East of England: 1,181; South East: 1,704; East Midlands: 771; South West: 808 (City Intelligence Unit, GLA 2021:11). We excluded from our study indicators that are not relevant (sense of belonging to Britain, civic engagement, volunteering and charity), obvious (responses from people living in most deprived areas are more negative in general than those from less deprived areas) and with very low values, for example, loneliness (around 7% across regions).

The Equality, Diversity and Inclusion Evidence Base for London includes data about communities' access to different types of housing, both renting and buying with a breakdown per prevalent ethnicity. It includes details about overcrowding, issues related to homelessness and rough sleeping, and the challenges that different groups encounter as minorities. This set also considers data about access to facilities for disabled and older populations, focusing on physical barriers that have a direct impact on social aspects of life, including isolation and loneliness.

The third subset of group 1 includes data about identity and values that characterise residents. This set considers a number of principles by which people conduct their public life in the city of London, including tolerance and politeness towards others, equality of opportunity, respect for the law, respect for people from different ethnic groups, freedom of speech or expression, justice and fair play and language barriers. This set mainly distinguishes between age groups: 16 to 24, 35 to 49, 50 to 64, 65 to 74 and 75 or over. The Citizenship Survey Identity and Values Topic Report has a base sample of people in England 8,752 (:12).

Dataset 2: housing regulations, policies and developers' drivers

For the second set, we considered three main sources: Design and sustainability, Housing design and quality (Mayor of London, London Assembly 2021), Equalities, Diversity and Inclusion Measures (Greater London Authority, 2021) and Community cohesion—an action guide. Guidance for local authorities (Local Government Association, 2004). This second set is representative of local housing regulations, policies and developers' drivers that underpin the design and building of housing in London.

The London Housing Design and Quality (GLA) contains guidelines to achieve a minimum standard of quality in housing. These include dimensional aspects (for example, minimum floor space, storage, floor-to-ceiling height, play space per child and orientation—e.g. for single and dual aspects) and general outdoor guidance (private outdoor space, requirements for wheelchair users). Each of these criteria is cross-referenced to London and national-level planning policy documents (Mae Architects, 2020). In addition, this set includes guidance on sustainability standards: Net Zero Carbon Homes, Whole-life cycle Carbon Assessment, Be Seen Energy monitoring, Air Quality neutral, Urban Greening and Managing heat risk (Mayor of London, London Assembly 2021).

The second subset we included is about Equalities, Diversity and Inclusion Measures, and it comprises questions of Housing affordability, Overcrowding, Accessible housing, Air quality, Homelessness, Rough sleeping and Tenure satisfaction. Such aspects focus on inequality measured by ethnicity, income, housing tenure, age, household type, nationality and area of the housing.

The third element of this second set is Community Cohesion—an Action Guide. This includes objectives like overcoming segregation, equal access, link to other services, resident-led approaches and tackling anti-social behaviour. A number of measures are identified here, for example, avoiding segregation, fostering interaction, ensuring equal access to diverse groups, improving links with community services and monitoring and avoiding anti-social behaviour.

Dataset 3: spatial features of resilient communities

In previous studies (Carta et al., 2021, 2022), we suggested that successful and resilient communities are characterised by urban features that include aspects like proximity, density and number of buildings and other urban typologies within given areas. In particular, we found that communities with a high score of resilience show a high concentration of transportation facilities (train and underground stations, bus stops and airports), educational buildings (primary and secondary schools, crèches and nurseries, universities and public libraries), entertainment facilities for sport and recreation and green areas (public gardens, parks and public open spaces). Our study on the resilience of Copenhagen suggests that green areas have a significant predominance over the other factors in contributing to resilience, with 83% of green data points (with each point representing a green element), against 8% of transport and 9% of education (Carta et al., 2021:12).

We summarised the urban features that are linked to the highest scores of resilience and that are relevant to housing in Table 3 (Appendix 1).

3.3 Rationalisation and Reduction of Criteria

In total, the 3 datasets generated 55 criteria, with some of them overlapping (addressing the same aspect from different premises). We then combined and clustered criteria on the basis of common features, obtaining a combined set of 27 criteria

Table 1 Example of coded criterion and related measurable outputs

Code	Feature	Example	Design criterion	Measure	
3.1.4	Green areas	Public gardens, parks and public open spaces	Proximity to facility	Metres, walking distance	m
			Number of facilities in area (radius to specify)	Integer	$\mathbb{Z}$
			Extension of park (S/M/L)	Area	m^2

as summarised in Table 4 in Appendix 1. To each of these features, we assigned a specific design criterion and a clear metric using 3 main measures:

- $\mathbb{Z}$ = Integer value 1-10
- m^2 = square metre
- £ = cost in GBP.

An example of this rationalisation of features into measurable design criteria is shown in Table 1 below.

We then clustered the 27 criteria again into 6 main groups by considering what could be realistically used in the generative model as an input and measure. In general terms, criteria 1 (cost per sqm) and 6 (links to other urban services) are objectives to be minimised, while criteria 2–5 are to be maximised.

Through a series of clustering and grouping, the 6 criteria encode the 3 main objectives of the initial datasets (cf. Appendix 1). The linear combination of the 6 criteria results in an overall value which we call Quality of Housing Development (Q), as shown in (1):

$$x_1a + x_2b + x_3c + x_4d + x_5e + x_6f = Q \tag{1}$$

3.4 Estimation of the Weights

The aim of this phase was to explore a robust method to assign values to the coefficients $a, b, c\ldots$ intended as weights that may have a different influence on Q. To do this, we associated each factor ($x_1, x_2\ldots$) to an existing dataset from the UK Office for National Statistics (ONS) or UK Government Department as described in Table 3. This allowed us to examine the distribution of data within the set and inform the better statistic modelling approach. Existing data from ONS and UK Governments have been used as proxies in this phase to explore possible distributions with publicly available data. With this, we want to simulate real distributions (that we would obtain from ad-hoc datasets that should be collected for a specific housing development) to calibrate the model.

To note that we only included the factors for which the association to a re-liable dataset existed. We excluded “shared and open spaces” and “win-dow area”, reducing the number of factors for the weighting exercise to 4. In the final calculation of Q in the generative model, we assigned average values (1 within normalised sets) to these 2 excluded factors.

We used the Index of Multiple Deprivation (IMD) as a proxy for the calculation of *Q*, as an inverted measure of quality of residential areas. All data used in these datasets are organised by Lower Layer Super Output Areas (LSOA), which also makes it easier for local urban areas to be managed.

To determine the weight of cost/sqm, we used the house price data and the average size of different types of dwelling, to create a “cost/sqm” figure for each Lower Layer Super Output Area (LSOA).

For “area per resident”, we obtained data on the number of various types of dwellings in each LSOA (detached, semi-detached, terraced and flats) and the number of people living in each of these types of dwellings. Combining with data on the average size of such dwellings, we were able to calculate a “sqm per person” value for each LSOA. This provides a more accurate description of the area per resident compared to data on the “number of household spaces” (i.e. number of dwellings) and “number of people per household”.

For links to urban services, we used the time taken to travel to an employment centre using public transport/walking from the dataset as per Table 3.

For the calculation of the outcome *Q*, we used the actual IMD scores, instead of the rankings. As the IMD is calculated in a different way for each country of the UK (England, Northern Ireland, Scotland and Wales), we have restricted the data used for this exercise to just those LSOA in England for consistency with the rest of the project.

Weights were calculated using multiple linear regression. The inputs shown in Table 2 were all standardised using Z-scores (to remove spurious effects associated with units of measurement) and used as explanatory variables in a model for the outcome (the IMD scores) which itself had been standardised using Z-scoring. The multiple linear regression thus gave an optimal set of coefficients which were then scaled so that they summed to four (the number of inputs). Despite the model being much simpler than we would aim for, the modelling still accounted for about two-thirds of the explanatory power that would be achieved by a much more complex model, so we deemed this to be sufficient to yield significant results for this experiment. We emphasise that all variables used here are proxies for data that may be used in a real-case scenario. We therefore estimated the following weights (Table 4).

The weight for “private outdoor space” is very low. However, this is largely because the IMD is so highly correlated to house prices and area per resident. Alternatives to the IMD that could be identified were those for “quality of life”, “wellbeing” or “life satisfaction”. However, these were not available at the LSOA level but only at the local authority level which is too coarse a level to be useful for our aim with this project.

In general, for the creation of weights for subsequent use, it is possible to fit quite complex models which allow for a variety of relationships between the inputs

Table 2 Final list of criteria to be combined

	Criterion	Dataset	Objective	
a	Cost per sqm	Dataset 1: social aspirations of communities	To be minimised	£
b	Area per resident	Dataset 1: social aspirations of communities	To be maximised	m^2
c	Shared and open spaces	Dataset 1: social aspirations of communities	To be maximised	m^2
d	Private outdoor space (garden/ balcony, etc.)	Dataset 2: housing regulations, policies and developers' drivers	To be maximised	m^2
e	Window area	Dataset 2: housing regulations, policies and developers' drivers	To be maximised	m^2
f	Links to other urban services	Dataset 3: Spatial urban features	To be minimised (expressed in walkable distance from development)	m

Table 3 Association of factors to existing dataset for distribution analysis. All used sets are on the project GitHub page: https://github.com/seelca/encoding_social_values

Factor	Dataset associated	Source
Cost/sqm	Mean house prices by middle layer super output area	ONS Link
Area per resident	Household spaces and Household size	ONS—Nomis official labour market statistics Link and Link (UK 2011 Census)
Private outdoor space	Analysis of Ordnance Survey (OS) data on access to private gardens, public parks and playing fields in Great Britain	ONS Link
Links to other urban services	Journey time statistics, notes and definitions: 2019	UK Government, Department for Transport Link Tables are on Link
Quality of Housing Development (Q)	Indices of deprivation 2019	UK Government, National statistics Link

Note that we only included the factors for which the association to a reliable dataset existed. We excluded "shared and open spaces" and "window area", reducing the number of factors for the weighting exercise to 4. In the final calculation of Q in the generative model, we assigned average values (1 within normalised sets) to these 2 excluded factors.

Table 4 Summary of the suggested weights for each criterion

Weight for "cost/sqm"	= 2.37
Weight for "area per resident"	= 1.20
Weight for "private outdoor space"	= 0.016
Weight for "links to other urban services"	= 0.41

and outcome such as polynomial relationships (squared, cubic, …), exponentials, interactions and multiplicative relationships as well as additive. It is also possible to assess the relative importance of these different types of relationships. This allows an understanding of the relationships between inputs and outcome to be developed and the ability to minimise the complexity of the modelling (in order to ease any computational difficulties) while maintaining the strength of the overall model.

3.5 Generative Model

Using the criteria selected, we built a parametric model in Rhinoceros Grasshopper (full script on GitHub). The model uses as input the factors "cost/sqm", "area per resident", "private outdoor space" and "links to other urban services" and their respective multipliers (Table 4). The generative model has been developed using a number of elements to determine the generation of housing solutions at a massing level, summarised in Fig. 1. These include area per resident, private outdoor space per resident, plot area, density, cost per unit and average distance to urban links. All these criteria have been then weighted using our statistical modelling (cf. Table 4).

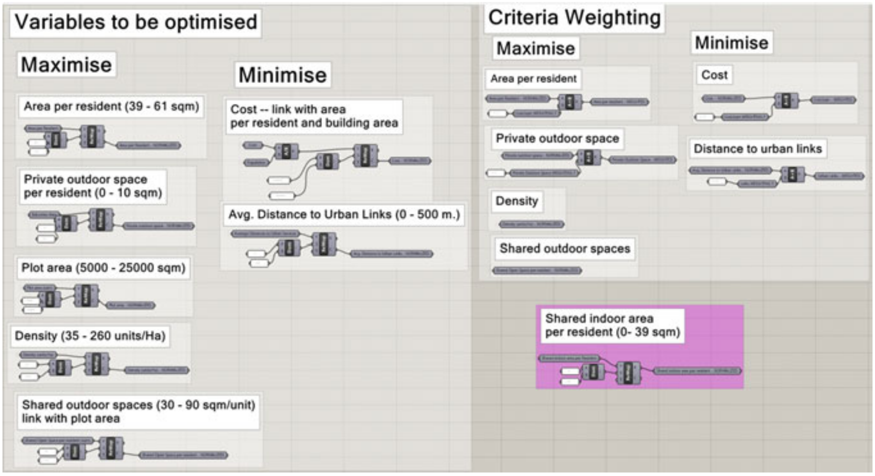

Fig. 1 Summary of the factors used in the GH generative model

Table 5 Assumptions used to initiate the generative model

Floor-to-floor height	3.5 m
Unit structural span	7.25 m
Balcony depth	1.8 m
Common areas' corridor width	1.5 m
1-bed area	52 m^2
2-bed area	70 m^2
3-bed area	86 m^2

The initial seed of the model is based on a standard 16 m deep building unit (with 2 units 7.25 m deep divided by a 1.5 m corridor) with common structural spans.

The model works under a number of initial assumptions (Table 5) that have been used to build the initial logic to generate the housing schemes.

Similarly, we introduced a series of constraints to produce the minimum and maximum values for each range, as per Table 6.

The model generates multiple housing configurations (Fig. 2) based on a set of initial values (within a given range).

We combined the factors as per (1) to obtain the value of Q (quality of housing development) as the final result of any combination generated. All values for each factor have been normalised (0–1) to be linearly combined. Each configuration is characterised by a value of Q. Each factor combination has different trade-offs,

Table 6 Constraints used to generate ranges

	Range	Source
Plot area size	< 0.25 ha (small sites), < 2.5 ha (larger developments)	The London Plan 2021 (link)
Building height	3–8 storey (9.6 to 25.6 m) 8–12 storeys (25.6 to 38.4 m) would be classified as tall building	Link (tall building) Policy C4.3.2 of Good Quality Homes for all Londoners SPG (link) Relevant London Plan policies: D6
Distance between buildings	13–22 m apart	Link Local planning (TBD)
Number of links	2–10 (walking distance)	arbitrary
Shared open space	30m^2 per house–90m^2	London Borough of Lambeth link
Cost per sqm	From £3,994 per m^2 to £19,439 (London boroughs)	ONS—link
Density	35–260 units/Ha (GLA Housing Density Study)	Link

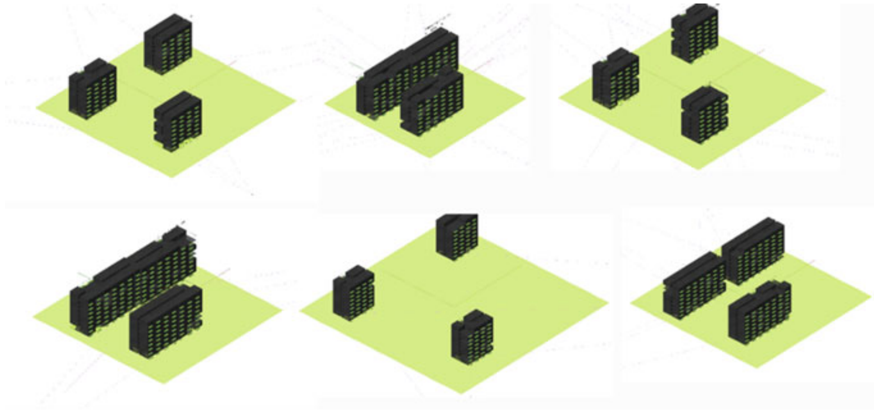

Fig. 2 Initial housing configurations before optimisation

for example increasing "area per resident" favourably increases *Q*,but also raises the "cost/sqm". In order to find the best trade-offs among the 4 factors, we used a multi-objective optimisation strategy implemented through the evolutionary engine Wallacei (cf. Showkatbakhsh & Makki, 2020). Wallacei uses the Non-dominated Sorting Genetic Algorithm II (NSGA-II) algorithm (Deb et al., 2002), which offers "*a much better spread of solutions and better convergence near the true Pareto-optimal front*" (Deb et al., 2002:182).

We implemented the optimisation using the 6 criteria as "genes" as per Table 2. In this particular experiment, we have not included the fifth criterion (windows area) as we have not been able to find a reliable dataset to assess the weights. We included this criterion anyway in the Grasshopper model for future developments. We also included a density parameter to control the number of units in the development. Area per resident, shared open spaces, private communal spaces (and window area) and density have been set to be maximised, while cost per square meter and links to urban services (expressed here in average distance from the building blocks entrance) were minimised.

The overall quality of development *Q* has been used as an objective for the optimisation. The NSGA-II algorithm is used here to find the most fitting solutions (spatial configurations for housing development) evaluating trade-offs between parameters to be maximised and minimised (Fig. 3).

3.6 Results

Firstly, we run 2 iterations to compare the criteria considered individually, as separate objectives and linearly combined, as one criterion. We run these two iterations using the weights resulting from our statistic modelling (Table 4). The first case (Q') yielded

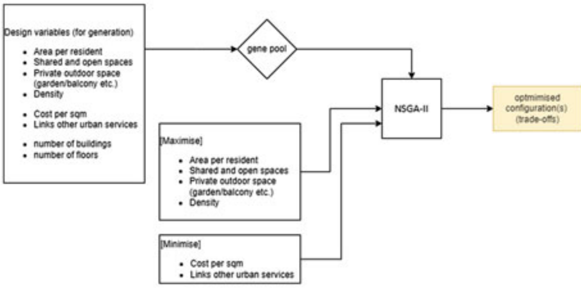

Fig. 3 Logic of the NSGA-II optimisation

a 6-dimensional representation of the objectives, while the second (Q”) produced a single-objective optimisation.

Secondly, we wanted to compare the impact of weights for each criterion in the optimisation. We run 6 iterations (Fig. 4) where we increased the weight of one criterion in turn (multiplier = 10), keeping the other 5 with a constant value (multiplier = 1) as summarised in Table 7 below.

4 Discussion

The highest performing configuration is iteration Q2 (Q = 5.23), where Shared open space has been emphasised (13.158 m^2 per person). The model seems to favour extreme solutions: either with the smallest number of buildings with large footprints and high number of floors (as in Q2 and Q4), or a large number of buildings with smaller footprints (as in Q3 and Q1). The lowest score is performed by Q5 (Q = 1.59) which seems to present an intermediate position between the 2 top scorers (Q2 and Q3). Although Q2 is the highest scoring, the second in the list (Q3 = 4.59) presents a better trade-off between all factors considered, with a lower density approach and a significantly lower cost (£3,994). The two highest scoring configurations (Q2 and Q3) are underpinned by emphasising shared spaces, both common (Q2) and private (Q3). This seems to suggest that overall the model considers shared spaces as a winning factor in the optimisation.

Comparing these results with Q’ (=3.48) and Q” (=3.84), where we applied the weights (Table 4) obtained with our statistic model without any additional multiplier, we observe that the model seems to find trade-off values that are near the average of the solutions generated with multipliers. The solutions that are closer to the average of all factors are Q” and Q1, as illustrated in Fig. 5. Such solutions present a more balanced trade-off among all parameters.

4.1 Limitations

While the combination of criteria from social values and aspirations, regulations and developers' drivers, and success factors for resilient communities is robust and clearly documented, these datasets should be improved with new data, collected ad hoc for a specific housing project. In fact, our work has included general datasets that are valid for the entire UK, with some detailed aspects of the City of London. A more detailed dataset describing a specific area and community would yield more accurate results and a more fine-grain generative model.

In this sense, the main limitation of this study is represented by the fact that ~~that~~ we used general datasets for the statistical estimation of the weights. We used existing

Table 7 Summary of iterations and results

	Strategy	Results	*Q* value
Q'	All 6 criteria used as individual objectives (multi-objective optimisation). This value of Q includes the weights from Table 4, but no additional multipliers are applied	Area per resident = 58 Private outdoor space = 10 Density = 85 Shared Open Space = 8307 Cost per sqm = £4,397 Distance to Urban Links = 3 Number of Buildings = 4 Number of Floors = 6	Q' = 3.48
Q"	Q value as linear summation of the 6 criteria used as objective (single-objective optimisation). This value of Q includes the weights from Table 4, but no additional multipliers are applied	Area per resident = 61 Private outdoor space = 0 Density = 301 Shared Open Space = 11,887 Cost per sqm = £3,994 Distance to Urban Links = 2 Number of Buildings = 1 Number of Floors = 9	Q" = 3.84
Q1	Area per resident (×10) Others × 1	**Area per resident = 61** Private outdoor space = 10 Density = 155 Shared Open Space = 12,089 Cost per sqm = £17,873 Distance to Urban Links = 9 Number of Buildings = 4 Number of Floors = 10	Q1 = 4.08
Q2	Shared and open spaces (×10) Others × 1	Area per resident = 1,61 Private outdoor space = 9.7 Density = 213 **Shared Open Space = 13,158** Cost per sqm = £15,261 Distance to Urban Links = 2 Number of Buildings = 1 Number of Floors = 12	Q2 = 5.23

(continued)

Table 7 (continued)

	Strategy	Results	Q value
Q3	Private outdoor space (×10) Others × 1	Area per resident = 61 **Private outdoor space = 10** Density = 96 Shared Open Space = 12,168 Cost per sqm = £3,994 Distance to Urban Links = 9 Number of Buildings = 5 Number of Floors = 6	Q3 = 4.59
Q4	Density (×10) Others × 1	Area per resident = 61 Private outdoor space = 10 **Density = 87** Shared Open Space = 12,388 Cost per sqm = £17,380 Distance to Urban Links = 4 Number of Buildings = 1 Number of Floors = 12	Q4 = 4.33
Q5	Cost/sqm (×10) Others × 1	Area per resident = 44 Private outdoor space = 0.1 Density = 363 Shared Open Space = 10,378 **Cost per sqm = £3,995** Distance to Urban Links = 5 Number of Buildings = 2 Number of Floors = 9	Q5 = 1.59
Q6	Urban links (×10) Others × 1	Area per resident = 61 Private outdoor space = 10 Density = 86 Shared open space = 10,172 Cost per sqm = £4,792 **Distance to Urban Links = 3** Number of buildings = 4 Number of floors = 6	Q6 = 3.28

sets as proxies to analyse distributions and infer the possible influence of individual factors on the calculation of the overall quality of housing development Q. For example, for the distribution of Q, we used the Index of Multiple Deprivation (IMD), as an inverted measure of the quality of residential areas.

Lastly, the generative model has been based on a number of initial assumptions (cf. Table 5) and predetermined value ranges (Table 6) which affect the generation of the solutions. We used generic assumptions based on local UK planning regulations. A more specific site, with local conditions, constraints and regulations would allow our model to generate more accurate solutions.

Fig. 4 Summary of housing configurations with different priorities: Q1 (Area per resident), Q2 (Shared open space), Q3 (Private outdoor space), Q4 (Density), Q5 (Cost per sqm) and Q6 (Distance to urban links)

	AVG	Q'	Q''	Q1	Q2	Q3	Q4	Q5	Q6
Area per resident (m^2)	51.076	6.924	9.924	9.924	-49.466	9.924	9.924	-7.076	9.924
Private outdoor space (m^2)	7.475	2.525	-7.475	2.525	2.225	2.525	2.525	-7.375	2.525
Density (ℤ)	173.250	-88.250	127.750	-18.250	39.750	-77.250	-86.250	189.750	-87.250
Shared Open Space (m^2)	11.311	-3.011	0.569	0.769	1.839	0.849	1.069	-0.941	-1.141
Cost per sqm (£)	8960.750	-4563.750	-4966.750	8912.250	6300.250	-4966.750	8419.250	-4965.750	-4168.750
Distance to Urban Links (ℤ)	4.625	-1.625	-2.625	4.375	-2.625	4.375	-0.625	0.375	-1.625
Number of Buildings (ℤ)	2.750	1.250	-1.750	1.250	-1.750	2.250	-1.750	-0.750	1.250
Number of Floor (ℤ)	8.750	-2.750	0.250	1.250	3.250	-2.750	3.250	0.250	-2.750
Q value	3.803	-0.323	0.037	0.277	1.428	0.787	0.527	-2.213	-0.523

Fig. 5 Heatmap of the normalised values from Table 7 with distances to average. The red values are more distant from the mean value for each factor. The green ones are closer, and the white values are the closest. Q" and Q1 have the most values in proximity to the average

4.2 Next Steps

The next steps for the development of this model include the following points.

First, the calculation of values of Q external to the model, using a scoring system, is developed in a different framework. Different values of Q obtained with different methods can be used to validate our model as we did in Carta et al. (2021), for example. Such externally calculated Q values could be, for example, from jury-based awards for housing developments (e.g. RIBA annual awards for housing), and should certainly include elements that are less reliant on economic factors (like the IMD). Externally calculated values of Q for a specific area would allow us to validate our model by comparison of results.

Second, we will seek funding to generate new datasets that capture information about specific areas and communities. With more specific data, we will be able to calibrate our model and produce more accurate results.

Third, we will be experimenting with more intelligent methods to evaluate trade-offs of the weighted design criteria to generate housing configurations, including Convolutional Neural Networks (CNN) and Graph Convolutional Networks (GCN), as we believe that graph-based methods may be helpful in dealing with programmatic relationships in housing design (del Campo et al., 2020).

5 Conclusion

This study shows how social aspirations can be encoded into design criteria, in combination with other drivers in housing developments, including local regulations and government agendas and successful aspects for resilient communities. Although the model is still in the prototype phase and very much dependent on a number of aspects that need calibrating, this work shows that encoding of social values into a computational workflow is possible and that the model (using UK-wide datasets) is able to yield promising initial results. This paper explains how the model works, providing some initial examples of possible applications, and suggesting how qualitative and quantitative data can be combined in practical design and planning applications.

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Actors@BIM: A Hybrid Formal Model for Cognitive Buildings

P. Govind Raj and Subrat Kar

Abstract Cognitive Buildings are a nascent area of research which envisions a paradigm shift from of a static notion of the building as a container of human activities to that of dynamic cyber-physical system capable of integrating, analysing and learning from the vast amount of sensor data generated from within a building and its environment. This paper presents a formal model called Actors@BIM capable of analysing static and dynamic constructs and configuration of a cognitive building. The model is hybrid as it combines two existing modelling frameworks, namely Building Information Model (BIM) and actors through a common formal meta-modelling framework of Bigraphical reactive systems (BRS). Combining BIM and actors within a single model provides a powerful abstraction to model both static and dynamic natures of modern building. The key idea of this formal model is that actors can reason about the spatial properties of a building and can take decisions about them. Since the model presented is a formal model, it is amenable to formal verification. In this modelling framework, the spatial aspects of the building are captured by a BIM model and the dynamic aspect of the cognitive building is captured through actors. These actors can be embedded within a spatial structure (i.e. BIM model). In essence, this formal model extends BIM by incorporating actors embedded within it, and they can reason about the static and dynamic properties of the space. The requirement of such a model is because of the emergence of cognitive/smart building and the lack of formal models to model, study and analyse static and dynamic constraints within such a set-up. Although there have been previous attempts to encode agents using BRS, they have not been studied in relation to BIM and cognitive buildings. Further, there have been previous attempts to model agents/actors which can reason about spatial structure; however, a cohesive model, encapsulating spatial structures

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and agents within those structures modelled using a common meta-modelling framework, is still lacking. We attempt to fill this gap in existing research through this work. The contributions of this paper are (a) A software library to model transform a BIM model to bigraph representation; (b) A formal semantics of the Actors@BIM Model; (c) A Domain-Specific Language to model dynamic agent behaviour within a cognitive building; and (d) Use case study of examples of formal verification of static and dynamic properties of a Cognitive Building using Actors@BIM

Keywords BIM · Bigraphical reactive systems · Actors · Informatic model

1 Introduction

Cognitive buildings are gaining increasing attention and can be thought of as a novel way of thinking about future built environments. It is closer to Le Corbusier's modernist vision of "machine habiter" where the technological aspects of a built environment add ability to sense, control, compute and actuate several parameters of the built environment, thereby enabling goals like user comfort, energy saving, navigation, etc.

The application of the Building Information Model (BIM) to cognitive buildings has been one of the most investigated research directions (Tagliabue and Yitmen 2022; Manzoor et al. 2021). However, BIM alone cannot comprehensively model cognitive building. BIM is capable of modelling the static aspects of a cognitive building (i.e. spatial properties, e.g. building geometries, floors, layout, etc.). However, an important aspect of cognitive buildings is the technological components (sensing, communicating, computing and actuating elements) that add the ability to cognition within a cognitive building. The behaviour of these elements is difficult to specify by BIM alone. Furthermore, BIM, although it is an industry standard for describing physical environments, lacks explicit static and dynamic semantics (Tsigkanos et al. 2016, 2016). As a result, BIM precludes any form of precise and automated formal analysis, such as model checking. In the AEC industry, predominantly rule-based verification procedures (represented as checklists) are commonly used. Commercial tools such as Solibiri Model Checker (Bim software for architects, engineers and Construction Industry 2022), etc., have inbuilt support for this kind of analysis. However, there is a significant gap in considering cyber and physical factors holistically, which is a key requirement in developing formal models for Cognitive Buildings.

As a result, this work introduces *Actors@BIM*, a hybrid formal model to represent and analyse the cyber and spatial elements of a cognitive building. Through a common meta-modelling framework of the Bigraphical Reactive System (BRS) (Milner 2009), it combines two different models, namely the BIM and the actor model of computation (Hewitt 2010; Agha et al. 1997) (hereafter referred to as actors), resulting in a "tower of informatic model" (Milner 2009). Within this framework, the BIM model is transformed into a bigraphical representation and actors can be embedded

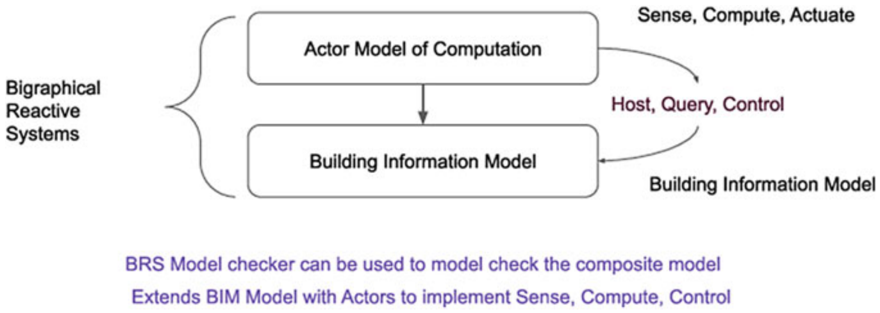


Fig. 1 High level view of Actor@BIM model

(i.e. hosted) within it. These actors are abstract and can represent cyber elements within the building, such as sensors, computers, actuators, communication devices and mobile phones carried by people, whereas the BIM model can be used to represent the spatial model of a cognitive building. Furthermore, these actors can also reason about the spatial aspects of a building by querying the BIM model through BIMQL (Mazairac and Beetz 2013). Since this model can capture both the cyber and physical elements of a cognitive building, it can represent a cognitive building more faithfully than BIM alone. Compared to previous efforts in this area (Eloi and Eloi 2015; Pereira et al. 2013), the current work distinguishes itself by employing a common meta-modelling framework of bigraphical reactive systems to describe both the spatial characteristics of a building and the behaviour of cyber components. Although BIM and Bigraphs have been combined in previous publications, the behaviour of agents introduced in BIM has not been clearly described in a generic way using a computational model similar to that of actors (Tsigkanos et al. 2016). This work attempts to close this knowledge gap. A high-level overview of the model is given in Fig. 1.

The following is the structure of the paper. Section 2 provides context for understanding the formal model of Actors@BIM. It provides an introductory overview of bigraphical reactive systems, the actor model of computing, and the actor model's bigraphical encoding. Actors@BIM is introduced and its semantics are specified in Sect. 3. The following section i.e. Section 4 provides an overview of BigBIM: A collection of tools based on the Actors@BIM concept. This is still being actively developed. It includes a BIM2BIGRAPH model transformer, BLang, a domain-specific language (DSL) for modelling with Bigraphical Reactive Systems, Actors@BIM DSL, which enables the use of Actors@BIM model, and a language-to-language translator that converts Actors@BIM DSL to BLang and then to a BigrapER (Sevegnani and Calder 2016) script, which can then be transformed to PRISM, thus enabling model checking of models described through Actors@BIM DSL. Thereafter, we present a brief use case for model checking the static and dynamic properties of a cognitive building in Sect. 5. Section 6 concludes the paper and provides future research directions.

2 Background

The following subsections are a brief overview of the background information required to read this work. We offer the reader with crucial canonical references for a more mathematical discussion of these subjects.

2.1 Bigraphical Reactive Systems

Bigraphical Reactive Systems (BRS) is a process algebraic formalism. BRS is a successor to numerous previously existing process algebra formalisms such as Calculus of Communicating Systems (CCS) (Milner 1980), *pi*-calculus (Milner 1999), action calculi (Milner 1996) and Chemical Abstract Machines (Berry and Boudol 1992). It was developed by Milner et al. (2009). BRS differs from its predecessors in that it is a meta-modelling framework that may be used to model/deduce other process algebraic formalisms. Other process calculus and formal models, such as CCS, *pi*-calculus, Petri-nets and actor models (Sevegnani and Pereira 2014), have been derived using BRS. Although the majority of the work in this field has focused on deriving existing process algebraic formalism, only a small amount of effort has gone into establishing a new process algebraic framework using BRS for a specific domain. This is where the current work is going.

A BRS is made up of Bigraphs and a set of reaction rules that describe how they can be transformed. As the name implies, bigraphs are made up of two (graph) structures: a *Place Graph*, which is a forest defined over a set of *nodes* and used to model containment relationships, and an *Link Graph*, which is a hypergraph defined over the same set of nodes as the place graph and used to model linkages or connectivity. These *nodes* have types, which are referred to as *Controls*. Nodes have *Ports* to which can be used to link edges. The number of ports in node is called its *arity*. Figure 2 provides an anatomy of the structural elements of a bigraph (Milner 2009).

A bigraph B can be specified through a tuple $(V_B, E_B, ctrl_B, prnt_B, link_B) : \langle k, X\rangle \rightarrow \langle m, Y\rangle$ where V_B is a set of nodes, E_B is a set of edges, $ctrl_B$ is the control map that assigns controls to nodes, $prnt_B$ is the parent map that defines the nesting of nodes, and $link_B$ is the link map that defines a link structure. The notation $\langle k, X\rangle \rightarrow \langle m, Y\rangle$ indicates that the bigraph has k sites which denote the presence of other unspecified nodes, m roots, a set X of inner names and a set Y of outer names. $\langle k, X\rangle$ and $\langle m, Y\rangle$ are called the inner and outer interfaces (or faces) of the bigraph. Bigraphs can be used to model and hence represent abstract notions like an abstract data structure (e.g. tree, lists) and concrete structures like building consisting of rooms, computers and agents etc. as shown in Fig. 3.

Though bigraphs can be represented graphically, they can also be represented through algebraic expressions in a process-algebraic manner. Equation *1-a* represents the containment relation, that is, P contains another node Q. Equation *1-b* represents the juxtaposition (i.e. placement side by side) of nodes P and Q. Equation *1-c*

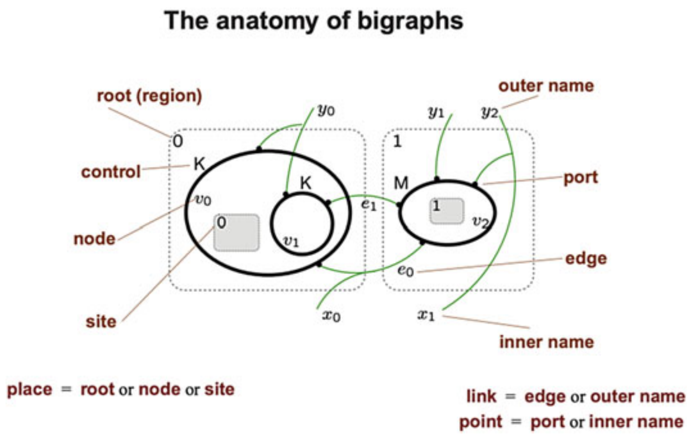
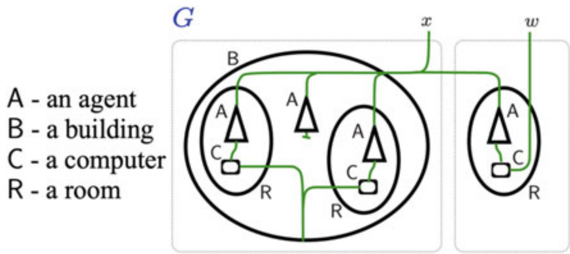


Fig. 2 Components of bigraphs (Milner 2009)

Fig. 3 An example bigraph (Milner 2009)



specifies *site*. A site in a bigraph represents nodes that were abstracted or unspecified. It can also be used during the composition of bigraphs as a placeholder for nodes. Equation *1-d* represents a node *P* with names from a set *k*. Port names can be used in cases where the node's control (i.e. its type) alone cannot uniquely determine it. Ports of the same name are connected, forming a hyperedge (i.e., an edge with multiple nodes), thus forming a *link*. Bigraphs can be contained in roots. They may represent systemic boundaries. Equation *1-d* represents the juxtaposition of two bigraphs *W* and *R* with separate roots. Graphical representations of Equations *1-a to 1-d* are shown in Fig. 4.

$$P.Q : \text{Nesting (P contains Q)} \quad \text{1-a}$$
$$P^{-}Q : \text{Juxtapose nodes} \quad \text{1-b}$$
$$-_i : \text{Site numbered i} \quad \text{1-c}$$
$$P_{k.}(Q) : \text{P with names in k containing node Q} \quad \text{1-d}$$
$$W \| R : \text{Juxtaposition of two bigraphs} \quad \text{1-d}$$

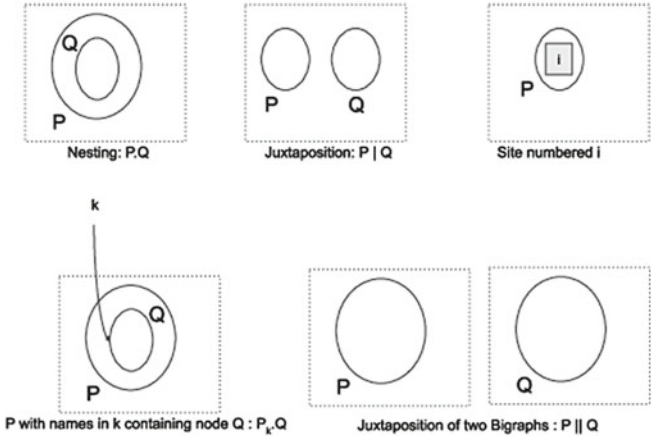


Fig. 4 Algebraic expressions of bigraph operations

Bigraphs can be combined to form larger bigraphs. Two bigraphs can be composed only if their interfaces match, that is, the outer interface of the host bigraph should match the inner interface of the bigraph that is being composed. This composition can be seen to be similar to the composition of functions in a functional programming language. This allows multiscale modelling of larger systems. In essence, simpler models can be composed to form larger complex models. Or two different modelling paradigms both represented through bigraphs can be composed as a single model as in this work.

2.1.1 Bigraphical Reactive System

Bigraphical Reactive Systems enhance bigraphs by including reaction rules that define how bigarphs can be modified. A reaction rule is of the form $R \rightarrow R'$, where R is referred to as *Redux* and R' is referred to as *Reactum*. Both the redux and the reactum are bigraphs. If a section of a bigraph matches the redux, a reaction rule can be executed. In the event that a match is identified, the redux is replaced by the reactum, much like a rewiring system. Hence, through a reaction rule, one can selectively rewrite portions of bigraphs, thereby bringing about dynamism/evolution of the system being modelled. These reaction rules can have probabilities associated with them (Archibald et al. 2021), allowing the quantitative model checking. The BigBIM tool discussed in Sect. 4 also supports specifying reaction rules with probabilities.

2.2 Actor Model

Carl Hewitt proposed the actor model of computation, which was later extended by Agha et al. (1997). The primary modelling concept in this approach is that of an actor. Actors have addresses and can interact with one another through asynchronous message passing. Messages are used by the actors to communicate with one another. Within the actor setup, there is a mailbox that keeps all pending messages, i.e., those that have been received but not yet processed. The recipient actor consumes the pending messages from the message box to process them. The internal state of an actor can be accessed by another actor from the outside only by sending a message. Because there are no shared mutable states between actors, this crucial feature decreases the risk of concurrency issues. The actor model has been adopted as the concurrency model in several programming languages such as *Erlang* (Virding et al. 1996), *Scala* (Haller and Odersky 2009), *Haskell* (Epstein et al. 2011) *Dart*, and also in frameworks like *Akka* (Roestenburg et al. 2016). When an actor receives a message, it can do the following:

1. **Send** a message to a different actor
2. **Spawn** a finite number of new actors, and
3. **Compute** its internal state so that the next incoming message is affected.

We provide the operational semantics through the Bigraphical Reactive system as in Sevegnani and Pereira (2014) in Sect. 2.3.

2.3 Bigraphical Definition of Actor Model

In this section, we briefly discuss the bigraphical encoding of actor model. We follow the approach as in Sevegnani and Pereira (2014). We specify the reaction rules corresponding to creating a new actor (NEW), sending a message to an actor (SND), performing a local computation step (FUN), removing an actor from the actor system (NIL) and receiving a message (RDY). For a detailed treatment and graphical representation of reaction rules, we refer the reader to Sevegnani and Pereira (2014).

1. **Nil**:Nil removes an empty actor.

$$R_{nil} = A_a.(Nil_0^-) \rightarrow a$$

2. **New**: New creates a new actor. We slightly modify the semantics from as presented in Sevegnani and Pereira (2014), so that the newly created actor has a reference to the address of its parent. This enables us to create hierarchies of actors and supervisory control require for engineering reliable systems Chechina et al. (2017). The node *Prnt* holds the reference to the parent's address.

$$R_{new} = A_a.(-_2 \text{-} New.(-_1 \text{-} Prnt_a \text{-} A_{a'}.(-_0)) \rightarrow A_a.(-_{2_1^-})^- A_{a'}(-_2 \text{-} Prnt_{a_0^-})$$

3. **Snd**: The semantics of SND sends a message to a recipient.

$$R_{snd} = A_a.(-_0 \text{-} Snd.(M_{a'}.-_2)_{\bar{1}})^{-}Mail \longrightarrow A_a.(-_{0_{\bar{1}}})^{-}Mail.(M_{a'}.-_2)$$

4. **FUN**: Through *FUN* a local computation effect is modelled. The resultant effect is a change in the local environment of the actor in which it is executed. There are two subrules of *FUN* which specified addition *add* and update of environment *upd* variables as shown below.

$$R_{fun} = A_a.(-_0^{-}Fun.(-_1)) \rightarrow A_a.(-_0)$$
$$R_{upd} = A_a.(Fun.(N.Int)^{-}-_0)^{-}E.(N^{-}-_1) \rightarrow A_a.(Fun^{-}E.(N.Int)$$
$$R_{add} = A_a.(Fun.(N.Int)^{-}E) \rightarrow A_a.(Fun^{-}E.(N.Int))$$

5. **RCV**: *RCV* and its sub-rules i.e. (RCV_{sub},RCV_{rem}) used to receive a message. While *RCV* initiates the receives process and substitution of a free variable, RCV_{sub} is specified for the actual substitution, RCV_{rem} is used for removing from the free variable.

$$R_{rcv} = A_a.(-_1 \text{-} Rdy.(-_0 \text{-} X_x))^{-}Mail.(-_3 \text{-} M.(-_2))^{-}Sub.(-_4) \rightarrow$$
$$A_a.(-_{0_{\bar{1}}})^{-}Mail.(-_3)^{-}Sub.(-_4 \text{-} X_x.(-_2))$$
$$R_{sub} = Sub.(-_1 \text{-} X_{x.}(-_0))||X_x \rightarrow Sub.(-_1 \text{-} X_{/x}.(-_0))$$
$$R_{rem} = Sub.(-_1 \text{-} /xX_x.(-_0)) \rightarrow Sub.(-_1)$$

3 Actor@BIM

In this section, we formally define Actor@BIM. The symbol '@' is used to convey the notion that actors are embedded within a BIM Model. Since both actors and BIM are represented as Bigraphs, we use the notion of bigraphical composition Milner (2009) to compose these two models into a cohesive model. The Actor@BIM model provides an extension to the BIM model and helps us specify the behaviour of entities like sensors, computers, actuators, and communication elements that may be present in a cognitive building. Furthermore, the introduction of actors within BIM helps us to model the behaviours of building occupants, their navigation within the building, and other scenarios through the use of Bigraphical Reaction Rules.

3.1 Actors@BIM Semantics

The *Sense-Compute-Control* paradigm (Bertran et al. 2014) is a powerful abstraction to model environments involving sensors, computers, actuators, and communication systems such as Cognitive Buildings. Within the Actors@BIM framework, actors represent all the sensing, computing, controlling, and actuating elements in a building, whereas BIM represents the building itself. Through the Actors@BIM model, we extend the actor model semantics presented in Sevegnani and Pereira (2014) with specific messages to develop a "*Sense-Compute-Control*" paradigm suited for modelling scenarios within a Cognitive Building.

Actors within Actors@BIM can form hierarchies. This is possible due to the modified semantics of the rule *NEW*, which transmits the address of the actor who produced it when creating a new actor. The benefit of building a hierarchical organisation of actors is that we can properly divide work among actors, resulting in specialised actors performing only one specific activity enabling a modular design, which is an excellent software engineering practice. In addition, reliability features, such as supervisory control and error handling mechanisms, can be incorporated as in Chechina et al. (2017).

As shown in Fig. 5, the actor at the root of the hierarchy represents the Cognitive Building itself. In one sense, this can be considered as *Digital Twin* Deng et al. (2021) of the cognitive building. At the next level, we have the Device Manager actor. Within the Device Manager group, there are actors that represent a Device Group. Each device type belongs to a specific group. For example, temperature sensors will have one group, smoke sensors will have another group, occupancy sensors will have yet another one, door openers could be another group, etc. The creation of a Device Group is handled at the Device Manager level. At the next level of hierarchy, we have actors representing an individual device like a temperature sensor, smoke sensor, occupancy sensor, door sensor, pathway sensor, etc. These actors can be considered as *Digital Twin* of an individual sensor that has been placed within the cognitive building. The actual connection of a device to the cognitive building network is beyond the scope of semantics.

We discuss the following activities:

- The device registers itself with the device manager by providing its ID and type.
- The device manager component manages registration by locating or creating the actor in charge of managing the device state. The address of this actor is returned as a response to the registration request.
- Once the address of the device actor is known, it can be communicated directly.

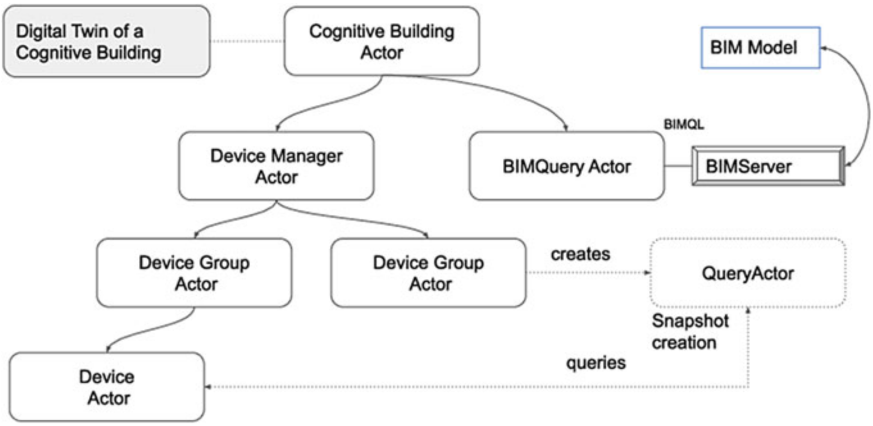


Fig. 5 Actors@BIM hierarchy

3.2 Actor@BIM Registration Protocol

Within the Actors@BIM framework, a newly created actor is in uninitialised state. This is indicated by the node "*Uninitialized(U)*" within the "*Status(S)*" node of Environment. The actor moves to the initialised state when it sends the message "*RegisterActor(RegAct)*" to its parent to register itself. Once registered, the parent has the address of the child and can send messages. This actor registration protocol is common for all instances of Actors@BIM. We specify this control flow using conditional bigraphical systems using the reaction rule shown in Fig. 6.

3.3 Heartbeat

This is across Actors@BIM HeartBeat(Address): This message is sent from an actor at a lower level of hierarchy to its parent. For example, from Devices to Device-Group, and from DeviceGroups to DeviceManager etc. This message is sent using the semantics of *Snd*. When receiving the HeartBeat message, it updates the actor's internal environment with the current location of the device and the current timestamp using the semantics of *FUN*. The current timestamp can be used to track the health of a DeviceActor. Each actor in the hierarchy sends a heartbeat message to its parent so that the parent actor can maintain references to its children. Similarly, in the event of proper shutdown of the actor, the parent actor can make appropriate decisions.

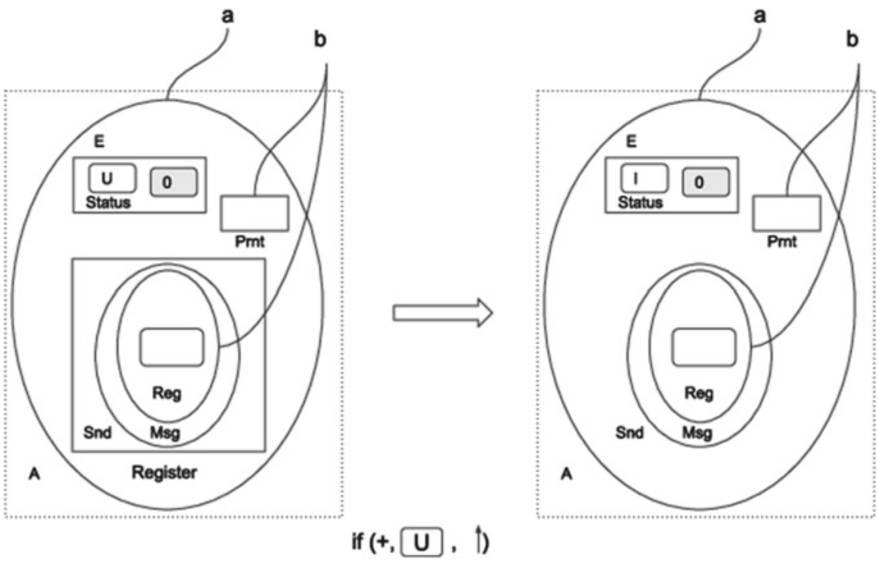


Fig. 6 Conditional reaction rule for registration

3.4 Device Manager

The Cognitive Building actor creates the Device Manager actor using the semantics of *NEW*. The device manager actor is responsible for registering the device actors. This actor checks for the corresponding Device Group actor. If a Device group exists, it transmits the registration request to the Device Group Actor; otherwise, it creates one and then transmits the request to register the Sensor Actor. There are two messages that define the behaviour of this actor.

1. RegisterDevice (DeviceType, DeviceId, SenderAddress): This message has two parameters, namely the *DeviceType* indicating the type of sensor, *SenderAddress* which is the address of the requesting actor. This address is used to respond back using the message *DeviceRegistered*.
2. DeviceRegistered (Address): This message is a response to RegisterDevice to the requesting Actor whose address is received in the RegisterDevice message. The DeviceRegistered message has the address of the Actor registered. The semantics of *SND* is used to send this message to the requesting actor.

The RegisterDevice message is received using the semantics of *RCV, READY* and stored with *MsgRcv*. After receiving, the semantics of *CheckDeviceGroup* is used to check for a DeviceGroup. It does this by looking at its local environment *ENV*. If the corresponding does not exist, a new one is created using *NEW*. The semantics of these are shown graphically through Figs. 7, 8, 9

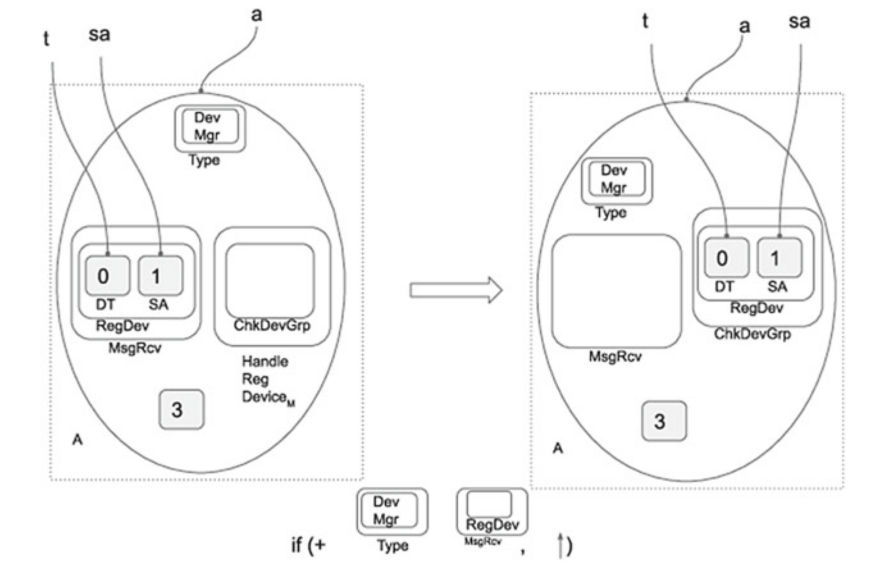


Fig. 7 Check for existence of device group

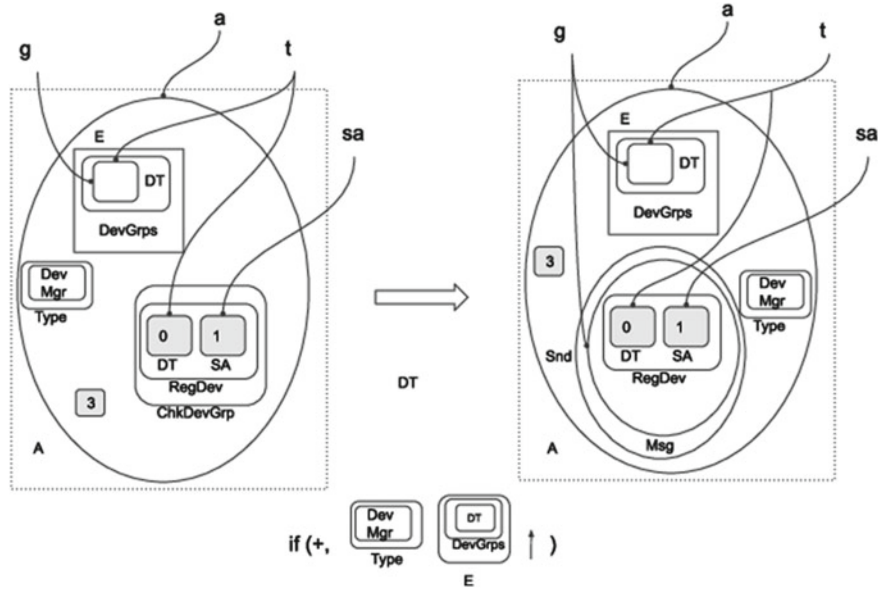


Fig. 8 Existence of device group

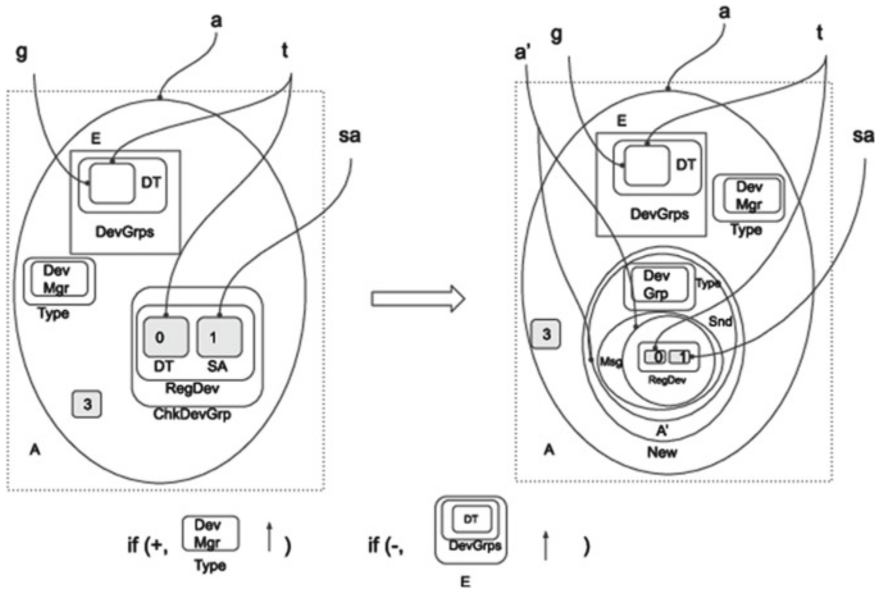


Fig. 9 Non existence of device group

3.4.1 DeviceGroup Actor

The device group actor is responsible for the following activities :

1. Device Registration:
2. Return Registered devices:
3. Track Devices: keeps track of the devices, both in terms of its location and its current health state.

The following messages define the behaviour of the DeviceGroup actor:

1. RegisterDevice (DeviceType, SenderAddress): This message registers a device. Registration involves creating a new actor for the device using the semantics of *NEW*. After the newly created device actor registers itself with with the DeviceGroup actor, it can be supervised.
2. DeviceRegistered (DeviceAddress): This message is used to send the DeviceAddress of a registered DeviceActor. This message is a response of RegisterDevice message.
3. GetDevicesByTypes (DeviceType, SenderAddress): This message is used to retrieve a list of devices by a particular device type (DeviceType), which is sent as a parameter. A separate query actor (i.e. QueryDeviceByType) is created using the semantics of *NEW* to implement this query. We discuss this actor in detail in Sect. 3.5. The query actor is created to scale the system, as for each query a separate QueryActor can be created.

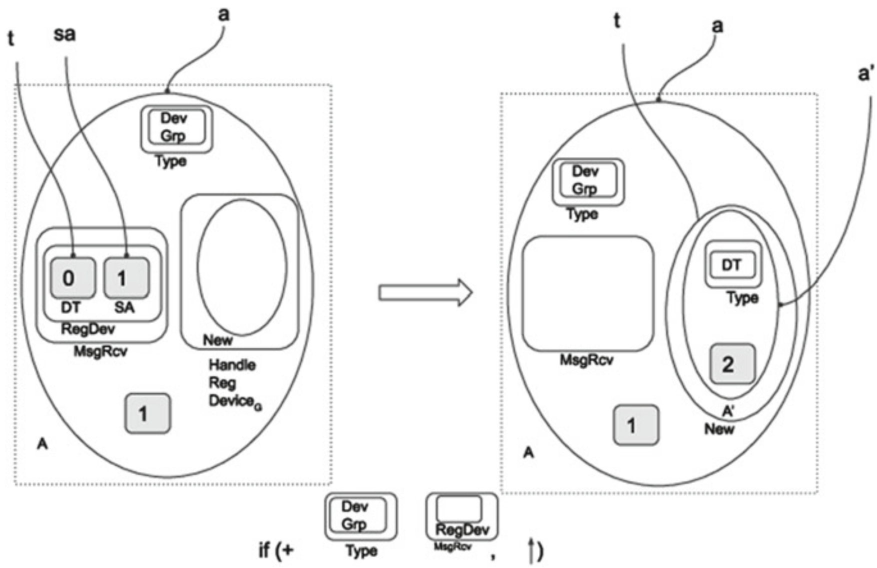


Fig. 10 Semantics for device group: register device

4. GetDeviceByLocation (Location): This message is used to retrieve a list of devices at a particular location. It is noted that devices can also be mobile (e.g. a mobile phone, robot) which can move from one place to another. The device registers its current location when they send a heartbeat using the TrackDevice message. Again for this query a separate query actor (QueryDeviceByLocation) is created using *NEW* to implement this query.

The semantics of these messages are shown in Figs. 10, 11, 12

3.4.2 DeviceActor

The DeviceActor represents the devices capable of sensing and actuating within a Cognitive Building. The specific way in which the device senses or performs actuation is considered internal (non-observable/silent action) and is abstracted using *FUN*

The following messages define the behaviour of the DeviceActor:

1. ReadStatus (requestId, SenderAddress): GetStatus returns the sensed value from a sensor or internal state of an actuator. For example, request to read temperature from a temperature sensor.
2. RespondStatus (requestId, value): This message is a response to the GetStatus message and responds with the status value. For example, the device responds with a temperature reading as a value of this message.

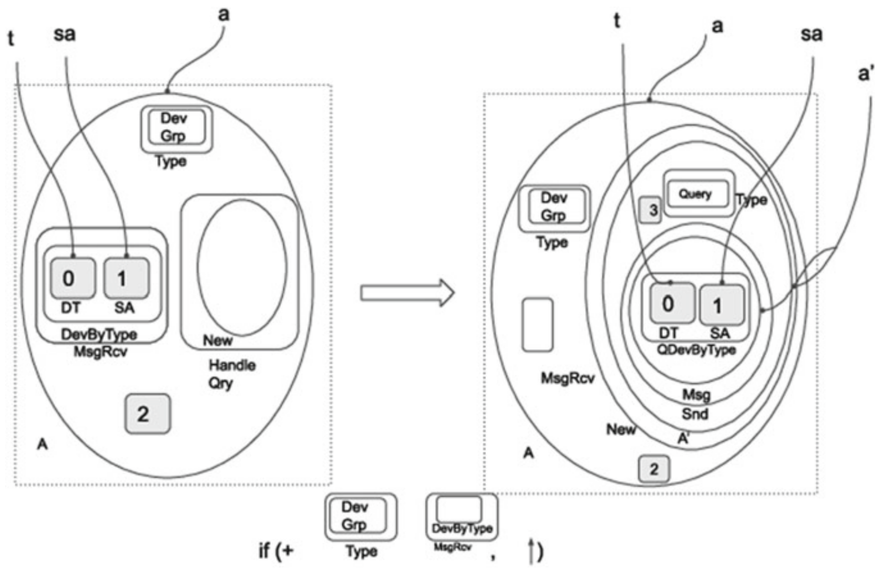


Fig. 11 Semantics for device group: query by device type

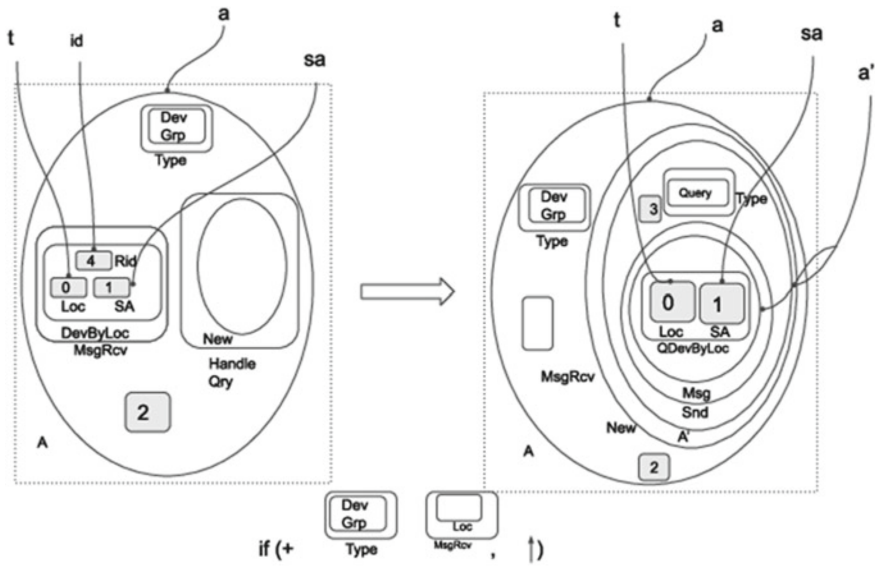


Fig. 12 Semantics for device group: query by device location

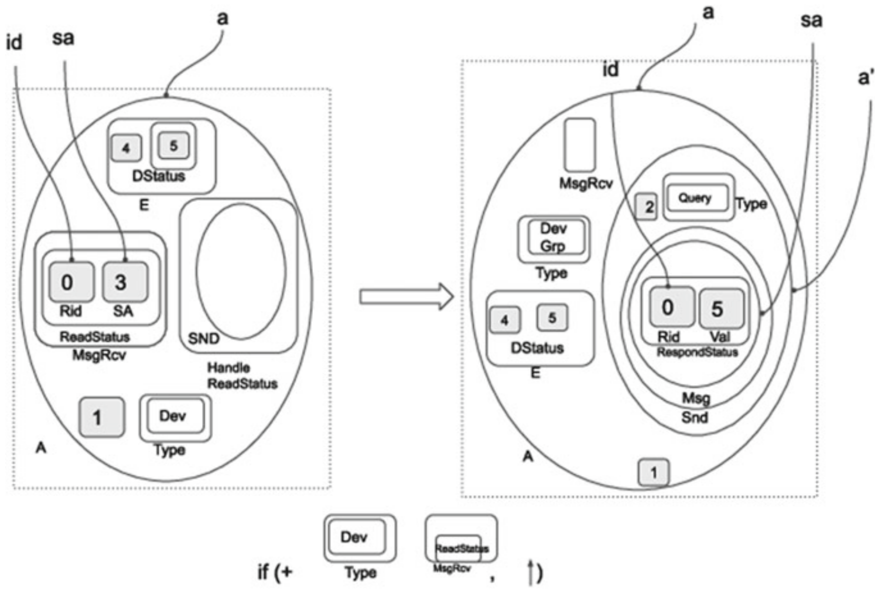


Fig. 13 Semantics for Device:: ReadStatus

3. PerformAction (requestId, SenderAddress, action): The perform action message is sent to actor to perform its internal function, i.e. sensing, actuating etc. As shown in Fig. 14, once the action is performed the device status (DStatus) within the environment is changed and the updated value is sent as the actionStatus in the *ActionPerformed* message.
4. ActionPerformed(requestId,actionStatus): Sent as a response to *PerformAction*

The semantics of the above message are shown in Figs. 13, 14

3.4.3 Query Actor

Building users and systems may want to query sensor / device values in the building or in a single area with several sensors. This may necessitate a query of all devices in a device group. The DeviceQuery Actor handles this. Remember that group membership is dynamic and that a DeviceActor may fail or a new DeviceActor may be formed at any time. Thus, the DeviceQuery actor can take a snapshot of the available actors and query their status using the *ReadStatus* message. Each query starts a new DeviceQuery actor. This helps scale the querying of the cognitive building's sensors and actuators. A DeviceQuery actor is created for each new DeviceQuery using the semantics of *NEW*. The DeviceQuery Actor inherits the DeviceGroup Actor's (i.e., its parent's) environment, where it keeps the device's state and location. The DeviceQuery actor sends itself messages to query the cognitive building. The semantics

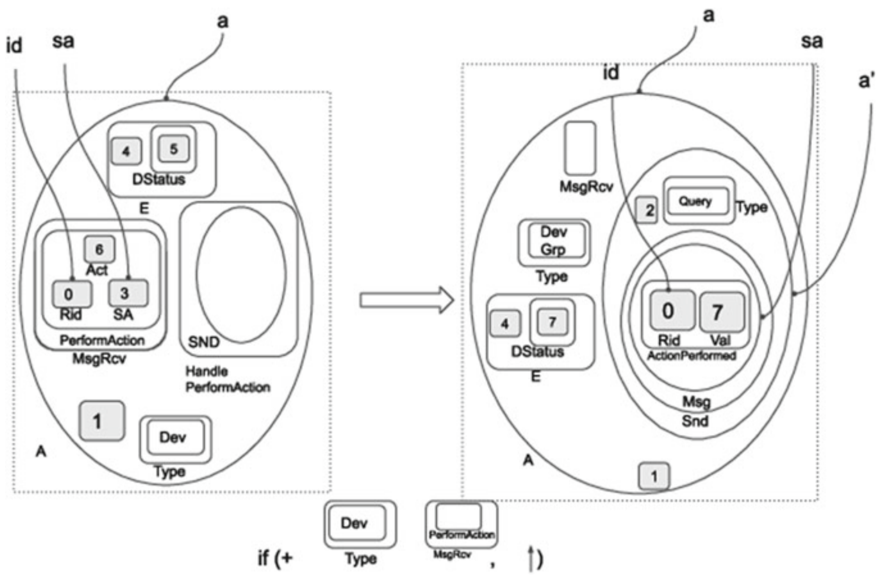


Fig. 14 Semantics for Device:: PerformAction

of *QueryDeviceByType* and *QueryDeviceByLocation* is shown in Figs. 15, 16. As shown in these figures, (*QryResp*) message is sent as a response to a query.

3.5 BIMQueryActor

While we transform a BIM Model into a Bigraph representation within the Actors@BIM framework to enable model verification, we retain the original BIM model so that not only domain experts but also other actors within the Actor@BIM model can query the BIM Model using BIMQL (Mazairac and Beetz 2013), a query language for BIM Models. Additionally, utilising BIMQL's *SET* keyword, actors in the Actors@BIM model can edit the values of custom attributes contained within a BIM model. This enables devices (represented as actors) within the Actors@BIM model to update sensed data (e.g., temperature, door open status, occupancy, etc.) as custom property updates within the BIM model. This can be used to query the BIM model in the future. For instance, "*Select ? MySpace Where ?MySpace.EntityType=IfcSpace and ? MySpace.temperature* > 35", selects all areas in the Cognitive Building with a temperature greater than 35 °C.

The BIMQueryActor is built on top of the BIMServer (Open source building information server 2022) open source project.

The BIMQueryActor conforms to the actor model semantics, which means that any actor in the Actor@BIM model can send this actor a message containing a

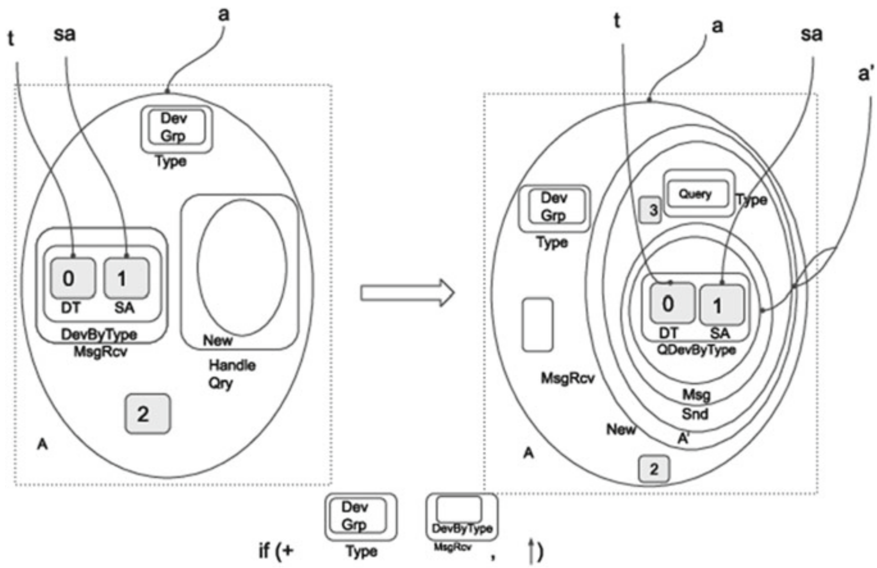


Fig. 15 Semantics for query by type

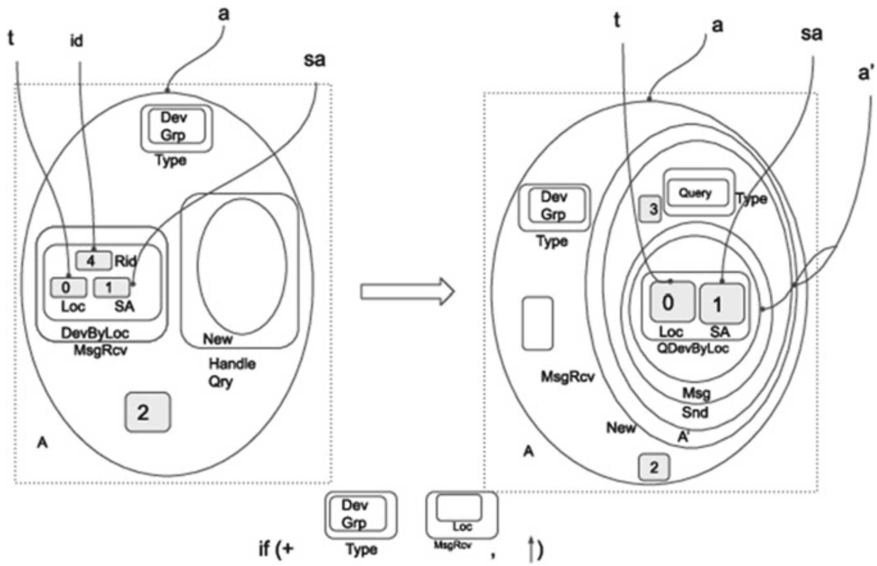


Fig. 16 Semantics for query by location

BIMQL Query. The actual BIM Model queried through BIMQL is abstracted away as an internal function of this actor utilising the *FUN* semantics.

4 BigBIM: A Tool Suite Utilising Bigraphs and BIM

This section provides the high-level architecture of BigBIM. We have used language workbenches such as Xtext(for Eclipse) (Bettini 2016) and Langium (2022) (for VSCode) to build this tool suite. Figure 17 shows the high-level architecture of the components of the transformation library.

The tool suite consists of the following components:

- BIM2BIGRAPH: The BigBIM tool lets you turn a BIM model into a Bigraphical representation. The transformer understands the semantics of IFC classes and converts the IFCXml into bigraph components, such as Place Graphs and Link Graphs, which show how spaces are contained and linked together. It makes the BIM hierarchy easier to understand and names entities that use the building by its real-world name. SMART bsDD has a data dictionary (bSDD buildingSMART Data Dictionary 2022). BIM2BIGRAPH module has two submodules viz a SAX an XML parser to parse the IFC XML document, a Semantic Mapper to map concepts in IFC to Bigraphs, and the jLibBig library (A Java library for Bigraphs and Bigraphical Reactive Systems 2022) which is used to create a bigraphical representation. While performing the BIM to bigraph conversion, the entity types in IFC (e.f. IfcDoor, IfcWall etc.) is looked up in bsDD and the simplified name is used as the control for the nodes. Semantic manipulation of IFC concepts is done by the BIM2BIGRAPH translator using the Semantic Mapper, for example, Rooms within a building are juxtaposed with each other and nested within a building. For this purpose, the bigraphical operations of juxtaposition (|) and nesting (.) are utilised. Similarly, multiple nodes are constructed for a wall; each is nested inside

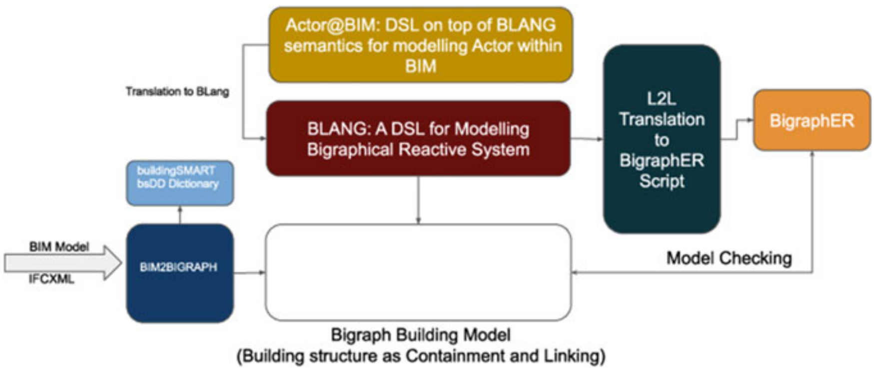


Fig. 17 High Level architecture of BIM2BIGRAPH

nodes that represent the rooms the wall spans. Similarly, two nodes are constructed for each door; these are nested within the nodes corresponding to the rooms that the door connects. For modeling connectivity, linkage between nodes is used (Link Graph). For example, to connect a room to another via a door, for example, a Door node is inserted in the relevant Room. Thereafter, the port of this door is connected to the door node associated with the Room to which it leads. A similar approach is taken for walls.

- BLang: As part of the BigBIM platform, we developed a domain-specific language (DSL) called BLang. BLang provides support for the definition and manipulation of Bigraphs and Bigraphical Reactive systems. After the BIM2BIGRAPH converts a BIM model to a Bigraph representation, the BIM representation can be manipulated using BLANG. These changes may involve abstracting certain features of the BIM model that are no longer relevant via the creation of "holes" or adding extra controls that are relevant. BLang can be used as a standalone domain-specific language (DSL) for modelling through bigraphs. It has first-class constructs to define bigraphs and manipulate bigraphs using bigraphical operators like nesting, juxtapositioning, linking, etc. Furthermore, it has constructs to define reconfiguration of bigraphs through specifying bigraphical reaction rules, including reaction rules with probabilities. Since we have developed a Langauge server that speaks the Language Server Protocol (LSP), support for BLang is possible in several IDEs. As illustrated in Figs. 18 and 19, we tried this with two distinct integrated development environments (IDEs): Eclipse and VSCode. Due to the fact that bigraphs are a graphical process algebric formalism, BLang also offers diagrammatic visualisation of the bigraphs defined in it. We have used the Sprotty library to build the diagramming support as shown in Fig. 19.

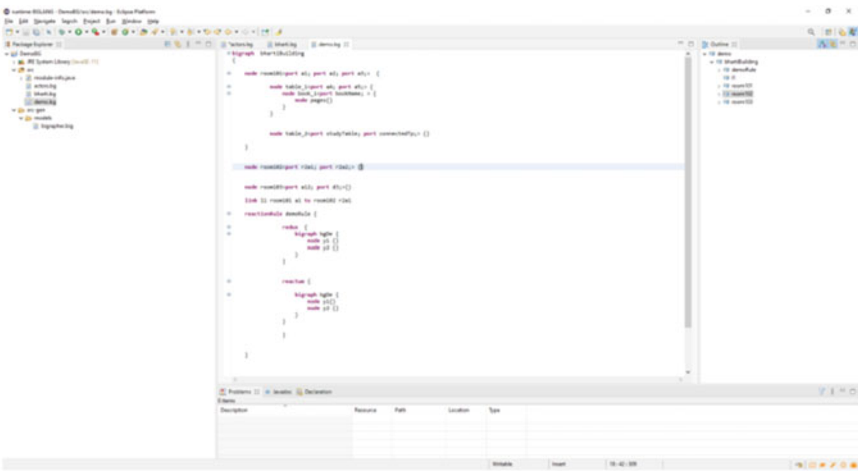


Fig. 18 BigBIM on Eclipse

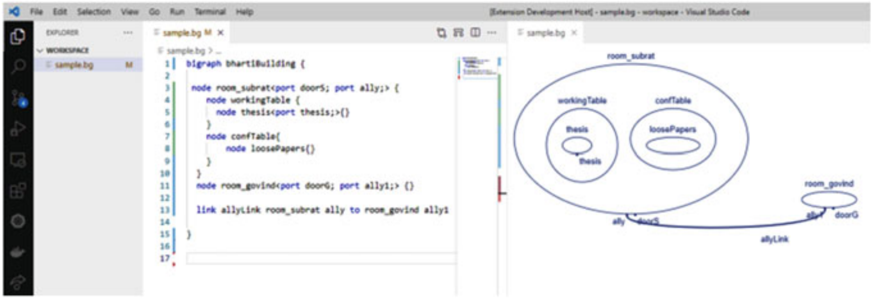


Fig. 19 BigBIM on VSCode

- Actors@BIM DSL: We conceived and developed Actor@BIM DSL, which is based on Actors@BIM Semantics.The Actors@BIM DSL enables the creation of different types of actors like devices representing a sensor, actuator, or communication device and can specify their placement within the BIM model. For example, temperature sensors, occupancy sensors, smoke sensors, automatic door openers, and access control devices can be placed within a specific room. First-class support for creating actors, hosting actors within a specific node of a bigraph, sending specific messages understood by Actors@BIM, migrating Actors to a different node in a bigraph (or BIM) model, specifying the messages and along with probabilities, mentioning supervision behaviour, querying devices, and sending a BIMQL query to BIM Query Actors is supported within the Actors@BIM DSL. The Actors@BIM DSL can be translated into BLang which can be further translated into a script that can be executed in BigraphER. These translations are handled using the L2L translation module discussed below. These behaviours specified using Actors@BIM DSL can be specified with an optional probability parameter that enables probabilistic model checking using BLang and BigraphER.
- L2L Translation Module: This module provides two translation mechanisms: (1) Actors@BIM to BLang and (2) BLang to BigraphER script. This module has been built utilising the framework provided by Language Workbenches (e.g. Xtext). These frameworks provided by Language Workbenches provides hooks to trigger the translation mechanism and to perform the translation when a particular keyword is encountered in the source language. Essentially, a function is triggered when a keyword in the source language is encountered. Within the function, the translation mechanism is encoded.
- BigraphER: BigraphER (Sevegnani and Calder 2016) is an open source suite of tools for rewriting, simulating, and visualising bigraphs. Additionally, it supports the model-checking of bigraphs via the PRISM model checker.

Figs. 18 and 19 show the integration of the tool suite with eclipse and VSCode, respectively. Figure 19 shows the high-level architecture of language server integration done within the BigBIM tool suite.

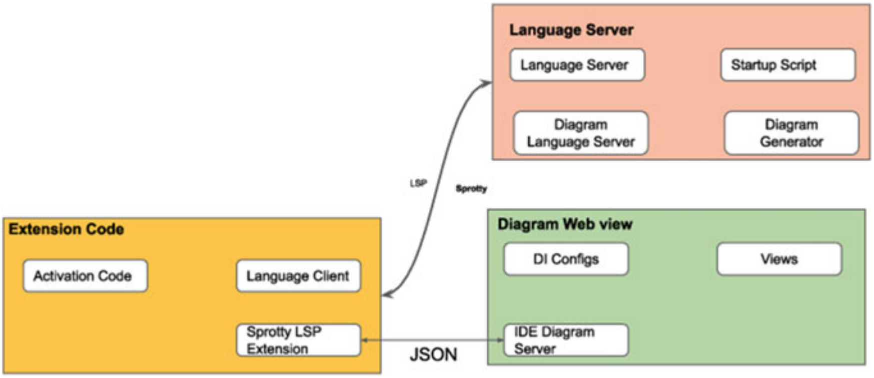


Fig. 20 Language server integration on BIGBIM

5 Case Study-Modelling and Verification

This section presents a case study using Actors@BIM to verify the static and dynamic properties of a cognitive building. Inspecting static properties means inspecting the building's plan for compliance. This is similar to the rule-based checking found in commercial tools. This case study uses the Indian National Building Code—Part 4 (National Building Code of India 2022) which enlists requirements for *Fire Safety*. Verifying dynamic properties may relate to checking behavioural properties of a components within a cognitive building. The case study uses a simple floor plan from Fig. 21 to briefly highlight the modelling and verification capabilities of the Actors@BIM model.

We assume that the BIM model corresponding to the floor is available. We convert the BIM model to a bigraphical representation using BigBIM.

We analyse two sets of requirements :

1. REQ-1 (Static): A safety requirement as specified in NBC is that in case a turnstile is present to restrict entry/exit an alternate entry/exit should also be present. This can be represented using bigraphs and hence within the Actors@BIM model as

$$Room_{recp}.T_{c,out} \wedge Roomrecp.Door_{c,out}$$

   Such requirements can be checked through *bigraph matching*. This is the same principle that is used to find a instance of *redux* within a bigraph when executing a reaction rule.
2. REQ-2 (Dynamic): In the case of a fire, cognitive buildings must open access controlled exit doors, turnstiles, and boom barriers. This is also an NBC requirement. BIM alone cannot model this requirement. All building components that can sense, control, and communicate are represented as *DevicesActors* in the Actors@BIM model. It is expected that each room has fire and smoke sensors.

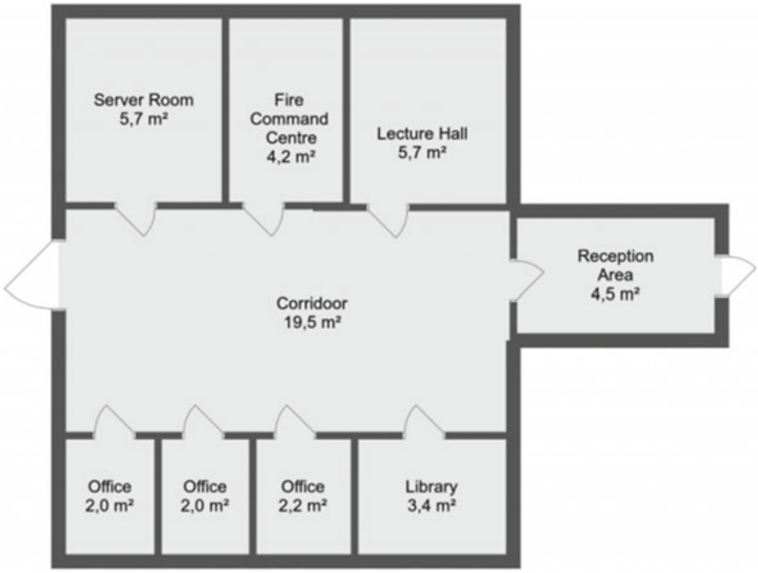


Fig. 21 FloorPlan

The *DeviceGroup Actor* can be queried using the semantics of *GetDevicesByTypes* to see if there is a fire within the cognitive building. *ReadStatus* on these devices can get the perceived value of a fire event. *PerformAction* messages can be delivered to access control devices to open doors in case of fire. Once the doors are open, the evacuation can begin. Further to validate a probabilistic branching temporal logic can be used to analyse the modelled system because the *Actors@BIM* model supports probabilistic reaction rules. For example, we can assume that the probability of sending a message (i.e. the semantics of SND) to be 0.8 and analyse whether system reaches a state where the doors are opened through a model checkers like PRISM which is integrated with BigBIM framework. Another method of implementing this in the Actors@BIM framework is to use a mix of device actors that set their detected parameters as custom BIM properties via the BIMQL *SET* keyword. Following that, the BIM Model may be queried for a fire event using the BIMQL actor. After determining the start of a fire, *PerformAction* messages can be sent to access control devices to open doors in the event of a fire.

6 Conclusion and Future Work

This article introduced a formal model *Actors@BIM*, which merges actors with a building information model (BIM) through the use of bigraphical reactive systems. This model enables the modelling and formal analysis of both static and dynamic components of a building environment. Additionally, we discussed the implementation of the prototype software framework, BigBIM, which enables the conversion of a BIM model to a Bigraph and the embedding of actors into Bigraphs through the Actors@BIM DSL. The framework interfaces with the PRISM model checker, which enables quantitative model checking of Actor@BIM models. We have highlighted several areas of potential future research. To begin, we want to extend the Actors@BIM model to incorporate cooperative and collaborative behaviours and model them using game-theoretic approaches and equilibrium checking, among other techniques. We envision that by doing so, we may represent larger structures, such as Smart Cities, as a real Collective Adaptive System. Second, to facilitate the usage of Actors@BIM by designers and architects, we would extend the DSLs (BLang and Actors@BIM DSL) to be graphical, allowing them to be easily employed during the initial phases of cognitive building design. Finally, we want to stabilise the BigBIM framework and make it available as open-source software in order to solicit feedback from the AEC community.

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Generation of a Large Synthetic Database of Office Tower's Energy Demand Using Simulation and Machine Learning

Ammar Alammar and Wassim Jabi

1 Introduction

A building's skin or façade is a key factor in determining the comfort and energy consumption of the building. This is because buildings are exposed to dynamic environmental factors such as solar radiation, temperature precipitation and wind and these outdoor conditions change continuously throughout the day and the year. Regardless of the outdoor climate which changes constantly, a building's skin has been typically designed as a static envelope. Fixed or static shading devices are limited in terms of their responsiveness to indoor or outdoor environmental conditions and this leads to unacceptable performance once these systems have been installed, especially if changes are required over time (Tabadkani et al., 2021). In addition, studies have shown that static facades are no-longer favourable and have limitations in terms of attaining the desired energy efficiency, adequate daylighting and control flexibility (Al-Masrani & Al-Obaidi, 2019). On the other hand, adaptive façades are capable of and effective in responding to variable climatic conditions. To that end, numerous studies have been conducted regarding substituting the static envelope with an adaptive one.

Different types of adaptive façades have been developed in terms of materials, components and systems and further developments are expected in the future (López et al., 2017). These adaptive façades have unique features or behaviours that repeatedly and reversibly change over time according to variable boundary conditions and

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respond to changing performance requirements with the aim of improving the overall building performance (Loonen et al., 2014). To achieve a high-performance building with an adaptive façade is challenging due to the complexity of the system. The building envelope is influenced by a variety of physical domains (thermal, luminous, air quality, etc.) which make it difficult to accurately predict the performance of a building with an adaptive façade (Loonen et al., 2017); most building performance simulation (BPS) tools were not developed to predict building performance with an adaptive façade. Adaptive façade systems are difficult to predict due to their numerous functionalities and complexities; thus, the current paper presents a methodology for predicting adaptive façade energy performance early in the design process using machine learning (ML) approaches to overcome the limitations of BPS tools. ML-based approaches to evaluate building performance appear to be more efficient than conventional simulation-based approaches (Chakraborty & Elzarka, 2019). In various studies, decision trees (DTs) have been effectively used to assess a building's energy consumption. As a result, decision trees could be used to predict the performance of a building equipped with an adaptive façade if it is sufficiently trained with big data.

2 Predicting the Performance of Adaptive façade s with Current Tools

Innovative materials and technologies have been developed in the adaptive façade field and these can be enhanced with the use of building performance predictions. Additionally, in the design of adaptive façades it is crucial to predict building performance accurately to produce high performance buildings. According to Geyer and Singaravel (2018), evaluating the performance of adaptive façade systems during the early stage of the design is critical for determining its applicability. Loonen et al. (2017) claimed that it is a difficult task to predict the performance of buildings with adaptive façades because the system is mainly affected by the building's local boundary conditions, interactions with its occupants and other building systems. Additionally, the authors investigated simulation techniques for both static and adaptive building envelopes. The simulation process is easier in traditional static envelopes and requires certain input parameters such as the U-value and G-value in order to make predictions. The lack of available tools is a significant factor limiting studies into adaptive façade performance prediction. Loonen et al. (2017) mentioned that most software packages are described as complicated digital modelling and simulation processes and they are not user-friendly. In addition, most of the existing tools lack the ability to simulate adaptive façades within their built-in objects, apart from a few software packages that target specific types of technologies, such as thermochromic (TC) glazing technology. However, these systems experience only physiological changes, making it extremely difficult to integrate numerous variables that change over time (Sheikh & Asghar, 2019). According to Loonen et al. (2017), there are two main factors that determine the applicability of adaptive façades, as follows:

Modelling time-varying facade properties: Facade specifications (i.e., material properties or position of components) need to be changeable during simulation runtime to properly account for transient heat transfer and energy storage effects in building constructions (Loonen et al., 2014). Many state-of-the-art BPS tools have restricted functionalities for accomplishing this feature.

Modelling the dynamic operation of facade adaptation: During the operation of adaptive systems, the performance of the system is entirely dependent on the scheduling strategy (i.e., control logic) that is utilised to change the façade. Moloney (2011) states: "The design outcome in a project with kinetic facades is a process, rather than a static object or artifact."

3 Decision Tree (DT)

The decision tree is a technique that is frequently used in a wide variety of applications for classification and prediction purposes (Tung et al. 2005). A decision tree divides a set of data into multiple specified classes by employing a flowchart-like tree structure, hence providing a description, categorisation and generalisation of the given datasets (Yu et al., 2010a, 2010b). The decision tree model has a number of advantages over other models, including its simplicity of use and ability to predict with high accuracy without the need for extensive calculations. Several applications have incorporated decision tree approaches into building analysis studies (Ahmad et al., 2017). Tso and Yau (2006) compared three modelling techniques to estimate average weekly electricity energy consumption in Hong Kong (Tso & Yau, 2007). They discovered that both decision tree and ANN are more appropriate models than regression models due to their ability to analyse and predict energy consumption patterns. Haghighat et al. (2010) published another study in which they developed a prediction model to optimise building energy performance with the use of decision trees (). They used a decision tree to estimate energy use intensity (EUI) in a residential building, revealing that by utilising the decision tree approach, it is possible to precisely categorise and anticipate the energy consumption of a structure, resulting in a high-energy-performance construction.

A random forest is a collection of decision trees that can be used to make predictions. Breiman (2001) states that the random forest was initially developed as a technique for optimising the conventional decision tree method. Additionally, the author advised using a random forest as a predictive regression method. Ahmad et al. (2017) used a random forest algorithm to predict the hourly electricity usage of HVAC systems at a hotel in Madrid. Ma and Cheng (2016) employed random forests to determine the relevant levels of 171 characteristics associated with residential building regional energy consumption intensity.

4 Methods

The current study's methodology comprised three main stages (see Fig. 1). The initial phase involved creating a generative parametric simulation of office spaces equipped with an adaptive façade shading system using EnergyPlus which also functioned as the training data. In order to conduct a thorough energy analysis, the simulation settings, input parameters, material properties, occupant loads, zone programme, occupancy schedule, and thermal settings were determined. The second phase included the implementation of an automatic control system to activate the system on an hourly basis in response to two specified environmental sensors. The aim of this process was to develop a synthetic database of hourly cooling energy consumption (Wh/m^2) for use as training data. The final phase involved developing and validating a decision tree surrogate model to estimate the hourly cooling demand of an adaptive façade system in a closed office environment. For training and testing, the synthetic datasets from the simulation were imported into the decision tree model. Then a hybrid parameter tweaking approach was used to achieve the most accurate model.

4.1 Simulation Setup

As a case study, a typical mid-rise office building was developed which is located in central Riyadh, Saudi Arabia. The office building is 30 storeys and has a height of 120 m which is representative of the common height scenario found in the centre of King Abdullah Financial District (see Fig. 2a). All floors of the building have the same layout and core area measurements: 35 m * 35 m, giving a total floor space of 1225 m^2. Specifically, only shared side-lit office zones with an adaptive shading system were investigated on each floor of the proposed office building which faces the primary orientations (north, south, east and west) in order to evaluate the influence of an adaptive façade on energy performance (see Fig. 2b). Table 1 presents the spatial dimensions and characteristics of the office room.

The building context varied in each simulation (low, medium and high) to test energy loads at each level and in all the main orientations (north, south, east and west). The variation in heights of the surrounding contexts acted as one of the main features of geometric variation in the study. In addition, the average height of the surrounding buildings was used parametrically to control the vertical location of the office room in each orientation, in accordance with a lower-than-average, average, and higher-than-average height setting. This was intended to simulate the varying amounts of sunlight and daylight that the offices in a building receive. The generative parametric office tower rules and its urban context is illustrated in Fig. 3, which shows how the model were set up parametrically (generative parametric tower). The vertical location of the office is calculated using the following formula:

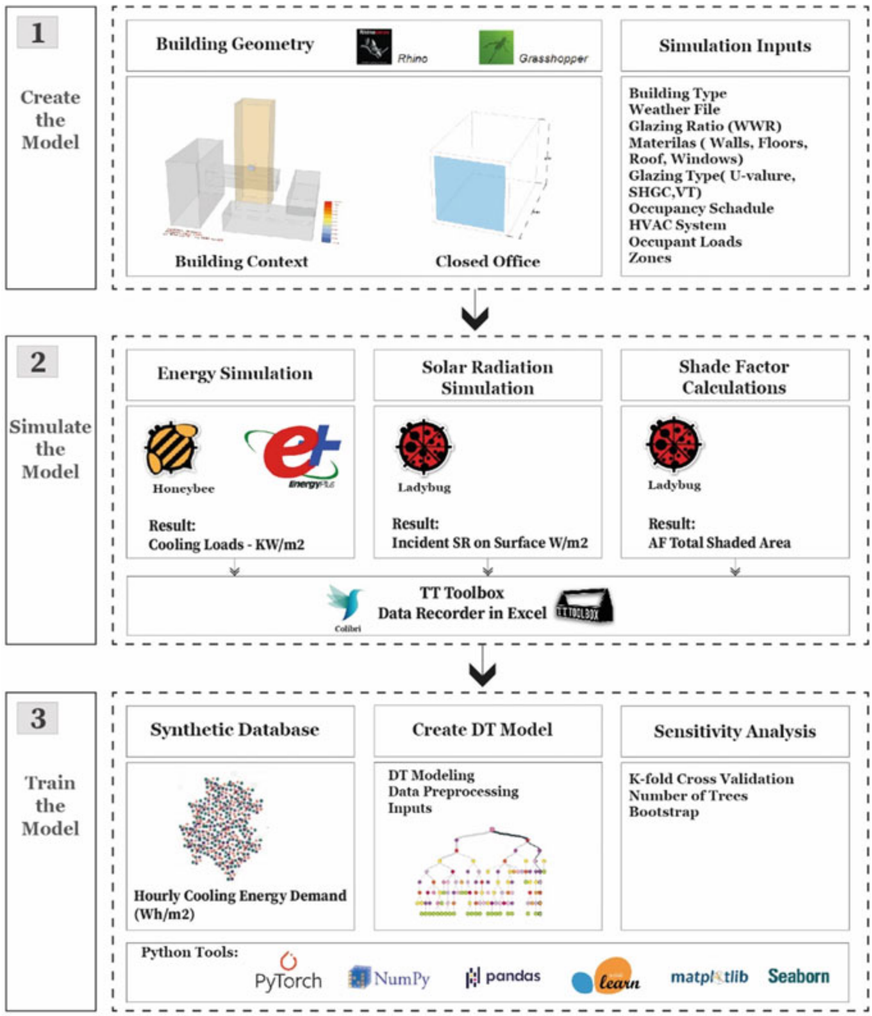

Fig. 1 Framework of the study

$$a = \sum B00 + B01 + B02 + B03/n$$

$$l = (a) * 0.50$$

$$h = (a) * 1.50$$

where a = average, l = lower than average, h = higher than average B = building context, n = number of variables.

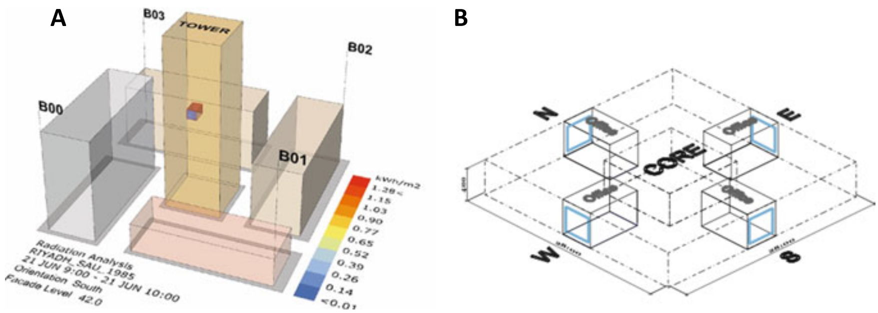

Fig. 2 **a** The 3D parametric urban context, that change parametrically in each simulation, **b** A single closed office room facing main orientations

Table 1 Spatial dimensions and characteristics of simulation inputs

Parameter	Assigned value(s)
Location	Riyadh, Saudi Arabia
Space type	Shared Office Room
Zone program	Closed Office Zone
Glazing ratio	80%
Room width	4.00 m
Room floor height	4.00 m
Room length	6.00 m
Shading reflectance	70%
Interior wall, ceiling, floor	Adiabatic
Cooling set points	24 C
Heating set points	22 C
HVAC system	ideal air load system
Number of people	2 people
Zone loads Lighting density	3 W/m^2
Number of occupants	0.5 ppl/m^2
Equipment load (W/m^2)	2 W/m^2
Infiltration ratio	0.04 cfm/sf (~0.000203 m^3/s m^2 façade)
Schedule	Sun.-Thur. 08:00 – 18:00
Prototype unit	0.80 * 0.80 c
Shadow calculation method	Time step frequency
Solar radiation sensor point 1 (P1)	3.00 m height
Operative temperature point 2 (P2)	1.5 m height

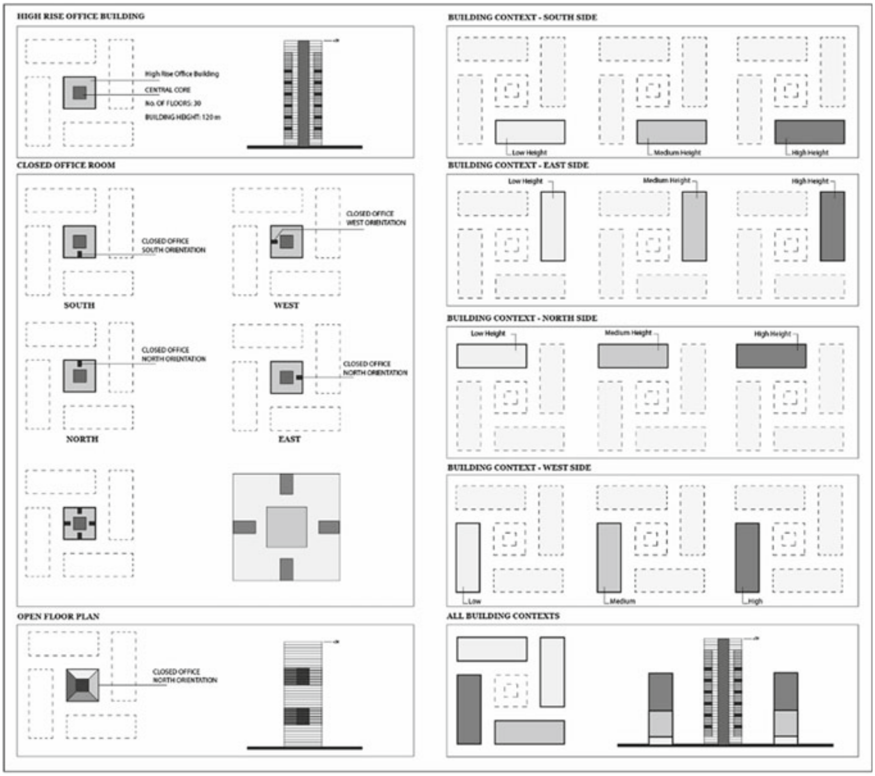

Fig. 3 Parametric model generation rules

4.2 Validation of the Base Model

Validation is an essential step in the simulation process to ensure that the hypothetical model is correct and represents the real environment. One of the most definitive validation methods is to compare model results with existing cases. In this study, examples of case studies are used to support the validity of the base model. The base model was established based on existing case studies and design guidelines for office buildings which exemplify the typical characteristics of office buildings. In addition, the simulation settings and parameters were determined using ASHRAE benchmark.

The annual energy consumption for the base model of the study which does not integrate an adaptive façade system shows coherence with the five case studies examined. Fasiuddin and Budaiwi (2011) conducted a study on five commercial buildings in Saudi Arabia and provided detailed statistics for various factors, among which was annual energy consumption data. The annual energy consumption data for these case studies were obtained from the utility bills provided by the management or by the Saudi Electric Company (SEC) (Fasiuddin & Budaiwi, 2011).

	Case A	Case B	Case C	Case D	Case E
Gross annual consumption (kWh)	31,452,70	10,056,92	3857,49	2799,05	2107,93
Annual consumption (kWh/m^2)	273.5	267.8	275.5	249.9	263.5

Based on the above cases, the average annual consumption per unit area (m^2) for all five buildings is approximately 266 kWh/m^2/year. The developed base model was validated by comparing the simulation energy results with the annual energy consumption of the above reviewed case studies. The EUI of 266 kWh/m^2/year serves as a typical annual consumption for commercial buildings in the studied region and provides the basis for comparison. Thus, an average annual consumption per square meter less than or equal to the above value is considered to be performing within the normal range of energy consumption. However, this value could be optimised when implementing the adaptive façade system. For the studied base case, the annual energy consumption result generated from the simulation averages 232.7 kWh/m^2/year (base case-south orientation = 263.2 kWh/m^2/year, base case-west orientation = 270.9 kWh/m^2/year, base case-north orientation = 184.6 kWh/m^2/year, and base case-east orientation = 212 kWh/m^2/year). The values of 232.7 KWh/m^2 and 266 KWh/m^2 are not significantly different and the difference between the energy consumption values in the case studies and the base model is due to the use of different settings. For example, the lighting density was higher in the case studies compared to the base case model. The model of the study considers 3W/m^2 to be the average value of the considered benchmarks, whereas the case studies consider a value of 13W/m^2. In addition, the case studies use a range of 8 to 11 W/m^2 for equipment power density, whereas the base model considers 2W/m^2 to be the average benchmark value (ASHRE, 2010). This comparison verifies the capability of the study's base model and the validity of the simulation outcomes.

4.3 Inputs Parameters

The dynamic input parameters were based on a variety of factors such as the building's exterior wall U-values, the U-values of different types of glazing and the adaptive façade shading system's dynamic behaviour changes, including the hour, date, month, orientation, building context, solar radiation (SR), operative temperature, shade factor (SF), and opening ratio. A dynamic shading system integrated into the building exterior has the potential to significantly reduce energy consumption. As a result, certain variables were examined to determine whether an adaptive façade system could improve a building's energy efficiency. The dynamic input parameters used in the current study to conduct the energy analysis are listed in Table 2.

Table 2 Dynamic simulation inputs

Dynamic input parameter	Assigned value(s)	No. of iterations
Orientation	South, west, north, east	4
Building context 00	Low, medium, high	3
Building context 01	Low, medium, high	3
Façade level height	Lower than average, average, and higher than average	3
Exterior wall – U-value	0, 1, 3 W/m^2 K	3
Glazing type – U-value	0, 1, 2, 3 W/m^2 K	4
Total no. of iterations		1,296
Month	March, June, September, December	4
Day	01 – 31	31
Hour	1:00–24:00	10
Shading states	A, B, C, D, E, F	6
Total no. of hourly cooling data		1,581,120

4.4 Construction Materials

The EnergyPlus recommended database (ASHRAE materials) was used to define the office's material characteristics selecting ASHRAE 90.1–2010 climate region number 1 which was assigned to a hot, dry region. Various types of external walls with different U-values were investigated for the office room. The interior walls were made of gypsum board with a U-value of 2.58 which indicates that no heat is transferred across these partition walls. The model's energy simulation also considered the effect of the glazing. Thus, different glazing systems (single, double and triple glazing) were explored for the studied model which has a variety of solar heat coefficients and thermal transmittance U-values (Gadelhak & Lang, 2016). The specifications for the building material parameters used in this investigation are listed in Table 3.

A closed office programme zone in accordance with the EnergyPlus (US Department of Energy's (DOE) office building zones (DOE 2016) was selected in all offices. These closed offices are conditioned with the default set at an ideal air load system in EnergyPlus for HVAC. In addition, the model was set for an hourly time step to calculate the energy demand of the office room. The operating time for cooling and heating was assumed to be five days per week (Monday to Friday from 7:00 to 18:00). The temperature setpoints of the HVAC system were considered to be 24 °C for cooling and 22 °C for heating. The HVAC system was set to work automatically to maintain the desired internal temperature.

Glazing type (Glaz)	U-value (W/m^2 K)	Solar heat gain coefficient (SHGC)	Visual transmittance (τvis)
Single glazing (SG)	5.82	0.82	0.88

(continued)

(continued)

Glazing type (Glaz)	U-value (W/m^2 K)	Solar heat gain coefficient (SHGC)	Visual transmittance (τvis)
Double glazing—clear (DG)	2.71	0.72	0.80
Double glazing—low-e coating (DG)	1.63	0.28	0.65
Triple glazing—Krypton filled (TG)	0.57	0.23	0.47

4.5 Automatic Control Logic

Existing BPS tools do not fully enable the adaptive behaviour of a façade to be simulated and there is a lack of a widely accepted approaches for designers to utilise when developing a control logic to test the system early in the design process. As a result of these constraints, the study developed a control scheme using the Energy Management System (EMS), an embedded feature of EnergyPlus that allows for the definition of sensors, controllers and actuators on hourly time steps (Hong and Lin 2013) (see Fig. 4). The external adaptive façade shading system is controlled by two outdoor and indoor sensors. Different shading states were designed that vary hourly and the shade factor of each shading state was calculated annually to be translated as a transmittance schedule, as well as calculating the annual incident solar radiation on the outside surface.

Sensors such as solar radiation and operative temperature (OT) were used in a closed (feedback) loop control system to adjust the opening ratio of the adaptive façade system. The first sensor point (P1) was placed at the corner of the outside wall to collect incident solar radiation on the surface, while the second sensor point (P2) was placed in the centre of the room at a height of 1.5 m to record the room air temperature. Regardless of how complicated the system is, the shade factor strategy was examined. As a result, a simple parametric unit shaped as a kinetic prismatic modular element was designed for the purpose of the current study with scaling and translating movements. Six different shading states were developed based on solar radiation and operative temperature thresholds: State-A 100%, State-B 80%, State-C 60%, State-D 40%, State-E 20%, and State-F 0% (see Fig. 5). When the external total solar radiation on the exterior surface and operative temperature surpassed the predetermined threshold, the shade system closed. The solar radiation range was 0-450W with a 50W step, whereas the operative temperature range was 21–24 °C. These criteria were established in accordance with several previous research studies that recommended an activation threshold that was appropriate for each climate zone (Touma and Ouahrani 2017; Yun et al. 2017; Tabadkani et al. 2020b). To accomplish this, an EMS conditional statement was coded to alter the required opening ratio based on the given program logic (see Fig. 6). When the solar radiation is equal to or

Table 3 Characteristics of materials used in the simulation

Name of material	Thickness (m)	Layers	U-value (W/m^2 K)	R-value (K m^2/W)
ASHRAE 90.1–2010 EXTWALLMASS CLIMATEZONE 1	0.2412	1IN Stucco 8IN CONCRETE HW RefBldg 1/2IN Gypsum	3.690821	0.270942
ASHRAE 90.1–2010 EXTWALL MASS CLIMATEZONE ALT-RES 1	0.277737	1IN Stucco 8IN CONCRETE HW RefBldg Mass Wall Insulation R-4.23 IP 1/2IN Gypsum	0.983672	1.016599
ASHRAE 90.1–2010 EXTWALL METAL CLIMATEZONE 1–2	0.154367	Metal Siding Metal Building Wall Insulation R-9.45 IP 1/2IN Gypsum	0.573406	1.743964
ASHRAE 90.1–2010 INTERIOR WALL	0.188	G01a 19 mm gypsum board F04 Wall air space resistance G01a 19 mm gypsum board	2.580645	0.3875
ASHRAE 90.1–2010 INTERIOR FLOOR	0.7291	F16 Acoustic tile F05 Ceiling air space resistance M11 100 mm lightweight concrete	1.449209	0.690031
ASHRAE 90.1–2010 INTERIOR CEILING	0.3007	M11 100 mm lightweight concrete F05 Ceiling air space resistance F16 Acoustic tile	1.449209	0.690031

Fig. 4 Energy management system (EMS) principles

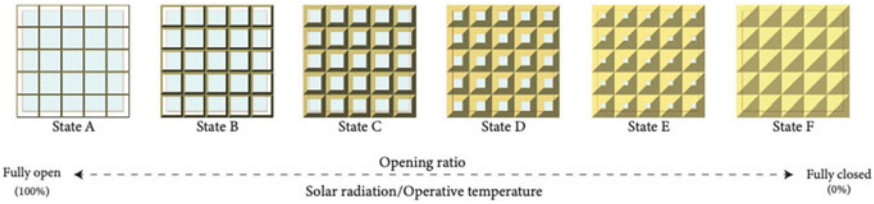

Fig. 5 Variation of the adaptive façade based on solar radiation and operative temperature

less than 50W and the operative temperature is equal to or less than 21 °C, the shade (State A) is completely open. Shade (State F) is completely closed when the solar radiation is equal to or greater than 450W and the operative temperature is greater than 24 °C. The additional shading states that fall between these two criteria were also studied (see Fig. 7).

The shade factor is calculated in response to the hourly changes in the opening ratio of each shading state. Because the grid method is similar to the ray-tracing method found within the Ladybug plug-in which is linked to the Radiance software, this method was adopted in the current research to calculate the shaded area of all of the six proposed shading states for a total of 8,760 h of the year. The shade factor ranges from 0 to 1 based on the percentage openness of the shading system, sun angle and sun position. As an example of this, Fig. 8 shows samples of different shading states when the shading system is 80 and 40% open with the grid method for shade factor calculations. To this end, the calculated shaded area of the distinct shading states was then translated into the transmittance schedule and called out within the EMS interface to select the state based on the defined threshold.

5 Modelling with Random Forest (RF)

In the current study, 1,296 simulation iterations of an office room with adaptive façade were generated using a variety of inputs to train the model. The total data collected included 3,794,688 (1296 * 4 months (122 days) *24 h) hourly cooling energy data. The cooling loads in KW/m^2 are the output by the decision tree model and thirteen variables were used as inputs: month, hour, day, orientation, building 00, building 01, façade level height, glazing type U-value W/m^{2}K, exterior wall U-value W/m^{2}K, adaptive façade opening ratio, adaptive façade—shade factor, solar radiation W/m^2, and operative temperature. Table 4 illustrates the characteristics of the input data and the ranges of each input. The generated energy results database was uploaded to the Design Explorer webpage which is a web-based tool allowing comparison analysis between the studied input parameters (see Fig. 9). To construct the decision tree model, three main steps need to be considered: (1) data pre-processing; (2) model training and hyper-parameter optimisation; and (3) model validation (Westermann & Evins, 2019).

```
EnergyManagementSystem:Sensor,
   S1,            !- Name
   StateA,    !- Output:Variable or Output:Meter Index Key Name
   Schedule Value;  !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
   S2,            !- Name
   StateB,    !- Output:Variable or Output:Meter Index Key Name
   Schedule Value;  !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
   S3,            !- Name
   StateC,    !- Output:Variable or Output:Meter Index Key Name
   Schedule Value;  !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
   S4,            !- Name
   StateD,    !- Output:Variable or Output:Meter Index Key Name
   Schedule Value;  !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
   S5,            !- Name
   StateE,    !- Output:Variable or Output:Meter Index Key Name
   Schedule Value;  !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
   S6,            !- Name
   StateF,    !- Output:Variable or Output:Meter Index Key Name
   Schedule Value;  !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
   S7,            !- Name
   ZZZ,    !- Output:Variable or Output:Meter Index Key Name
   Surface Outside Face Incident Solar Radiation Rate per Area;  !- Ou

EnergyManagementSystem:Sensor,
   S8,            !- Name
   YYY,    !- Output:Variable or Output:Meter Index Key Name
   Zone Operative Temperature ;  !- Output:Variable or Output:Meter

EnergyManagementSystem:Actuator,
   myA1,            !- Name
   TrNS-SHD,            !- Actuated Component Unique Name
   Schedule:Year,         !- Actuated Component Type
   Schedule Value;        !- Actuated Component Control Type

EnergyManagementSystem:ProgramCallingManager,
   MyComputedTransProg,     !- Name
   BeginTimestepBeforePredictor,  !- EnergyPlus Model Calling Point
   MyComputedTransSch;     !- Program Name 1

EnergyManagementSystem:Program,
   MyComputedTransSch,     !- Name
   Set StateA = S1,!- Program Line 1
Set StateB = S2,!- Program Line 1
Set StateC = S3,!- Program Line 1
Set StateD = S4,!- Program Line 1
Set StateE = S5,!- Program Line 1
Set StateF = S6,!- Program Line 1
SET SOL = S7,!- Program Line 2,
SET OT = S8,
   IF (SOL <= 50) && (OT < 21),
SET myA1 = StateA,
   ELSEIF (SOL <= 50) && (OT > 24),
SET myA1 = StateB,
   ELSEIF (SOL <= 50) && (OT < 24) && (OT > 21),
SET myA1 = StateA,
   ELSEIF (SOL > 50) && (SOL <=100) && (OT < 21),
SET myA1 = StateB,
   ELSEIF (SOL > 50) && (SOL <=100) && (OT > 24),
SET myA1 = StateC,
   ELSEIF (SOL > 50) && (SOL <=100) && (OT < 24) && (OT > 21),
SET myA1 = StateB,
   ELSEIF (SOL > 100) && (SOL <= 200) && (OT < 21),
SET myA1 = StateC,
   ELSEIF (SOL > 100) && (SOL <= 200) && (OT > 24),
SET myA1 = StateD,
   ELSEIF (SOL > 100) && (SOL <= 200) && (OT < 24) && (OT > 21),
SET myA1 = StateC,
   ELSEIF (SOL > 200) && (SOL <= 300) && (OT < 21),
SET myA1 = StateD,
   ELSEIF (SOL > 200) && (SOL <= 300) && (OT > 24),
SET myA1 = StateE,
   ELSEIF (SOL > 200) && (SOL <= 300) && (OT < 24) && (OT > 21),
SET myA1 = StateD,
   ELSEIF (SOL > 300) && (SOL <= 350) && (OT < 21),
SET myA1 = StateE,
   ELSEIF (SOL > 300) && (SOL <= 350) && (OT > 24),
SET myA1 = StateF,
   ELSEIF (SOL > 300) && (SOL <= 350) && (OT < 24) && (OT > 21),
SET myA1 = StateE,
   ELSEIF (SOL > 350) && (SOL <= 400) && (OT < 21),
SET myA1 = StateF,
   ELSEIF (SOL > 350) && (SOL <= 400) && (OT > 24),
SET myA1 = StateF,
   ELSEIF (SOL > 350) && (SOL <= 400) && (OT < 24) && (OT > 21),
SET myA1 = StateF,
   ELSEIF (SOL > 450),
SET myA1 = StateF,
   ENDIF;

EnergyManagementSystem:GlobalVariable,
   myglobeA1;            !- Erl Variable 1 Name

EnergyManagementSystem:OutputVariable,
   Weighted Shade Fraction Schedule,  !- Name
   myglobeA1,            !- EMS Variable Name
   Averaged,           !- Type of Data in Variable
   SystemTimestep;        !- Update Frequency
```

Fig. 6 The conditional statement coded within EMS

A random forest regressor is an algorithm based on decision tree s. decision trees are tree like structures where at each node an 'if–then-else' decision is taken about the value of an input. Based on the outcome of this decision, the tree can split into different branches. At each node, a similar decision as explained above is taken with respect to an input. The process is continued until the leaf nodes where the output is established out. A random forest regressor is a collection of such decision trees where each of the trees take a random subset of inputs to learn the 'if–then else' rules. In our experiments, random forest modelling is employed because most of the inputs are categorical and a few are continuous. Because decision trees are highly

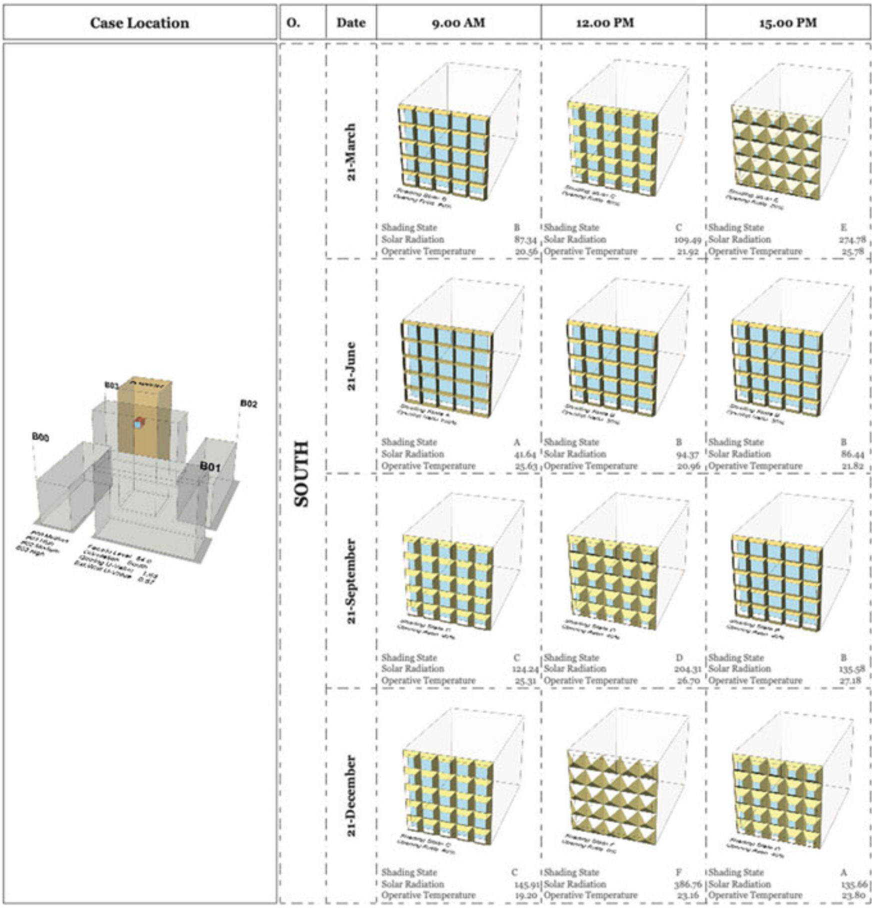

Fig. 7 Sample of hourly shading state variations chosen for three hours (9:00AM, 12:00PM, 15:00PM)

suitable for categorical as well as continuous inputs in their learning setting, random forest modelling offers a significant advantage.

There are a variety of performance indicators to quantify the model's accuracy and determine the model's precision. Based on literature, Some of the common used evaluation metrics are the root mean square error (RMSE), R-squared (R2), and mean absolute error (MAE), which used to measure the network's performance (Amasyali and El-Gohary 2018). The following formulae are used to calculate the performance measures:

$$\mathrm{RMSE} = \sqrt[2]{\frac{1}{|y|}\sum_{i=1}^{n}(y_i - \hat{y}(i))^2}$$

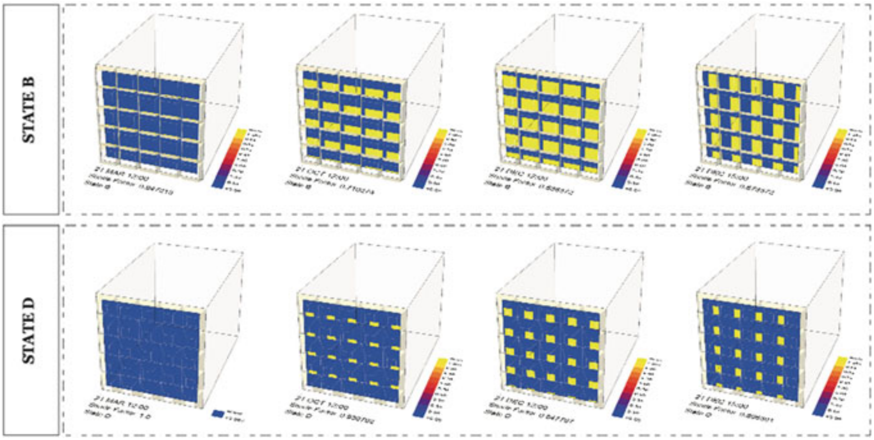

Fig. 8 Shade factor calculation for some selected cases

Table 4 The input data used for the ANN modelling

Input parameter	Input neuron type	Data range
Hours	Discrete	(1, 2,…, 24)
Month	Discrete	(March, June, September, December)
Day	Discrete	(1,2,…0.31)
Orientation	Discrete	(0,1,2,3) – (South, West, North, East)
Building 00	Discrete	(0,1,2) – (Low, Medium, High)
Building 01	Discrete	(0,1,2) – (Low, Medium, High)
Facade Level Height	Continuous	8–60
Glazing Type—U-value W/m^2K	Discrete	(0,1,2,3) – (SingleG0, DBL-Glz001-Clear, DBL-Glz002-low-e coating, TripleGlz-Krypton Filled)
Exterior Wall—U-value W/m^2K	Discrete	(0,1,2)
Adaptive Façade—Opening Ratio	Continuous	0–1
Adaptive Façade -Shade Factor	Continuous	0–1
Solar Radiation—W/m^2	Continuous	0 – 400
Operative Temperature—C	Continuous	14.00 – 30.00

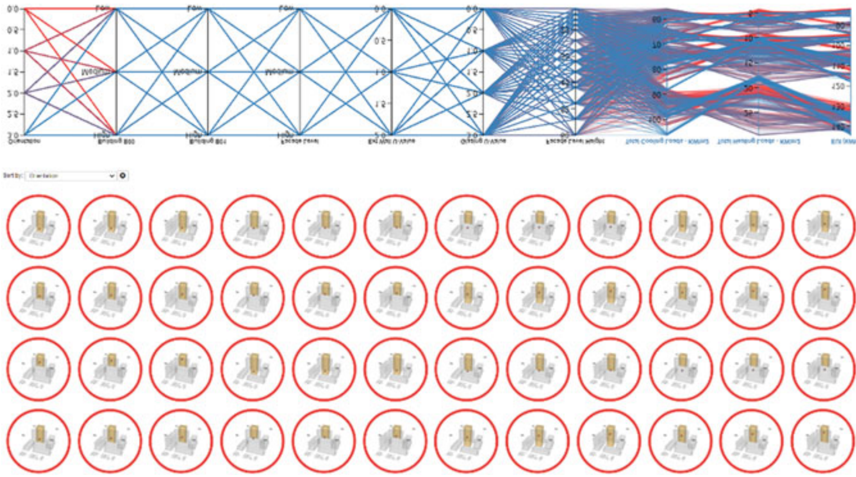

Fig. 9 Web-based of all generated cases of cooling loads (KWh/m^2) (http://ttacm.github.io/DesignExplorer/?ID=BL_3fQFpeE)

$$\text{MAE} = (\text{y}, \hat{y}) = \frac{1}{|y|}\sum_{i=1}^{|y|}|y(i) - \hat{y}(i)|$$

$$R^2(\text{y}, \hat{y}) = 1 - \frac{\sum_{i=1}^{|y|}(y(i) - \hat{y}(i))^2}{\sum_{i=1}^{|y|}(y(i) - \overline{y})^2}$$

According to the above equation, y_i represents the output of the i-th data point, y(i) is the predicted value of the i-th data point, and y- represents the mean of y. Here, y^(.) is the function approximated by the decision tree, and |y| represents the number of prediction cases. The RMSE value is the square of the difference between the actual and predicted cooling load levels. The MAE, on the other hand, defines the absolute value of the difference between the two. The distinction is often referred to as the residual. Both values can be any positive integer greater than zero and a model is said to function well if both values are as small as possible. The R^2 value is used to determine the scatter of predicted values around the regression line. It is often referred to as the coefficient of determination in statistics. IIt is defined as the ratio of variance explained by the model to the total variance or as the following equation:

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}}$$

where SS_{res} is the sum of the squares of the residuals and SS_{res} is the total sum of the squares which is a measure of variance in the data. For an optimal model, SS_{res} will be exactly equal to SS_{res} and, hence, the R^2-value is 1. Additionally, the R^2-value varies between 0 and 1 and the greater its value, the more accurately the model is able to predict.

5.1 Data Pre-Processing

The operations required to process categorical data inputs are referred to as 'data pre-processing.' Rather than using categorical inputs directly, they must be given an appropriate mathematical representation to improve the network's performance. The following data are used as discrete inputs in the current study: hours, month, date, direction, building 00, building 01, glazing type U-value, and external wall U-value. One example of hot encoding (Seger, 2018) is the pre-processing of categorical inputs. One-hot encoding is a mathematical technique for numerically describing categorical variables as a vector of zeros and ones. The vector's dimension will be equal to the number of possible values. One is assigned to the coordinate that corresponds to the value of the variable, while the remaining coordinates are set to zero. For instance, if a variable accepts values of high, medium or low, high is represented by [1,0,0], medium by [0,1,0], and low by [0,0,1].

5.2 K-fold Cross Validation

The purpose of k-fold cross validation is to choose a suitable combination of hyper-parameters such as the number of trees and bootstrap. To tune these hyper-parameters, a grid search with a k-fold cross-validation experiment is undertaken. In k-fold cross validation, the data are split into k folds. Among these k number of folds, (k-1) folds belong to the training data and the remainder to the testing data. The experiments are performed k times and each time the testing fold varies without repetition. The benefit is that each fold in one or other experiment becomes part of the training as well as the testing. Hence, the bias that can result from the binary splits is avoided. Initially the whole dataset is split into training, validation and testing sets. 80% of the data are assigned to the training set, 6.67% to the validation set and the remaining 13.37% are assigned to the testing set. The k-fold cross validation is then undertaken on the training fold. The value of k chosen is 5. The data split procedure is graphically represented in Fig. 10. Note that when undertaking k-fold cross validation, one among the fold becomes the testing set and remainder becomes the training set. In this case, one-third of the testing case will be reserved as a validation set for that particular instance of the validation procedure.

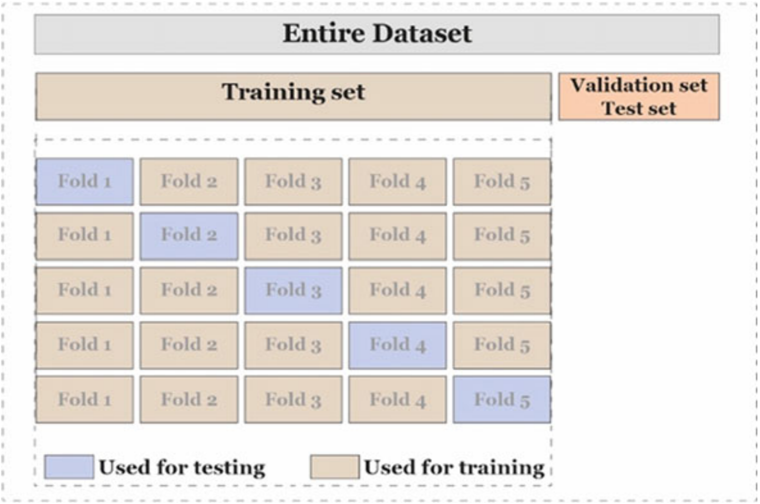

Fig. 10 The data split procedure

5.3 Optimization of Random Forest

Numerous hyper-parameters are required for random forest modelling, as follows: (1) Number of trees: The number of trees represents the total number of decision trees utilised in the random forest algorithm. The number of trees is adjusted from the set of $\{10, 20, 30, 40, 50, 60, 70, 80, 90, 100\}$. (2) Bootstrap: Bootstrapping is a statistical technique that employs random sampling from the training data. The bootstrap selects training data randomly with replacement. That is, each time a datapoint is chosen, the probability of it being chosen again and being added to the training set is equal. This strategy helps reduce the large variance of random forest models and protects against overfitting. Without the bootstrap option, the random forest algorithm is trained on the full dataset.

6 Result of Cooling Loads Prediction

This section discusses the prediction of the cooling load from the input data. The result of k-fold cross validation is given in Fig. 11. The figure contains the average RMSE, MAE and R^2-score for each of the parameter combinations. On the x-axis, bootstrap combinations are given separately along with their performance with different options for the number of trees (visualised as bars). From the experiments, the following observations can be made.

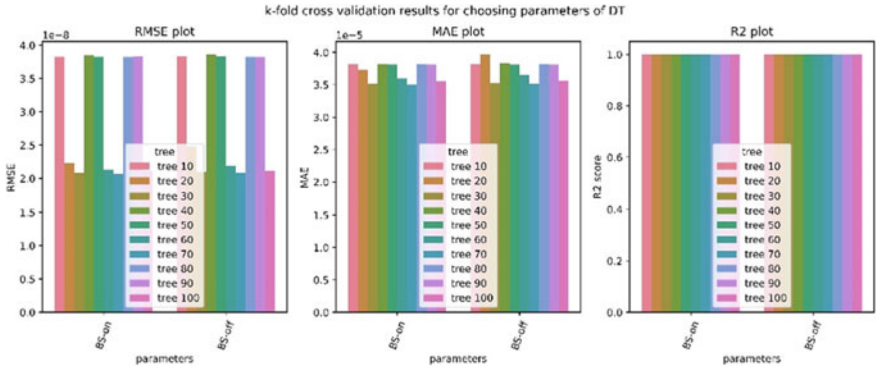

Fig. 11 The result of cooling load prediction. The figure corresponds to the results visualization of hyper-parameter tuning in random forest (BS stands for Bootstrap option)

1. The performance of the whole parameter combinations is excellent because the RMSE varies between the range of 2 × 10^-8 to 4 × 10^-8, MAE varies in the range 3.5 × 10^-5 to 4 × 10^-5, and the R^2 score is close to one.
2. There is no significant difference when the bootstrap option is enabled or not.
3. Increasing the number of trees causes the performance to exhibit an oscillatory behaviour, although the difference in performance is negligible.
4. From the experiments, the optimal model has the following hyper-parameter combination: Bootstrap option enabled and a total of 30 trees.

Figure 12 illustrates the performance metrics corresponding to the best performing models with respect to the number of trees. The results are for the bootstrap option enabled. In the k-fold cross validation, the optimal result is observed when the number of trees is 30, the ccp-alpha value is 0 and the bootstrap option is enabled. The final test results are as follows: the RMSE is 1.986 × 10^-8, MAE is 3.168 × 10^-5, and the R^2-score is 0.99985. These results correspond to the model performance selected after cross-validation with the entire training data and tested with the 20% test data. A result visualisation of random forest prediction for a randomly chosen 100 points is given in Fig. 13. It can be seen that for most of the data points, the actual and predicted value is almost the same or the prediction is very accurate.

7 Conclusion and Recommendations

The current research examined an alternative approach for evaluating the performance of adaptive façade systems, thereby resolving the issues associated with making predictions with the available BPS tools. To accomplish this, a decision tree surrogate model was utilised to estimate the hourly cooling loads of adaptive façade in hot areas. Rhino/Honeybee Grasshopper and Ladybug plugins were used to generate sufficient synthetic datasets of cooling demands for the adaptive façade

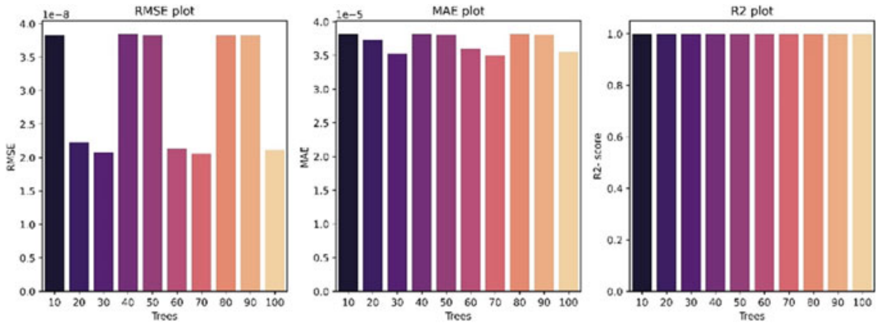

Fig. 12 Performance metrics corresponding to the best performing models

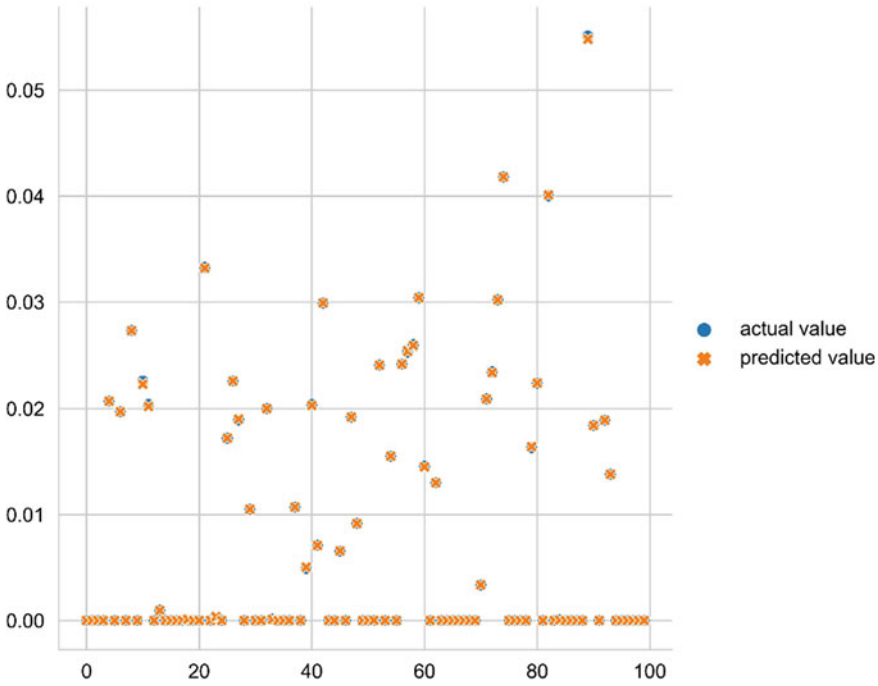

Fig. 13 The plot of the actual and predicted values for a set of 100 randomly chosen test points in the case of cooling load prediction

models. Several fixed and dynamic inputs were chosen that reflect the dynamic fluctuation of the adaptive façade system, design conditions and building envelope parameters with cooling loads as the targeted outcome. Subsequently, the data obtained were used to train, validate and test the suggested decision tree model. In addition, a hyper-parameter tuning study was performed to determine the optimal prediction model. It was found that when developing a ML surrogate model, it is essential to employ a substantial dataset to ensure highly accurate prediction outcomes. The random forest approach was utilised because most of the inputs were of a categorical nature and only a few were continuous. Random forest modelling benefits greatly from the fact that decision trees are well-suited to both categorical and continuous inputs in their learning environment. When using k-fold cross validation, the best results are obtained when using 30 trees, a ccp-alpha of 0, and the bootstrap option. The R^2-score was 0.99985, the RMSE was 1.986–0.10–8, and the MAE was 3.168 $\times$ 10–5. Using a range of random examples, the final model was tested, revealing that the predicted and actual values were similar, thereby indicating a high-prediction model. One of the main limitations of this study is the unavailability of real data; thus, simulation is used in this study to collect data because it is the most cost-effective way when data isn't available, or time and money are the main constraints. Furthermore, with simulations it is possible to analysis a wide range of design scenarios and complex modelling that cannot be accomplished easily on a real-world scale.

Because the model is fixed to a particular climate, its applicability to other climates must be determined in future research. Moreover, there is a need to test the model with other types of adaptive façade and determine if the shade factor is sufficient without the requirement of a specific geometry. For future work, the model will be imported into the grasshopper interface to test a set of new scenarios that is not part of the data used to build the developed decision tree model and compare the prediction consumption time and resources between the developed model and the existing BPS tools using large-scale generation of data. By applying this, it is possible to determine how many cases are required by DT prediction to beat the efficiency of BPS tools. Future work may include a comparison of various ML models such as artificial neural networks and recurrent neural networks. Additional future planned work regarding the adaptive façade system includes the use of other environmental control scenarios to automate the behaviour changes of the adaptive façade system.

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Strategies of Learning and Control of Robotic Manufacturing Methods in Architecture

António Morais, Bruno Figueiredo, and Paulo J. S. Cruz

1 Introduction

The versatility of anthropomorphic industrial robots justifies the growing interest among professionals and researchers in the Architecture and Construction fields (Gramazio et al., 2014). Architecture and Construction are among the industries that less invest in the digitalization of tasks and jobs (Agarwal, 2016). There are some reasons for that. For example, most of the work that is done by this industry is still being performed on-site, a complex environment to work due to the many variables that interfere in the tasks, such as weather, various teams of workers working side by side, and dangerous places like irregular terrain.

The lack of capacity of Architecture and Construction to follow other industries in the digitalization process it has delayed a change of paradigm in the way how architects and engineers design and build their projects.

Nevertheless, in the last 15 years, the advances in modeling software and CNC technologies are powering new fabrication methods in the Construction industry, and through that evolution, new methods like the use of Robots are emerging (Gramazio et al., 2014).

Since the early years of 2000, a series of research groups all over the world are exploring the idea of using robotics and automation technologies in Architecture and Construction. At the same time, they are also looking for new ways of manipulating materials and architectural shapes in a very controlled but customized way (Hack,

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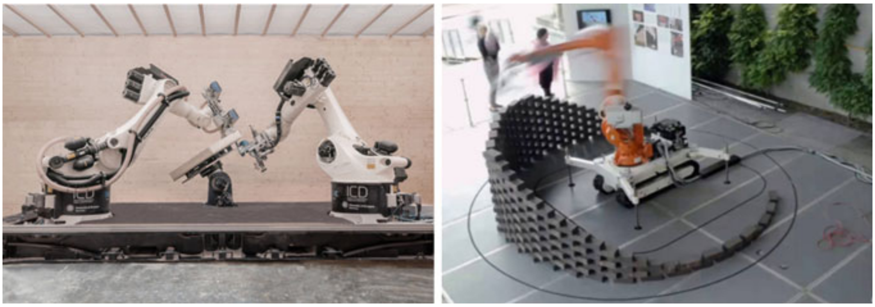

Fig. 1 **a** Robots at ICD, Stuttgart, 2019 **b** Mobile robot at ETH, Zurich, 2011

2014). Until recently, robots were programmed using complex software that are only accessible to experienced automation professionals. But, due to the interest of creative industries like Architecture and Design for that kind of technologies, new ways of controlling these devices have been created based on visual programming languages through API's like *Grasshopper* or *Dynamo* (Fig. 1).

Throughout the various research teams that are exploring robotics in Architecture, the most used robot is the anthropomorphic robotic arm. This type of robot raises many possibilities for almost every manufacturing task, such as drilling, cutting, painting, or extruding materials with fewer restrictions than any other machine in accordance with the tool attached to the flange.

If a university or industry holds a robotic arm, usually it is assigned to work in a specific task or project. Interrupt the work or research test to teach or give training, it may not be feasible. The use of inexpensive mini robotic arms controlled with an *Arduino* board or similar can be a way to a first contact with robotic fabrication and the kinematics of an industrial robotic arm.

If this type of small robot can be controlled with the same programming method that controls an industrial robotic arm, it can be a good practice to use it for an initial contact with the robotic control and programming interfaces. The use of these mini robotic arms has other positive points in the early phases of learning, such as easy replacement of damaged parts and easy upgradeable hardware and software due to the open-source principles on which it is based.

2 Methodology

The focus of this paper is the different ways through which is possible to control and program robotic arms in the fields related to architecture and design. Thus, it presents visual programming methods and applications that are allowing to architects control a robotic arm with little knowledge of scripting languages.

The methodology starts with the research of some of the main plug-ins that are used to control robotic arms through visual programming API'S like grasshopper.

As a proof of concept of the use of these tools, this paper tests the assembly and programming of a mini robotic arm controlled by an *Arduino* board and Kuka Prc. *Kuka Prc* provides a library of robotic functions that can be directly integrated into a parametric design environment. The aim of the changes made to this mini robotic has the purpose of controlling it using the same programming methods used to control industrial robotic arms. The final goal with this implementation is to be able to train people in robotic manufacturing, without the need to rely on an industrial robotic arm.

To demonstrate the programming workflow of the mini robotic arm using visual programming methods, first is showed the programming of a common industrial robot applied to a structure designed for this purpose. Then the same code is applied to control the same task with the real physical movement of the mini robotic arm, proving that both robots can be controlled with the same code.

3 Robotic Control

There are online and offline programming methods to control a robot. Online programming considers that the programmer must be close to the robot and consists in the act of physically moving the robot's joints, through the path that needs to be performed.

The offline programming method is the most common in Architecture and Construction. This type of programming is characterized by the use of software on a computer external to the robot to create the paths from a base model. This process has some advantages, with the most significant being the fact that it is not necessary to be near the robot or stop it to do its programming, unlike what happens in online programming.

3.1 Visual Programming of Robots

The new programming paradigms, such as visual programming languages, facilitate the development and use of parametric and computational models to operate different types of Robots (Stumm, 2016).

The use of these tools is growing rapidly in AEC (Architecture, Engineering, and Construction). For that, contributes to the fact of being accessible, modular, and operating in an easy to interpret interface. In contrast with the text-based programming languages, visual programming emerged to be a resource compatible with professionals with lower skills in written programming languages (Davis & Burry, 2011).

Some of these examples are *Kuka Prc*, Fig. 2, an add-on created by the *Association for Robots in Architecture* by Braumann (2011), Hal Robotics, created by Thibault Schwartz to control ABB Robots, or Furobot created by the company Fab Union and

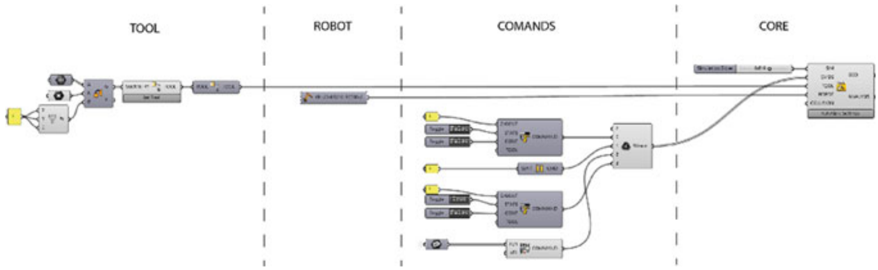

Fig. 2 Definition of a robotic routine in *Kuka Prc*

compatible with different brands o robots. All of these plug-ins have been created to facilitate the control of robots through visual programming environments as the example of *Grasshopper interface*, an API in *Rhinoceros,* or even *Dynamo* in *Revit*.

These tools allow the exploration of new design options while allowing the simulation of the manufacturing and assembly processes.

For the purposes of this paper, Kuka Prc has been chosen to control the mini robotic arm. The main reason that justifies this option is the fact that at the time of this paper is being installed at the school of Architecture, Art, and Design of University of Minho, a Robotics laboratory with Kuka Robots where the objective is to use this add-on to operate the Robots.

4 Construction of a Mini Robotic Arm

The main goal of this work is to use a mini robotic arm controlled with an *Arduino* board, as an alternative to the use of an industrial robotic arm, as an introductory equipment to teach robotic manufacturing in an academic environment.

Its accomplishment was divided into 2 interlocked phases: (1) Hardware modifications and (2) Control optimization.

4.1 Hardware

The *Thinkerkit Braccio* mini robot is composed of a kit of pieces and electronic hardware that builds a 5 degrees of freedom robot. To be able to control this mini robotic arm through *Kuka Prc* and use all its capabilities, a 6th axis has been added to be the most similar as possible to a common industrial robotic arm. For the task that is proposed in this paper, a gripper will be used and for that reason, a new one has been produced. Nevertheless, the mini robotic arm can be coupled with some other end effector like a PLA extrusion head or some lightweight tools.

4.2 Control

The Robotic system created with the mini robotic arm, Fig. 3, behaves similarly to a common Robotic system. That system has a controller, a manipulator, and a tool. The *Braccio*, "from factory", only allows control through the *Arduino IDE* application, an open-source code compiler widely used in the programming of various types of electronic applications. That compiler uses written programming language. This method has several limitations for creative use since that only allows point-to-point programming, which is time-consuming and affects negatively the degree of complexity and precision of the tasks in which this Robot can be used.

To be able to control the mini robotic arm through visual programming methods, first it was necessary to select an add-on that allows Grasshopper information to be sent to the Arduino board. There is an add-on for Grasshopper that was developed to receive and send data between Grasshopper and Arduino boards. That add-on is *Firefly*. This add-on has been developed by Andy Payne and Jason Johnson and can send or receive data from micro-controllers like *Arduino* boards through *Grasshopper*. With that plug-in is possible to control stepper motors, receive data from sensors and use that information to control and manipulate data inside *Grasshopper* (Payne, 2013).

Figure 4 illustrates the workflow created to control the mini robotic arm. To accomplish that, the following stages were considered: from the model designed in *Rhinoceros* or *Grasshopper*, a computational model has been defined and subsequentially read by *Kuka Prc* in order to simulate the path of the robotic operation with the specified robot; from this definition created in *Kuka Prc*, the values of the rotation of the different axis are retrieved and send to *Firefly* which communicates with the *Arduino* board that control the servo motors that moves the axis; the connection between *Firefly*, and the physical *Arduino* board is made through a USB cable.

Kuka Prc works through a library of definitions of default robots. These ready to work definitions contain all its characteristics, such as the maximum speed of

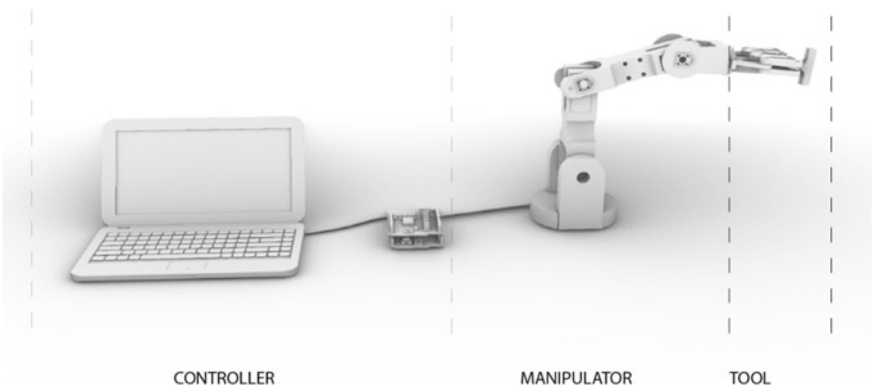

Fig. 3 Robotic system created with the mini robotic arm

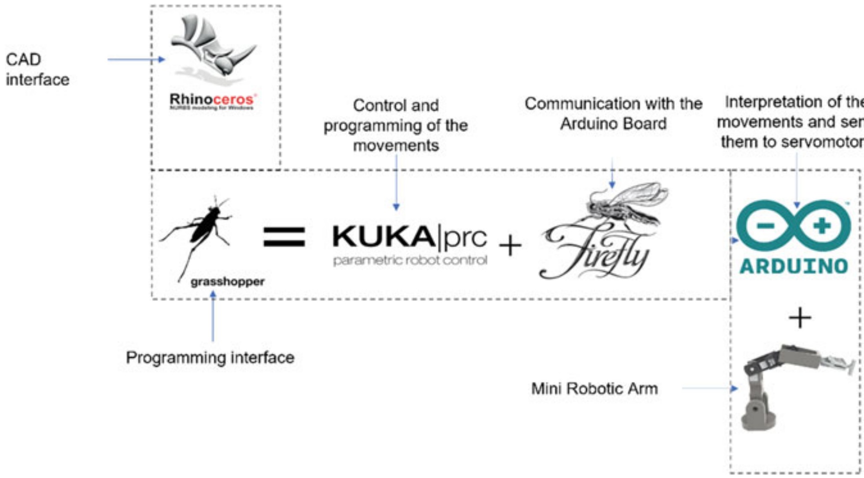

Fig. 4 Workflow to control the mini robotic arm

operation, minimum and maximum angles of rotation, and dimensions. Since the mini robotic arm, it is not in the *Kuka Prc* library, a custom robot was introduced through the data corresponding to its characteristics like dimensions, angles, tools, and speeds of operation.

5 Proof of Concept

As a proof of concept of the control method demonstrated throughout the paper, a sequential wood structure was designed using the API *Grasshopper*. The main goal is that this prototype could be assembled robotically with the programming workflow created in the previous chapter to control the mini Robotic arm. The process of prototyping is divided into 4 parts: (1) create a digital model of the pavilion, (2) discretization of the structure into a set off parts compatible with the constrains of the robotic arm, (3) definition of the path for the robotic assembly; (4) implementation of the workflow for the assembly of the prototype.

5.1 Prototyping with the Mini Robotic Arm

The first phase consists in designing the pavilion. This structure has the objective of showing the possibilities and advantages of the articulation between the design and manufacturing stages mediated by computational models.

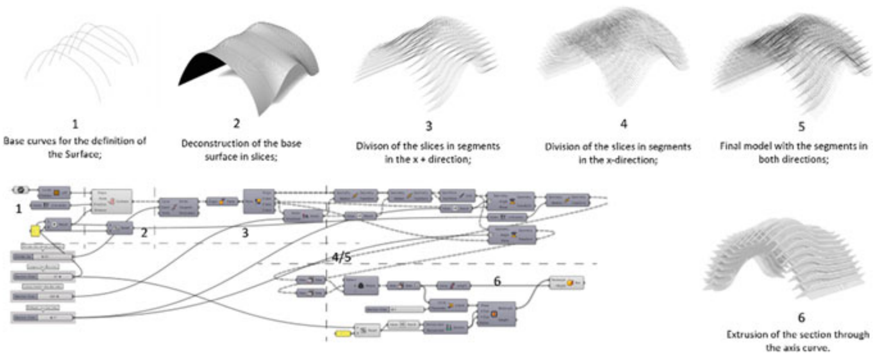

Fig. 5 Parametric definition of the design of the Pavilion

This type of prototype has been widely developed by investigation groups and universities. Some of these examples are *Gramazio & Kholer* from *ETH Zurich*, that developed "The sequential Structure" in 2010, and in 2015 students from the Institute of Advanced Architecture of Catalonia (IAAC) designed and built the pavilion "Fusta Robotica". In common, these two structures have the fact that both have been constructed by students of advanced studies in Architecture has a first contact with robotics.

The structure proposal departs from the idea of a small pavilion constructed with small wood elements with the particularity of have different angles and locations for its placement. The pavilion is only an experimental pavilion with no attributed end (Fig. 5).

The design process of the pavilion, represented in Fig. 6, has been initiated by the parametric definition of a set of sequential profile curves that define the overall shape, limits, and supporting parts.

One limitation of the definition created in *Grasshopper* is that the frames are built in parallel to the XZ plane which constrains the direction of the length of the pavilion. From the set of curves previously defined, the surface of the pavilion has been generated. Then, the surface has been divided into frames with a distance equal to the section of the wood elements. It was considered that all the structural elements have the same section.

The base curves have been divided into segments with the same length. These segments will be the central axis of the wooden elements and the number of divisions will influence the density of the frames that makes the pavilion. The wooden elements needed to be rotated to create the displacement between the frames. That displacement has been done through the interleaved rotation of 180° on a positive direction and 180° on the negative direction. This resulted in the overlapping of the wooden elements, allowing the creation of intersection points that enables the fixation of that's elements with screws, resulting in a frame system that supports itself.

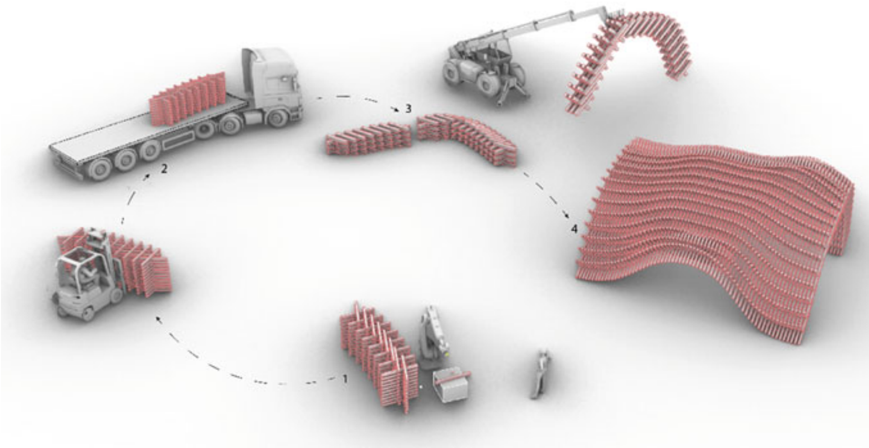

Fig. 6 Assembly schema of the pavilion: (1) Robotic assembly; (2) Transportation; (3) Final assembly of the modules (4) Put the frames in final position

The wooden elements have been considered to have a length of 1.20 m by a quadrangular section of 0.15 m in real scale. Since the prototype has been thought to be made at the scale 1:20, the elements will have 60 mm in length by a quadrangular section of 6 × 6 mm.

Through this parametric scheme, a pavilion with the dimensions of 4.20 m in width by 8.00 m in length with 2.60 hight has been created using 1800 wooden elements.

5.2 *Discretisation and Assembling*

This experiment considers off-site manufacturing and implementation of Robotic fabrications processes. For that reason, is relevant to understand that the structure that is going to be assembled by the robotic arm needed to be manufactured, moved, transported, and assembled in its final location, but on the other side, at the end of the life cycle of the pavilion, the process of disassembly could also be made using a robotic de-fabrication system allowing the reuse of materials.

The logistic process in which the structure is assembled by modules, transported, and assembled on gantries at its final location, is represented in Fig. 6.

In order to assemble the structural model with the mini robotic arm, several steps have been considered. (1) As shown in Fig. 7, the pavilion was divided into 19 groups with dimensions compatible with the working area of the robot. In this case, the robot's working area is measured on the XY plane since the robot will overlap the wooden elements horizontally; (2) reorient the groups individually to the XY plane, the plane compatible with the robot's working area.

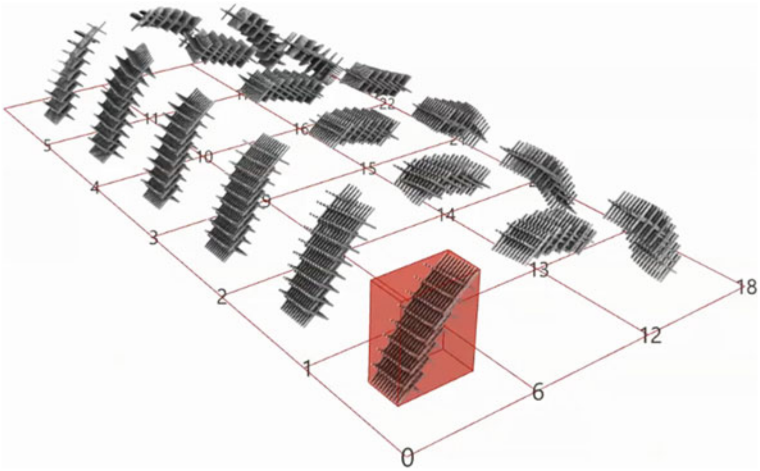

Fig. 7 Division of the structure into modules

In this specific case, there are no other restrictions for the size of the modules, but their dimensions could be adapted in order to adjust, for example, weight limits or dimensions imposed by transport constraints.

To divide the structure in parts, from the limits of the horizontal projection of the pavilion, a rectangle surface has been made to contain all structures. That surface has been divided into rectangles with the maximum dimensions of the robot working area in XY plane. These dimensions change according to the model of the robot. This division, represented in Fig. 7, results in 19 similar rectangles, every with one compatible with the robot's working area.

These modules have been sorted and labeled from 0 to 18. That sorted order corresponds to the order in which every one of the modules will be assembled. Using that order, a *Grasshopper* definition has been implemented to select the module and reorient it in the XY plane to subsequently be assembled.

5.3 Create the Routine for the Assembly of the Prototype

The use and programming of the mini-Robotic Arm is like programming an Industrial Robotic Arm. The method of programming was divided into 2 steps. The first was to select the correct robot in *Kuka Prc*, the robot that will run the program. This is important because if the robot selected doesn't correspond to the robot that is in use, although the simulation runs well without errors, the dimensions of the working envelope of the robot will be wrong and the code will not run when uploaded to the robot controller or the robot can be damage.

The second step was the visual confirmation that the module that has been oriented correctly and was inside of the robot working envelope. For that reason, a circle has been made around the limit of the robot working area. The points of the module that needs to be reachable by the robot gripper must be inside of the circle as shown in Fig. 8a.

The next part of the definition was to decompose the timber elements into their parts in the digital model, Fig. 8b. Through that process, have been found the centers of the wooden elements.

That center points will be used to the gripper grab the wooden element. These points are represented in Fig. 9.

Those points are transformed into planes, with the center point being the center of the plane, and the axis being the direction of the plane that orients the *TCP* (*Tool center point*). That makes possible the orientation of the gripper. It is important that all the planes from each wooden element have the same orientation. Only with these

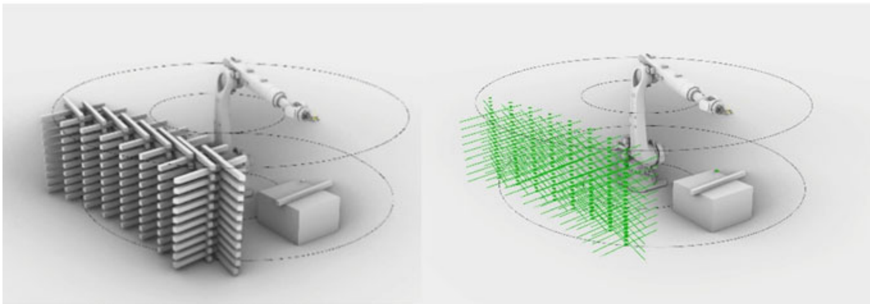

Fig. 8 **a** Reorientation of the module in XY plane **b** Deconstruction of the wood elements

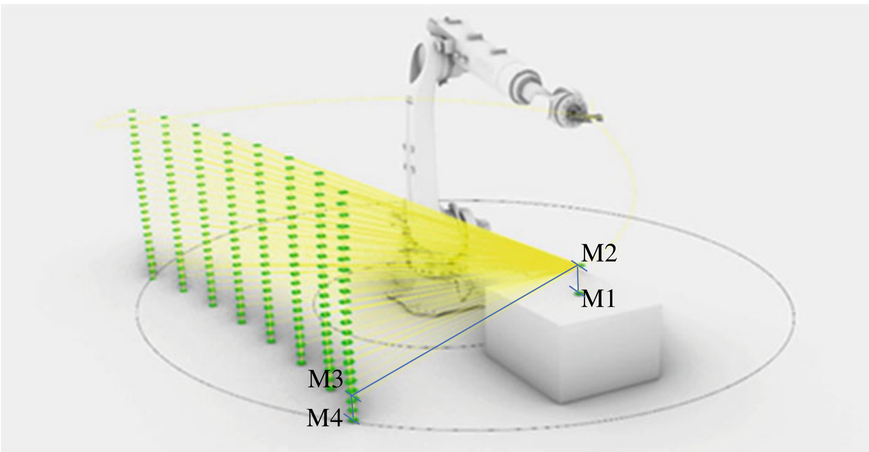

Fig. 9 Creation of the path of the robot

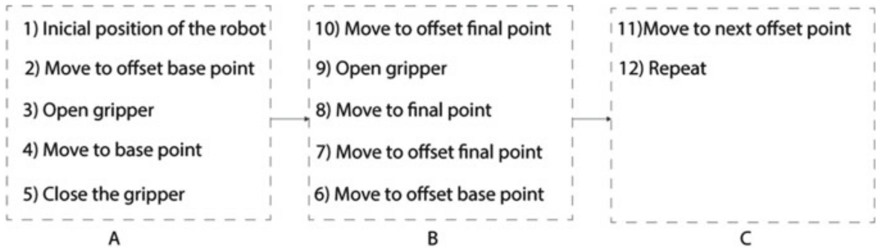

Fig. 10 Table with the robot commands by order

planes oriented in the same direction is possible to ensure the correct assembly of the module. These planes are represented in green color in Fig. 9. On the right side of the image, is the table with the base wood element (feeder). On the left side of the figure, are visible all the final points that will construct the final assembled structure.

For the trajectory to be more controlled, new control points have been created to guarantee that the movement of the end effector doesn't it any other element that is already in place. In this case, an offset was made on the z-axis of all base points.

Throughout this process, 4 points have been obtained that arrange the trajectory of the robot. These points are represented in Fig. 9 as M1, M2, M3, and M4.

Figure 10 is specified and sorted the movements of the robot by order. The commands, by order, are: (1) the robot is on the start position); (2) moves the TCP in direction of the first midpoint (M1); (3) Opens de gripper; (4) moves the TCP to the base point to catch the wood element (M2); (5) close the gripper; (6) it moves again to the first mid-point (M1); (7) moves to the final offset point (M3); (8) moves to the final point (M4); (9) opens the gripper to release the wood element; (10) moves again to the final offset point (M3); (11) moves to the next offset point and continuous the progress until the last wood element of the code is correctly placed on its final position.

In order to Kuka Prc be able to recognize the points of the geometry as Kuka commands, the points must be transformed into Kuka Prc commands (Fig. 11). The command used for the movement was "*Linear Movement*", which allows a movement in a straight line between different points selected in a given order. The points are always introduced on the command as planes referenced by three-axis (X, Y, Z). The trajectory is represented in Fig. 11 in yellow.

For the connection of all the commands, it is necessary to specify the order that they will run. The correct order is synthetized on the table represented in Fig. 10. To the connection off all the commands, all the data was concatenated in a final list, as represented in Fig. 11 in Kuka Prc.

That list is then connected to the Robotic System that has been previously defined and then the simulation is generated in the *Rhinoceros* viewport. To be able to control an industrial robot, through the *Kuka Prc*, the data created for the simulation is transformed in Kuka KRL, the language that controls Kuka Robots.

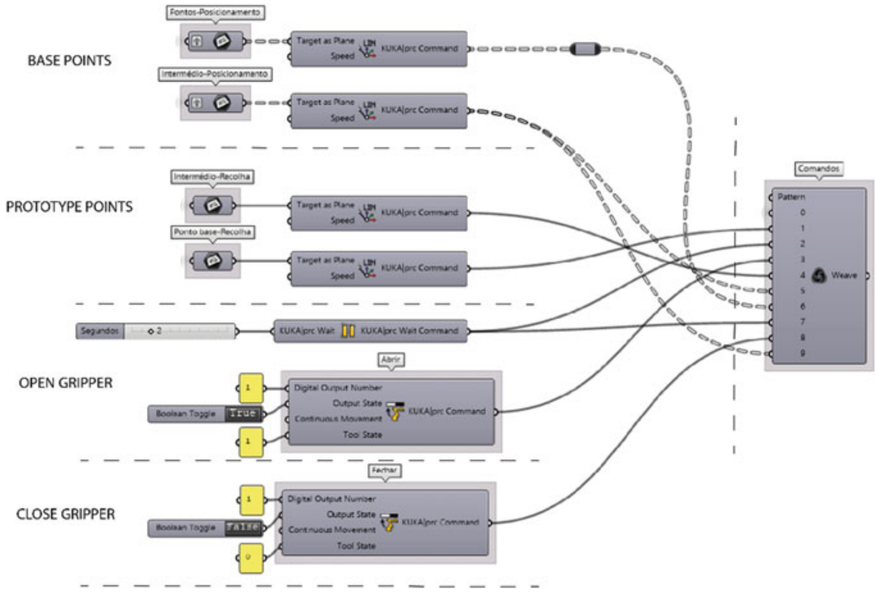

Fig. 11 Commands in Kuka Prc by order

5.4 Assembly of the Prototype with the Mini Robotic Arm

To be able to use the mini robotic arm and construct the prototype, the Grasshopper definition made before needed to be adjusted. Each robot has its limitation in terms of area of action, load, and velocity.

The robotic system, which includes the definition of the robot that is in use, is switched for the system created with the dimensions and characteristics of the mini robotic arm, that already have been done in *Kuka Prc*. The module from the sequential structure was scaled down to 1:20 since the scale of the mini robotic arm is around that in reference to an industrial robotic arm.

The execution of the assembly of the prototype has been divided into two parts. The first corresponds to the simulation phase, represented in Fig. 12 where the objective is to check if everything is working correctly. The second part is the real assembly of the prototype at a scale 1:20, represented in Fig. 13, and the final prototype in Fig. 14.

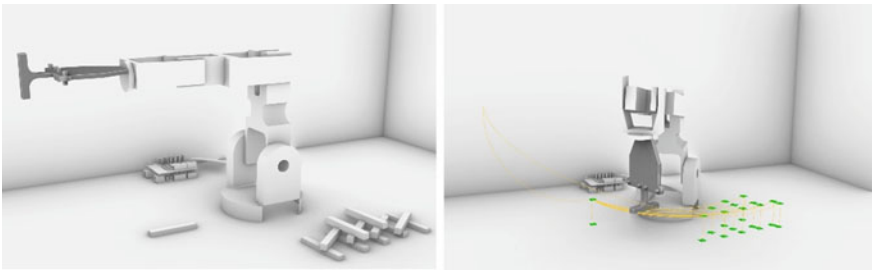

Fig. 12 **a** Batting of the module in XY plane **b** Deconstruction of the wood elements at scale 1:20

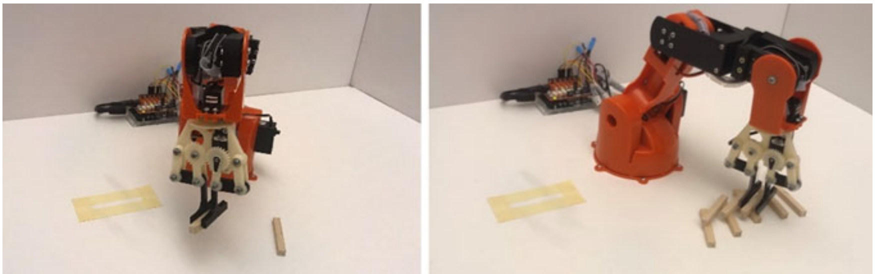

Fig. 13 Assembly of the prototype with the mini robotic arm

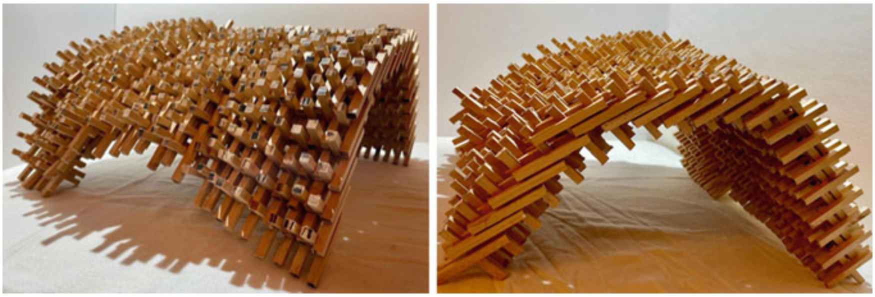

Fig. 14 Final prototype assembled with the mini robotic arm at scale 1:20

6 Conclusion

The creation of routines to control Robotic Arms suffered changes in its complexity in the last decades with the growing interest from professionals from industries that usually don't have this kind of interest, like architecture and design. New ways of control have emerged without the need for big knowledge of programming languages. To facilitate that articulation between the design and the manufacturing stages, new add-ons have been developed to make easy the control and definition of robotic routines from parametric models, such as the *Kuka Prc*, an add-on for *Grasshopper*. This possibility is implementing a new paradigm in design and manufacturing stages in Architecture and Construction.

The wooden sequential structures have been used in the last years as a way of introducing the robotic field to people that never had any contact with that kind of technology. The use of this type of structure is justified by the fact that is a good first practice as an introduction to robotic control because it needs a good control of the planes and the path since the angles between the pieces haven't the same.

This work was done with the main objective of finding an alternative way to have access to robotic arms. The modification and the use of the mini robotic arm show that is possible to have a small robotic arm, controlled through easy to acquire hardware, that can perform almost the same tasks that a real-scale robotic arm. In terms of control, the programming of the mini robotic arm proved to be a challenge similar to that of programming a common industrial robotic arm, but with the advantages of portability and low maintenance required, something that can be beneficial when it is a piece of equipment that intends to be used by students as a first contact with robotic mechanisms.

This paper has shown that is possible to create a robotic routine, simulate it in *Grasshopper* with *Kuka PRC*, have physical feedback of that routine with the use of the mini Robotic Arm, and in the future use the same code in an Industrial Robotic Arm.

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