

Alberto Garcia-Diaz
J. MacGregor Smith

Facilities Planning and Design

Second Edition



Springer

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Alberto Garcia-Diaz • J. MacGregor Smith

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*With our deepest gratitude, we dedicate this
book to our wives and our children:*

Irmis A. Garcia

Gabriel A. Garcia

Daniel A. Garcia

Martha Blakey Smith

Kathryn Blakey Smith

Professor J. MacGregor Smith passed away at his home in Amherst, Massachusetts, on February 7, 2024. He received his PhD in Industrial Engineering from the University of Illinois at Urbana-Champaign in 1978. His thesis focused on Steiner Trees and network optimization. That fall he joined the faculty at the University of Massachusetts in the IEOR Department. During his 44 years of teaching and research at UMASS, he published over 160 papers in reviewed journals. He authored several books over the years including a comprehensive handbook Introduction to Queueing Networks that integrates queueing network theory and their practical applications in industry. His research was his passion; he was working on matrices the day he passed. His research lives on in the work of his students.

Preface

This textbook is concerned with the principles of facilities planning and their application to service, business and product manufacturing operations. It is intended to provide upper division undergraduate students with the fundamentals of facilities planning, design, location and material handling, especially as they apply to industrial manufacturing facilities. The textbook can be used in a university setting, a two-year college, or other type of higher-education institution offering a course on facilities planning having a mix of lectures (2 credits) and lab (1 credit). To a great degree, it is especially designed for majors in industrial engineering and related engineering disciplines (e.g., engineering technology, mechanical engineering, civil engineering, architectural, etc.) that are interested in facilities planning. While the focus is on industrial facilities, the concepts and design methodology are applicable to many other building types and service sector activities. Various case studies are discussed in the book to link the concepts of the book and what actually occurs in practice.

One of the unique features of the book is the *factory design project*. The project serves as a unifying interconnector for the organization, teaching and learning of concepts and procedures presented in this book. The *factory design project* has been extensively tested at Texas A&M University, the University of Tennessee, and the University of Massachusetts at Amherst. Students, working in small teams of three to five members, plan a factory for a selected pre-designed product of their own choice. The project is developed within a conceptual approach that emphasizes the use of information-based manufacturing strategies. From the bill-of-materials to the routing sheets, layout planning charts, selection of equipment, material handling systems and final designed layout, the students investigate all aspects of facilities planning. Identification and costs of the equipment, materials, personnel, material handling system, office space and partitions are also addressed in the project. The lectures derived from the text as well as the text organization center around the factory project. This natural symbiosis embodied in the text and the academic setting of the factory project work quite well because the lecture and laboratory exercises are constantly being learned and reinforced as the factory project evolves over time. All

this makes it a unique textbook. The text and the factory project are natural integration tools for the students since it motivates them to combine their knowledge from a broad range of courses. This is also why it is situated at the junior/senior level year of the curriculum. It is not too early, yet not too late either to become an integration tool. Students must utilize concepts of materials science, manufacturing processes, calculus, statistics, physics, chemistry, engineering economy, as well as marketing, economics, ergonomics, psychology and work-place design.

While in some way the book and the factory project could be conceived as a capstone design type of course, the intent is to focus on facilities planning and design and provide a comprehensive, interesting and challenging intellectual pursuit. We envision most students, after taking the course, coming away with a great sense of accomplishment and learning because of the breadth and depth of the project experience. There are several computational tools and techniques included and used throughout the book. Students must use spreadsheets for the equipment, material, and personnel costs, graphics layout tools such as AutoCAD and quantitative layout and location algorithms, and even queueing networks.

After teaching an undergraduate course on Facilities Planning at the University of Tennessee and the University of Massachusetts for many years and getting feedback from other colleagues and numerous students, the authors saw the need to update and reorganize the content of a few chapters and extend some of the concepts and techniques in the first edition of the textbook to include new software methodologies and algorithms that we have developed since the book was first published in 2007. Our goal is to provide the students with a more comprehensive knowledge base in addition to facilitating and making the project experience more efficient and effective. We also took the opportunity to update the lectures and software supplements of the book since we feel that these lecture slides and software supplements, which are downloadable from the textbook website, are a valuable asset for the instructors and their students using the textbook. Specifically, the content and organization of Chaps. 4, 5, 6, 7, 8 and 11 have been reviewed and properly revised, including additional examples.

The main focus of the improvements in this second edition is to make the textbook more effective in providing students with specific knowledge and skills gained through the Factory Project. To this aim, in addition to the software and files containing the format and content for the reports documenting the results of each of the six sections of the overall project, the following new procedures were added.

- Chapter 4 (Layout Planning Procedures) now has a new From-To Chart excel program that will accept defective product probabilities for all machines performing the manufacturing processes identified in the Process Planning section. This significant improvement makes the project more realistic. The previous version of this file assumed zero defective products.
- The section on Facilities Layout Programs in the new version of Chap. 4 has been significantly improved by including two programs (CRAFT, GMAFLAD). The students can choose either the original program FLAP, or CRAFT or GMAFLAD to be used in their project. Software and instructions for their

use are available through the website to supplement the material provided in the textbook.

- Chapter 5 has been restructured to include a conceptual approach to site planning (topic fully addressed in Chap. 10) and to present optimization procedures that were previously placed in Chap. 6. As a result of this, Chap. 6 has been revised and reorganized to serve as a survey of computerized procedures for layout design.
- Most of the traditional layout design procedures are based on optimization models, specifically quadratic programming models or mixed integer linear programming models. Chapter 6 has been updated to include besides the description of traditional computerized procedures, an illustration of software integration to optimize the factory layout. Additionally, this chapter includes the STEP program that can be selected for the factory design projects as well.
- Chapter 11 (Office and Personnel Layout Planning) has been substantially modified to include new concepts of office arrangements and available software. In particular, two files have been created to improve the resources available for the students to develop Sect. 11.8:
 - A new excel file has been created to document all calculations resulting in direct and indirect costs, as well as the product price per unit.
 - The CRAFT excel software has been added to allow students more flexibility in the selection of the procedure to perform Sect. 11.8. Section 4.11 now includes user instructions and a demonstration of the procedure.

In closing, we would like to express our appreciation and gratitude to numerous students at Texas A&M University, the University of Massachusetts and the University of Tennessee for their suggestions to improve the textbook and for contributing in varying degrees to the programming, improvement and application in their projects of some of the software used in the textbook. We recognize through the textbook those who have provided specific software-related contributions.

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Textbook Website

<https://facilitiesplanning.wixsite.com/my-site>

Factory Design Project Overview

- Factory Layout and Material Handling Project Overview.pptx

Forms and Checklists

- **Forms**
 - Group Names & Product Description.docx
 - S1PL.docx
 - S2MCT.docx
 - S2MMR.docx
 - S2MRT.docx
 - S2RS.docx
 - S3LPC.docx
 - S3MHT.docx
 - S4PRC.docx
 - SUMMARY.docx
 - TEMPLATE.docx
- **Checklists**
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 - Checklist Section II
 - Checklist Section III
 - Checklist Section IV
 - Checklist Section V
 - Checklist Section VI

Machine Database

- AccessRuntime
- Machine Database.mdb
- mc.mdb
- Manufacturing Processes and Machines.pptx

Material Database

- Selected Material Costs.pdf
- Selected Material Costs.xlsx

PPT Presentations by Topic**Project Presentation Guidelines**

- Presentation Grading Sheet.xlsx
- Project Team Presentation Guidelines

Project Section Summaries**Reading Guide**

- Reading Guide.docx

Software

- CNET_V1
- Combinatorics.xla
- Conveyor Analysis Software
- CRAFT
- Decision Support Methodology
- DSS-MHE-UTK
- FLAP
- FROM-TO-CHART
- GMAFLAD
- GQNET_V1
- Optimize_xla
- polymer_processing
- QAP
- SIMAN
- STEP
- UNIT COST CALCULATION

**SAMPLE PROJECT
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Chapter 1

Fundamental Principles of Facilities Planning and Design



1.1 Introduction

Facilities planning is concerned with the design, layout, location, and accommodation of people, machines, and activities of a system or enterprise (manufacturing or service) within a physical spatial environment. People, machines, vehicles, and processes are accommodated within the physical environment so that the objectives of the system or enterprise (e.g., hospital, bank, manufacturing, telecommunications call center) housed within the facility can be satisfactorily achieved following the iterative procedure outlined in Fig. 1.1.

This chapter introduces many of the fundamental principles and concepts germane to all of facilities planning. In Sects. 1.1 and 1.2, the fundamental principles underlying the design process are examined. The objectives of facilities planning are discussed in Sect. 1.3, while the fundamental concepts of manufacturing systems are described in Sect. 1.4. Fundamental morphologies of basic layouts germane to all types of facilities planning are presented in Sects. 1.5 and 1.6. An overview of the types of facilities found in service systems is presented in Sect. 1.7. Renovation or reengineered facilities are discussed in Sect. 1.8 and constraints on facilities planning and design in Sect. 1.9. Section 1.10 concludes the chapter.

1.1.1 What Is Design?

The design process is an *activity* aimed at the production of a plan (i.e., a schematic or course of action) that, if executed, leads to no undesired or unanticipated consequences [4]. Thus, design is intended to be a logical, rational, and systematic activity.

Of first importance in the design process is the definition of the design problem or scope of work. This is the most difficult undertaking, because to define the design

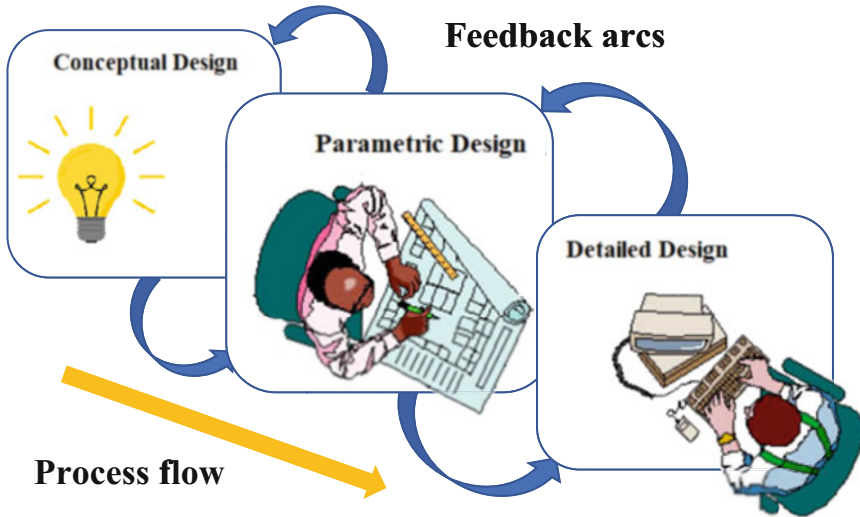


Fig. 1.1 Facility planning and design process

problem is tantamount to indicating its solution. That design problems are difficult is well known. In fact, design problems are often called *wicked problems*—because of their complexity and intractability [4].

1.1.2 Characteristics of Design Problems

The following are seminal characteristics of design (wicked) problems [5–7]:

- C₁: No definitive problem formulation.
- C₂: No exhaustive list of permissible operations.
- C₃: No stopping rule.
- C₄: No *single* criterion for correctness.
- C₅: Many alternative solutions.
- C₆: Every wicked problem is symptomatic of another wicked problem.
- C₇: No immediate or ultimate test of a solution.
- C₈: Every wicked problem is a one-shot operation.
- C₉: Every wicked problem is essentially unique.
- C₁₀: We are morally responsible for our actions.

How difficult wicked problems can be is illustrated in the following scenario. Suppose you are newly employed as an industrial engineer in a production factory and your manager suggests that you develop a layout of machinery for a new *flexible manufacturing/assembly system* (FMS/FAS) for one of the product lines. A sample dialogue of the conversation between you the engineer, denoted as *E*, and the

manager, denoted as M , is presented to illustrate the dynamics of the decision-making process:

M We are currently losing market share in our product line, and our overseas competition is becoming more aggressive. I would like you to look into the creation of a flexible manufacturing/assembly (FMS/FAS) system to replace our current way of manufacturing our product line. Let us focus on the midlevel product mix with medium production-level demand.

E O.K. (Being fresh out of school, how could you say no!)

She gives you a memo describing what she wants and sends you back to your desk.

Pretty soon you will start to wonder what she really wants. Especially you will want to know what an FMS/FAS is all about, because you see nothing wrong with the current layout and production line. Before too long you will probably be back in the manager's office asking for more information.

E Let me ask you one question here. Just what is wrong with the current process? Why do you think we need an FMS? Also, what is the difference between an FMS and an FAS?

This illustrates characteristic C_1 of a wicked problem. Even the manager may have no clear idea of what the problem entails, because she got her information from someone higher up in the organization.

M Well, those are good questions. Let me get you some of our annual reports for the last 5 years and you can begin to see why an FMS/FAS is needed. You just got your Ph.D. so you should be able to assess the appropriateness of an FMS/FAS.

E But—I don't really know where to begin!

This illustrates the *second* characteristic (C_2) of a wicked problem. There is no exhaustive list of possibilities and no clue as to how to start analyzing the problem. Should you read the literature on FMS/FAS? Should you talk to the FMS/FAS experts? Should you take a survey? Should you visit similar plants with FMS/FAS facilities? How should you initiate the solution process?

The *third* characteristic (C_3) of a wicked problem is that we do not know when to *stop* working on it. Perhaps implementing the FMS/FAS will improve production; however, we may want to improve production further, which will require more effort. Usually with a wicked problem we always feel we can do better, till time, patience, and money become exhausted and we end up opting out for whatever solution has emerged at that point in time. Alas, a major paradox of design decision-making is that on the one hand we do not know where to start C_2 and on the other hand we do not know when to stop C_3 .

E It may seem obvious to you, but it is not clear to me just exactly what we mean by flexibility. How does flexibility impact costs, due dates, work-in-process, and many of the other objectives in our production environment?

A *fourth* characteristic (C_4) and certainly one of the most relevant to us in this textbook is that wicked problems have no single criterion for correctness. They have “good” or “bad” solutions, not necessarily right or wrong ones. Either the FMS/FAS will improve productivity or it will not, but only to a certain degree—other factors enter the picture and may cloud up the overall evaluation. This multifaceted approach to a wicked problem is central to our multicriteria point of view, and we shall elaborate upon it throughout this book.

- M Also, I believe the FMS concept will improve productivity and we will not have to go to high-speed dedicated lines, since the market demand should remain relatively flat over the next few years. We may want to consider a cellular layout, too.
- E But—what is a cellular layout? How does it differ from a flexible one? Now I am really confused as to what to do!

Alas, there are many alternative solutions to our wicked problem (*fifth* characteristic C_5). Is an FMS/FAS really the solution? What about the cellular layout—would it really increase production output? Why cannot we simply improve the scheduling system? Will the FMS/FAS do all that is claimed for it? Maybe the solution is that the other product lines should be integrated into a multiproduct line?

- E Well, it seems fine to follow through with the FMS/FAS, but did you ever think that the reason we are losing market share might be that we are not getting the product to the market fast enough?
- M That is a good point, and I had not really considered that in any depth.

The *sixth* characteristic (C_6) underscores the symbiotic relationships between related wicked problems. While implementing an FMS/FAS may improve productivity, problems with the inventory control, scheduling, and reordering system may also affect productivity. The warehouse may have an inefficient material handling system that is delaying part and subassembly shipments to the shop floor. Thus, by implementing the FMS/FAS we may only cure a symptom of a much deeper problem, which is due to material handling inefficiencies.

- E You know, I hate to be skeptical here, but even with implementation of the FMS/FAS, how are we going to measure its performance over time?
- M Good question—and as the FMS/FAS becomes operational, new products may have to be manufactured, demand may change, new tools and material handling systems may emerge and have to be integrated into the FMS/FAS. But I think we need to follow through on the FMS/FAS idea, I can feel it in my gut.

The *seventh* characteristic (C_7) emphasizes that there is no immediate or ultimate test of a solution. Certainly, the context for the solution changes with time, and thus our original conception of the solution to our wicked problem must also change. Even the manager’s intuition, although forthright, may be ill conceived.

- E You know, once we decide to implement the FMS/FAS, it will be very difficult to change the layout and machinery without incurring some major expenses.
- M Yes, this is one irony of an FMS/FAS—it usually is not as “flexible” as one may be led to believe.

This *eighth* characteristic (C_8)—that wicked problems are *one-shot* operations—is very frustrating when one is trying to develop general approaches to problems. Once a design solution is set in motion, it is difficult to undo things without grave consequences.

- M We also may want to implement the FMS/FAS in our other plant on the West Coast, if we are successful here in the East.

While productivity is common to all industrial organizations, the problem context surrounding productivity changes from plant to plant. The West Coast is simply not the same as the East Coast in terms of weather, work force, lifestyles, and so on. Each implementation of an FMS/FAS is different. One likes to apply general principles to solving wicked problems, but there are really very few because the context is so dynamic. Thus, every wicked problem is essentially unique (*ninth* characteristic C_9).

Finally, the *tenth* characteristic is that we as engineers and designers must do our best to resolve the wicked problem, because we are morally, ethically, and professionally responsible for our actions—not to mention liable if we make a mistake. Not only is our job at stake, but often the well-being of our fellow engineers, coworkers, and even the manager may be affected if the FMS/FAS does not work out.

These rather dismal characteristics of wicked problems should not discourage us from attempting to resolve them. We must realize that we cannot expect solutions to wicked problems to be as readily available as solutions to tame problems (TPs).

1.1.3 Design Program

Another fundamental principle in facility planning is to identify the specific activities (e.g., departments) to be housed in the facility.

The essential activities of a manufacturing system (e.g., receiving, storage, shipping, milling, grinding) in a manufacturing facility are the fundamental processes that convert raw materials into finished goods. This list of activities can be represented as an n -dimensional *activity* vector $\mathbf{a} = (a, b, c, d, e, f, g, \dots, z)$. The activities in a service facility, such as a doctor’s office (e.g., reception, waiting, examination, testing, payment of bill, and leaving), are also fundamental processes that engage the people and staff in their enterprise or business. The fundamental activity vectors $\mathbf{a}$ of their processes are common to both manufacturing and service facilities. While the activities of a manufacturing facility are different from those of a service facility, there are many commonalities, which emerge in the facilities

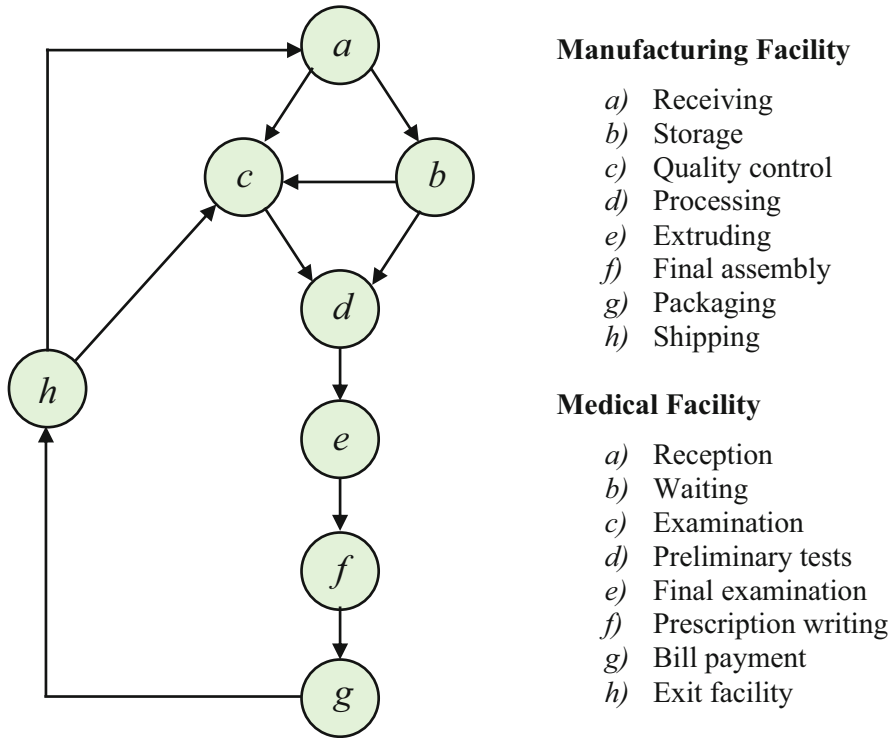


Fig. 1.2 Examples of manufacturing and service activities

planning process. For one thing, these activities must be housed in a physical environment with adequate area, a covering to keep off the elements, and interior light, heat, water, and energy in order to accommodate their needs.

One way to conceptualize the commonalities within a system is by a graph $G(N, A)$, where the nodes in set N represent the activity processes, and the arcs in set A represent the logical transitions or product flow between the activities. (See Fig. 1.2.) Once we have identified the activities and graphed their interrelationships, we have taken the first step in facilities planning. This diagram is called a planar graph or “bubble diagram” in architecture.

1.1.4 Design Process

Because of the vast number of variables in facilities planning and the complexity of the design problem, we must follow a guided iteration design procedure as, shown in Fig. 1.1 [2]. When starting out, once we have the design program defined, we normally employ general concepts called morphologies (design solution concepts) in order to initiate the design process. In the next, or parametric, stage, we settle on

Table 1.1 Expenditures on equipment and buildings (\$B)

Industry sector	2021	2020	2019	2018	2017
Mining	91.1	97.7	158.1	153.4	134.4
Utilities	177.8	182.2	172.6	151.0	133.9
Construction	44.9	52.15	50.4	39.0	35.0
Manufacturing	282.2	256.7	272.9	258.1	247.0
Transportation and warehousing	93.7	97.8	128.5	122.4	108.5
Information	194.5	169.8	176.8	175.1	158.9
Real estate and rental and leasing	158.3	136.0	181.2	173.9	161.4
Healthcare and social assistance	113.9	104.9	116.7	108.6	104.6
Others (except public administration)	532.3	501.5	550.7	517.6	498.1
Total	1681.7	1598.8	1807.9	1699.1	1581.8

Source: U.S. Census Bureau, Capital Expenditures for Structures and Equipment: 2021–2017

certain parameters (such as length, height, shape, and weight) to numerically scale the solution. In the final design stages, the specific equipment location and configuration details are laid out and tested before the final plan is completed.

The design process is essentially information deficient. At each stage, more detailed information is required. In effect, a design system is an information system [4]. It is founded on the resolution of fundamental design and planning issues [8], which interweave the conceptual, parametric, and detailed stages of design.

Facilities planning includes facilities location and facilities design. Facilities location refers to determining how the location of an activity supports the accomplishment of the intended objective of the activity. The study of the way the components of an activity support the accomplishment of its objective or objectives is within the realm of facilities design. This area includes: structural design, layout design, and material handling system design. In particular, facility layout is the field of selecting the most effective arrangement of physical facilities that allows the greatest efficiency in the allocation of resources needed to manufacture a product or perform a service. As stated by Muther [3],

Plant Layout embraces the physical arrangement of industrial facilities. This arrangement (installed or planned) includes the space needed for material movement, storage, indirect laborers, and all other supporting activities or services, as well as for operating equipment and personnel.

Facilities layout principles and techniques can be used in industrial and manufacturing plants, hospitals, airports, shopping centers, judicial facilities, prisons, office buildings, art museums, places of worship, educational facilities, and many other types of buildings. Again, while the range of possible building types is enormous, the focus of this book is on fundamental principles common to all facilities planning.

Table 1.1 shows in billions of dollars relevant expenditures that underline the importance of the area of facilities planning and design [10].

1.2 Hierarchical Cycle of Facilities Planning

As mentioned earlier, facilities planning and design normally proceeds in a hierarchical and cyclical fashion—from conceptual design, to parametric design, to detailed design.

Conceptual design refers to the overall design concepts or morphologies embedded within the facilities plan.

Parametric design is concerned with the assignment of numerical values to the parameters of the morphologies.

Detailed design is concerned with the final dimensioning, specification of equipment, materials, finishes, and furnishings, and formal approval of the design concept.

The cyclic nature of the design process stems from its complexity and the fact that some issues resolved at the conceptual phase directly affect the planning issues at the detailed phases and vice versa. In other words, you may return to the **conceptual** or **parametric** phases during the **detailed** phase for resolving some aspect of the design.

The dichotomy between top-down design and bottom-up design is discussed in the literature. Top-down design proceeds from the general to the particular, while bottom-up design proceeds in the opposite fashion. Both approaches have merits. Neither, however, is adequate by itself, because designers must work both ways simultaneously—a daunting task. Rather than choose one method or another, we develop an information system, integrating the issues that transcend these two approaches into one overall methodology.

1.3 Objectives of Facilities Planning

Objectives of facilities planning may be divided into two types: objectives of facilities location and objectives of facilities design.

The objective of facilities location is to determine the placement of all facilities needed to produce a product or service in such a way as to minimize all the components of the deliver-to-customers cost that depend on location aspects. The objectives of facilities design include:

- Improve material handling, material control, and housekeeping to enhance and facilitate the manufacturing process.
- Effectively utilize people, equipment, space, and energy.
- Minimize capital investment.
- Promote flexibility and ease of maintenance.
- Promote employee safety and job satisfaction.

1.3.1 Issue-Based Information Systems (IBIS)

When solving most real-world design problems, we need a methodology to guide us through the design process. We present here one such methodology, which we have found helpful in facilities planning projects. An illustration of it is provided in Fig. 1.3. It is based on raising planning issues about the design process. A planning issue could lead simply to an answer to a question or possibly to different points of

Conceptual design

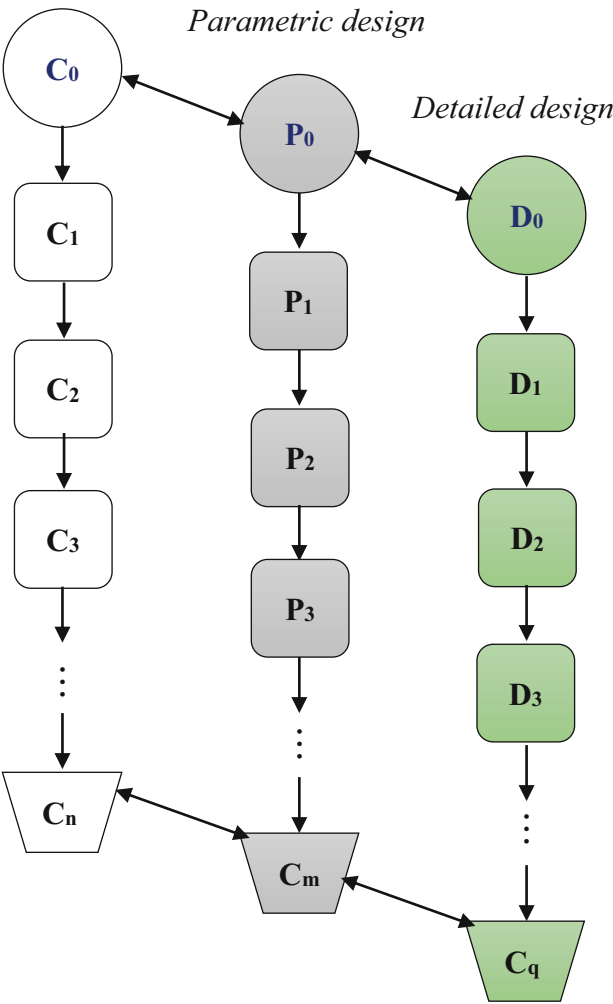


Fig. 1.3 IBIS process

view. Often it leads to a discussion about the best way to resolve the issue, thereby generating a useful discourse on design. The key outcome of an IBIS is to network together the planning issues, thus leading to a design methodology. The planning issues can be classified as conceptual, parametric, and detailed issues. Examples of these issues are provided below.

Conceptual Design Issues

- What are the basic needs and user requirements?
- Should the building be single-story or multistory?
- Is just-in-time (JIT) a reasonable strategy for the plant?
- Should there be warehouse storage within the building, or outside the building?

Parametric Design Issues

- How many employees and staff should be accommodated?
- Will the personnel numbers expand over time? By how much (percent) and when?
- What is the traffic flow matrix for the different products flowing through the departments of the facility?
- What are the material (total pounds) and equipment needs for the product(s)?

Detailed Design Issues

- Staff and employee costs (\$/year)?
- Administrative and other overhead costs (\$/year)?
- Distance between columns in the structural grid?

1.3.2 Site-Planning IBIS Example

Figure 1.4 shows a typical drawing of a site plan development. This IBIS example illustrates some of the critical issues involved in any site-planning design process. Although the picture was drawn at scale, dimensions are not shown to simplify the figure.

The design and planning information system includes the following basic issues:

- Where should the facility be located on the site?
- How large in square feet should the facility be?
- What shape should the facility be: square, rectangular, L-shaped, round?
- How will people arrive and park on the site?
- How many times a day will trucks arrive on the site? How will trucks, cars, and pedestrians interact?
- How should the building evolve over time (expand)? By how much?

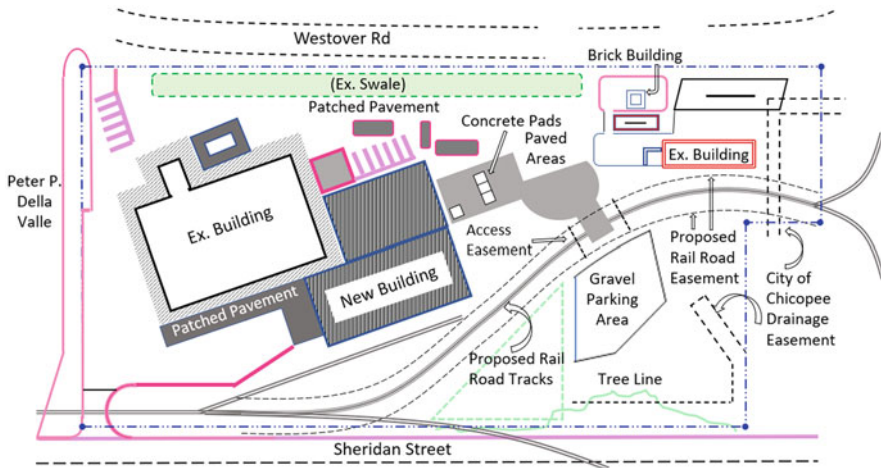


Fig. 1.4 Typical site plan development

- How should the facility and its staff and visitors be configured internally?
- How should the staff and visitors interact with the surrounding environment?

Resolving these issues is a complex planning problem. One needs to understand the fundamental principles that lead to a successful facility plan.

1.3.3 Decision-Support Computer Programs

To guide the students in completing their factory design project, we have developed a number of computerized decision-support and planning tools presented in Chaps. 4, 6, 7, 8, and 11 to provide decision-making support for the selection of material handling equipment and the recommendation of both office and plant layouts. In the Appendix of this textbook, a Decision-Support Methodology (DSM) is described in detail to perform all steps needed to calculate the unit cost of the product. An alternative simplified excel procedure is also presented in Chap. 11. Various other software tools including teaching aids are available on the website of the book accessible through the link <https://facilitiesplanning.wixsite.com/my-site>.

As the various conceptual, parametric, and detailed design issues are resolved, the facility plan will begin to take shape, as illustrated in Fig. 1.5. There are obvious interrelationships between the planning issues. For example, once we determine the ceiling height, this will affect the storage and warehousing design, the method of storage, the material handling system, floor area capacity and floor area needs, delivery of product to the workstations, and, eventually, the number of personnel needed.

For example, at the **conceptual** phase, one may choose a product layout concept for a manufacturing facility, then at the **parametric phase** determine layout and number of workstations (machines), distance between stations, type of material

Conceptual design

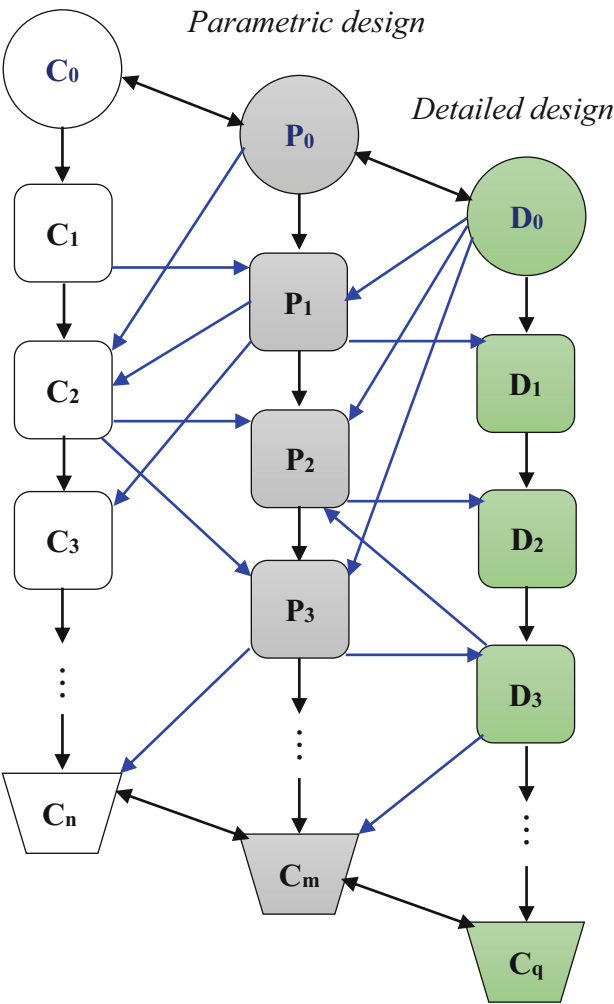


Fig. 1.5 Plan evolution process

handling system, and so on. Finally, the **detailed** design phase is concerned with the exact dimensioning and details for realizing the previous two phases, such as specifications of the powered conveyor, motor recommendation, means of support, slopes, speeds, and utility line feeds. These phases constitute a series of iterated steps, which may include many feedback loops. The overall intent is to arrive at a completed plan satisfying all the objectives, requirements, and constraints of the intended facility. As one becomes more experienced, hopefully, the number of feedback loops tends to diminish.

1.4 Mathematical Models in Facility Planning

What is the nature of mathematical models in facilities planning? Four types of models will be focused upon: *location* (Chap. 5), *computerized layouts* (Chaps. 4 and 6), *queuing and conveyor and storage models* (Chap. 8), and *warehouse storage and layout* (Chap. 9). Each model has an objective function, a set of constraints expressed in terms of decision variables, and known parameters.

The objective function indicates the measure of effectiveness of a vector $\mathbf{p}$ used to evaluate the performance of a solution. Examples of performance variables are *cost of construction*, *cost of machinery*, *material handling costs*, *utility costs*, *worker safety*, and *overall quality of the physical environment*.

The design variable vector $\mathbf{d}$ represents the decisions that are under our control. Examples include *the size of the overall facility*, *its location on the site*, *the structural grid spacing*, *aisle circulation pattern*, and *color of the floor*.

The contextual variable $\mathbf{c}$ represents the context that the solution needs to satisfy. Examples include *zoning ordinances*, *building codes*, *Occupational Safety and Health Association (OSHA) requirements*, *Americans with Disabilities Act (ADA)*, *the ergonomics of workers' heights, reach, and weight*, *structural properties of materials*, and *illumination and ventilation requirements*.

In a nutshell, the overall performance of a facility is a complex function of the constraints and decisions:

$$\mathbf{p} = f(\mathbf{c}, \mathbf{d})$$

Thus, another fundamental principle is the mathematical relationship between the performance variable and the contextual and design variables.

Every facility can be viewed as having a location and consisting of several components. *Location* is the placement of a facility in such a way that it will satisfy specified requirements concerning customers, suppliers, and other facilities with which it interacts. *Components* are the structure (building and services), layout (equipment, machinery, furnishings), and handling system (mechanism for required interactions in the layout).

Let us take our graph of activities in Fig. 1.2 and associate a location with each of the activity components in our vector. First, let us posit a grid layout as shown below.

5	6	7	8
1	2	3	4

Cell 1 is in the lower left-hand corner, followed by cell 2 to its right, and so on. Further, if we measure the distance in terms of grid units, then cell 1 and cell 2 are 1 unit distance apart, while cell 1 and cell 8 are 4 units apart. Having the distances helps evaluate the different layout solutions. (See more on this in Chap. 5.)

Table 1.2 Alternative arrangements of eight activities

Vector	Arrangements			
	1	2	3	4
a¹	<i>a</i> <i>e</i>	<i>b</i> <i>f</i>	<i>c</i> <i>g</i>	<i>d</i> <i>h</i>
a²	<i>e</i> <i>a</i>	<i>f</i> <i>b</i>	<i>g</i> <i>c</i>	<i>h</i> <i>d</i>
a³	<i>f</i> <i>c</i>	<i>e</i> <i>b</i>	<i>g</i> <i>a</i>	<i>h</i> <i>d</i>
a⁴	<i>c</i> <i>f</i>	<i>b</i> <i>e</i>	<i>a</i> <i>g</i>	<i>d</i> <i>h</i>
a⁵	<i>a</i> <i>e</i>	<i>c</i> <i>g</i>	<i>b</i> <i>f</i>	<i>d</i> <i>h</i>
a⁶	<i>e</i> <i>a</i>	<i>g</i> <i>c</i>	<i>f</i> <i>b</i>	<i>h</i> <i>d</i>
a⁷	<i>f</i> <i>c</i>	<i>e</i> <i>b</i>	<i>g</i> <i>a</i>	<i>d</i> <i>h</i>
a⁸	<i>c</i> <i>f</i>	<i>b</i> <i>e</i>	<i>a</i> <i>g</i>	<i>h</i> <i>d</i>

Then, for our given set of eight basic activities, the vector represents the location of activities in the grid layout according to their position in the vector, as shown below.

<i>e</i>	<i>f</i>	<i>G</i>	<i>h</i>
<i>a</i>	<i>b</i>	<i>C</i>	<i>d</i>

The location and layout of the activities of a system is a nontrivial combinatorial optimization problem. To see this, let us take the eight activities described for a manufacturing or service facility in Fig. 1.2, and generate some alternative layouts for these activities.

Mathematically speaking, we wish to map the activity vector **a** onto the cellular grid so that each activity will have an (x,y) Cartesian location. There are eight different activities, and suppose we have a 4 × 2 double-loaded corridor within which to allocate them.

There are 8 ways to choose the first location, 7 to choose the second, and so on—8! = 40,320 in all. Eight of these choices are shown below and Table 1.2 shows the corresponding arrangements on 4 × 2 grids.

$$\begin{aligned} \mathbf{a}^1 &= (e \ f \ g \ h \ a \ b \ c \ d) \\ \mathbf{a}^2 &= (a \ b \ c \ d \ e \ f \ g \ h) \\ \mathbf{a}^3 &= (c \ b \ a \ d \ f \ e \ g \ h) \\ \mathbf{a}^4 &= (f \ e \ g \ h \ c \ b \ a \ d) \\ \mathbf{a}^5 &= (e \ g \ f \ h \ a \ c \ b \ d) \\ \mathbf{a}^6 &= (a \ c \ b \ d \ e \ g \ f \ h) \\ \mathbf{a}^7 &= (c \ b \ a \ h \ f \ e \ g \ d) \\ \mathbf{a}^8 &= (f \ e \ g \ d \ c \ b \ a \ h) \end{aligned}$$

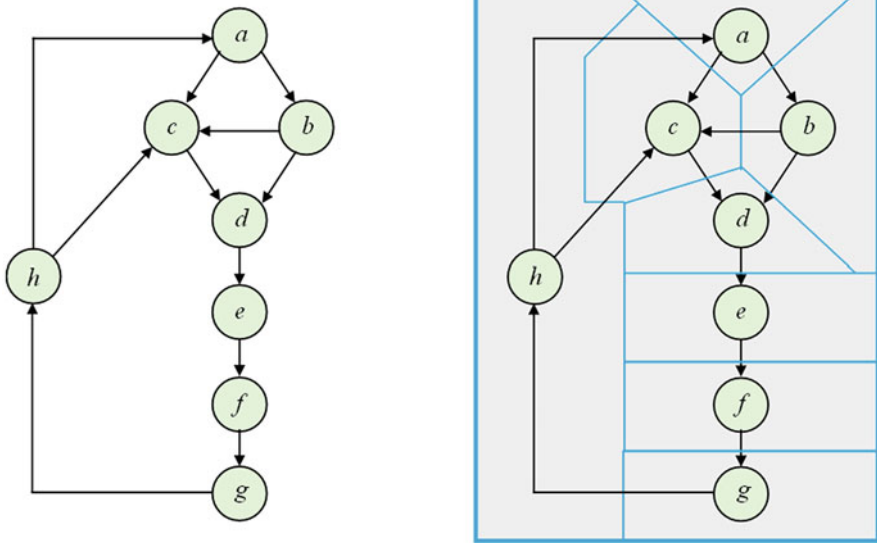


Fig. 1.6 (a) Planar graph and (b) block-plan layout

The combinatorial complexity of facilities planning is not only a fundamental principle that makes it an interesting challenge but also a realistic indication of its practical difficulty. In fact, as discussed in Chaps. 5 and 6, we shall present approaches based on the quadratic assignment problems (QAPs) designed to automatically generate solutions as we have done with the eight-activity vector problem. The QAP problem is a well-known NP-hard optimization problem.

An astute reader may notice that because of our node/arc precedence arrangement in Fig. 1.2, not every possible combination would be acceptable. In fact, one could go directly to a layout generation idea from the graph itself, and thus reduce the number of alternative layout arrangements possible. Figure 1.6b shows a block-plan layout generated from the planar graph shown in Fig. 1.6a. Figure 1.6b can be generated by imagining each node of the planar graph expanding at a uniform rate as in a bubble, until the bubbles intersect with each other according to the arcs and the external rectilinear perimeter.

Thus Fig. 1.6 has the essential characteristics of a floor-plan layout. All of this emanates from identifying the fundamental activities necessary in the layout.

Now, if we begin to add details in one of the alternatives, such as the ones mentioned below, we will have a very complex problem indeed.

- (a) The square footage is the requirement for each activity.
- (b) The number of pieces of machinery and manufacturing equipment.
- (c) The aisle width and circulation requirements for the material handling system.
- (d) The structural grid system.

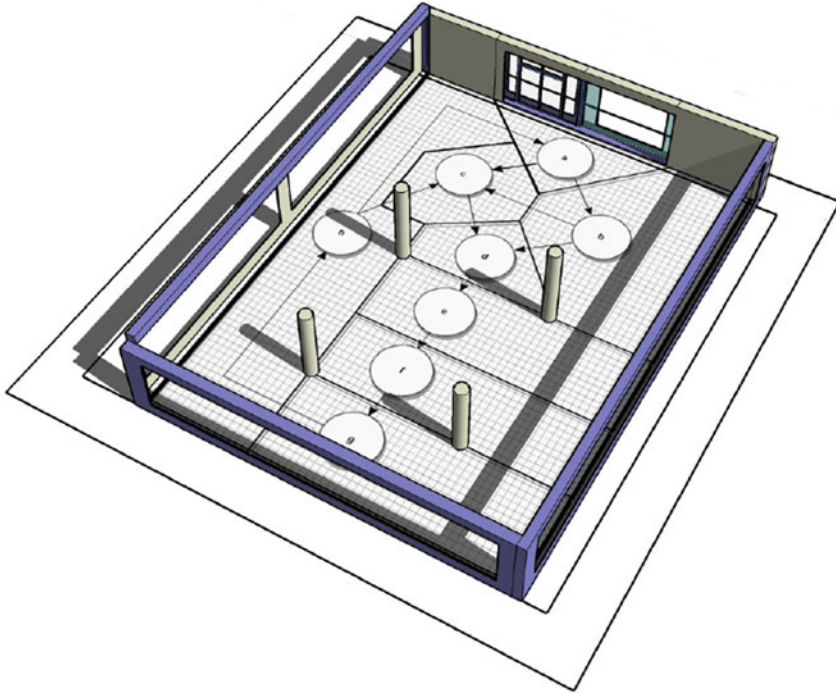


Fig. 1.7 Architectural development of plan

(e) Wall materials.

(f) Lighting, heating, ventilation requirements, and floor coverings.

The overall construction costs of the facility should include all the previous design decisions along with these structural, materials, and equipment decisions and the layout generation. The scope of such an undertaking requires that multiple disciplines besides industrial engineering be involved. These may include architects, structural, mechanical, electrical, and utility engineers.

Figure 1.7 illustrates the process of developing the facility. In the next section, we address some key definitions needed to understand facilities planning.

1.5 Manufacturing Systems Concepts

In order to provide a framework for our factory project, let us consider some of the essential concepts of manufacturing systems.

Nowadays, manufacturing facilities are viewed as part of a supply chain (Fig. 1.8) interconnecting raw materials, the manufacturing facility (highlighted node), warehouses, retailers, and customers. Flows of information between the facilities (orders

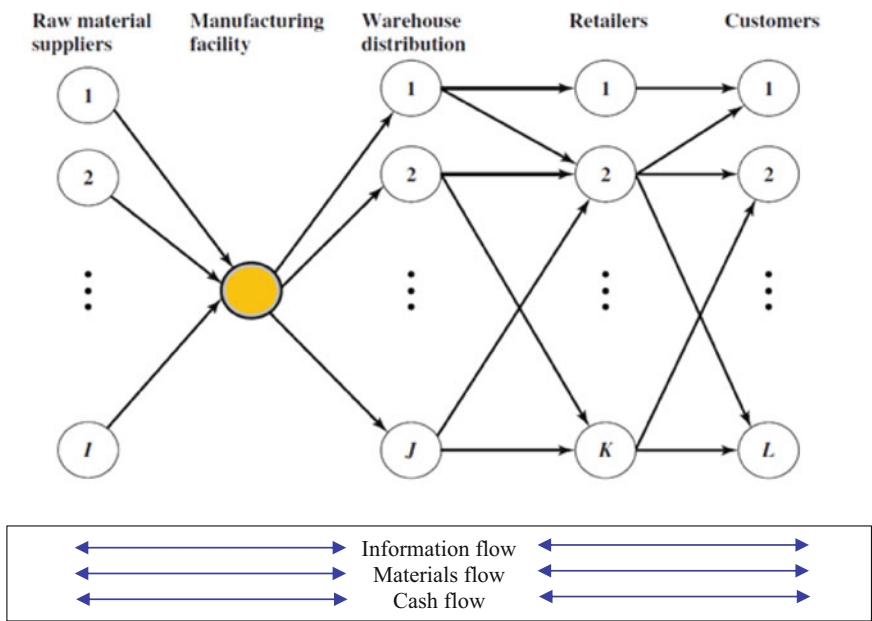


Fig. 1.8 Supply-chain network

for parts, and so on) are accompanied by flows of material as well as by the cash flows underlying all transactions.

One important concept is whether, and how much of, the raw materials and finished goods (warehouse quantities) will be housed in the manufacturing facility, since minimizing the inventory (having a “lean” facility) translates directly into profits. An important technology is that of radio-frequency identification (RFID), which is employed to provide information as a product flows along the supply chain. RFID tags are inexpensive microchips embedded in products, pallets, and other vehicles to transmit information about the product’s whereabouts to RFID readers (interrogators) and eventually to computers to process information along the supply chain [1]. These versatile tags provide important information about the product (such as location, inventory turns, processing costs, even quality information) to many manufacturing and service industries. Although not without critics of its cost in time and resources, it appears to be a significant step to providing timely information about products in the supply chain.

The purpose of manufacturing—manufacturing from an ideal point of view—is to make life in society better (remember the old GE commercial: “*We bring good things to life.*”) through the production of functionally desirable, aesthetically pleasing, environmentally safe, economically affordable, highly reliable, top-quality products. A manufacturing system performs the following essential functions:

- Product design
- Process planning
- Production operations
- Materials handling and transportation flow/facilities layout
- Production planning and control

Product design is responsible for taking input from marketing and for building a product. Process planning includes specification of operational sequences needed to transform raw material into finished product. Manufacturing operations are generally classified as forming (shapes are changed), treating (characteristics are changed), and assembling (material is added). Material handling is related to systems for moving parts, tools, and scrap. Facilities layout is concerned with the physical location of the production processes within each facility. Production planning and control is responsible for integrating marketing information, production capacity, and current inventory levels to determine production levels that will allow a firm to run smoothly and efficiently. More details about these processes, especially as they relate to the factory project, are provided in Chaps. 2, 3, and 4.

1.6 Types of Basic Manufacturing Layouts

Typical morphological layouts are described below. Most manufacturing layouts can be classified as either product or process layouts, or a combination of them.

- **Fixed-position:** material or major components brought together in a fixed location
- **Product:** low number of part types and high production volume
- **Cellular (group technology):** medium number of part types and medium production volume
- **Process (job shop):** high number of part types and low production volume

Three things can happen to material in the making of a product: it can be formed, treated, or assembled.

The classic types of layouts are the layout by fixed position, the layout by process, and the production line. During the last two decades, a fourth type has become important: the cellular layout (also known as the group technology layout).

1.6.1 Fixed-Position Layout

The fixed-position layout is one where the material or major component remains in a fixed place to which tools, machinery, people, and other pieces of material are brought together. Fixed-position layouts are used, for example, for airplanes, locomotives, ships, and other heavy machinery.



Fig. 1.9 Fixed-position layout

Figure 1.9 is an example of a fixed-position layout for the manufacture of gas turbines, steam engines, or airplanes. Here, we have compressed eight fundamental activities $\mathbf{a} = (a, b, c, d, e, f, g, h)$ associated with making a large gas turbine into one specific location. Obviously, the weight of the product is such that it is more efficient to move materials, machines, and engineers to work on the units than to move the turbines to various workstations throughout the plant.

1.6.2 Product Layout

The product layout (or production line) places one operation immediately adjacent to the next; the equipment needed is arranged according to the operational sequence. Figure 1.10 illustrates an example of a series of production lines for a high-volume production facility. The eight different production activities defined previously are associated with the eight different workstations along each of the product lines $1, 2, \dots, N$. Since the desired volume of the products is normally very high, dedicated production facilities with conveyors and other automated material handling devices are necessary in order to meet the production requirements. We shall have more to say about this type of layout example in later chapters.

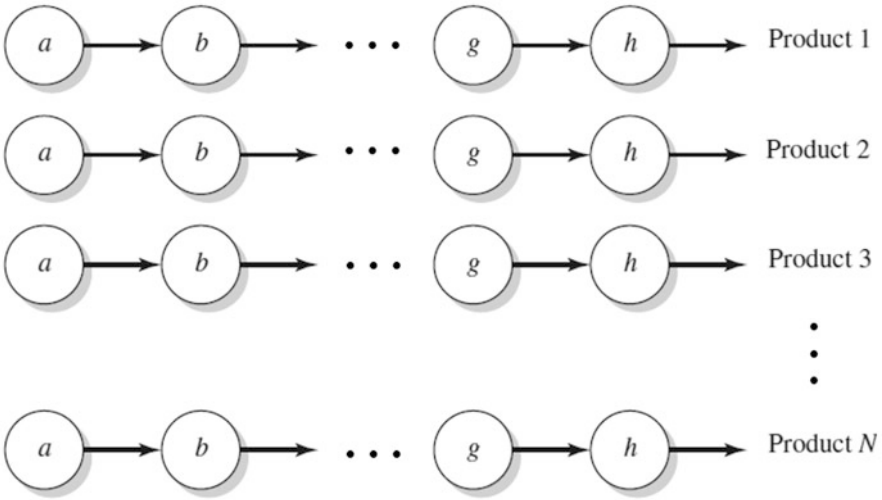


Fig. 1.10 Product layout

1.6.3 Process Layout

In the process layout, all operations of same type are grouped together along with the corresponding equipment to form production departments performing a common function. Figure 1.11 represents a job shop where large metal rolls are moved from one department (grinding, lathes, welding, and so on) to the next to complete the fabrication of the final product. Departments are represented by letters.

1.6.4 Cellular Layout

The cellular layout (or group technology layout) is based on the grouping of parts to form product families based on common machining requirements (and other aspects, such as shapes, material composition, and tooling requirements). This layout has a high part flow within cells and low flow between cells. Figure 1.12 illustrates a general configuration for a number of work cells arranged in a grid-like pattern. The work cell combines both manufacturing and assembly operations, so that it is very efficient, and the quality of each part is carefully monitored by the individual worker. This type of layout is often referred to as a “one-piece flow.” We shall have more to say in Chap. 8 about the dynamic material handling flow analysis of this type of layout.

Figure 1.13 provides details on the composition of a single cell designed to manufacture a small hand tool. The fabrication of small tools can be very different from the manufacturing of standard tools. Examples of these tools include holding

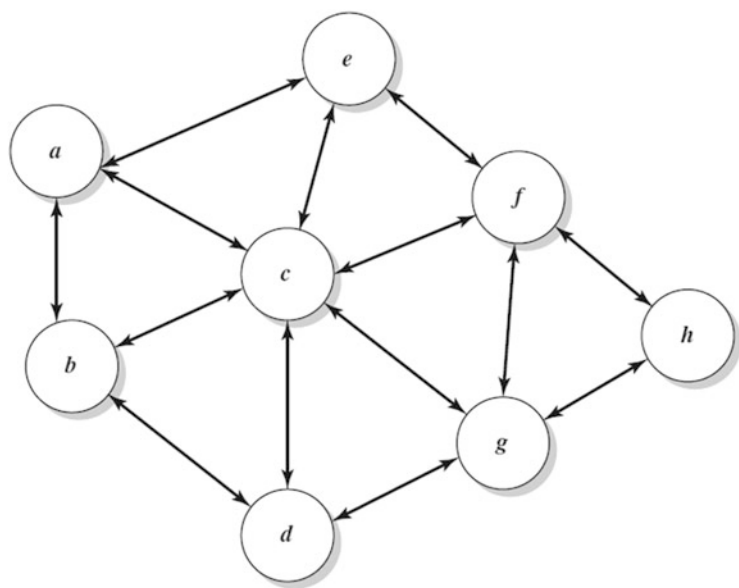


Fig. 1.11 Process layout

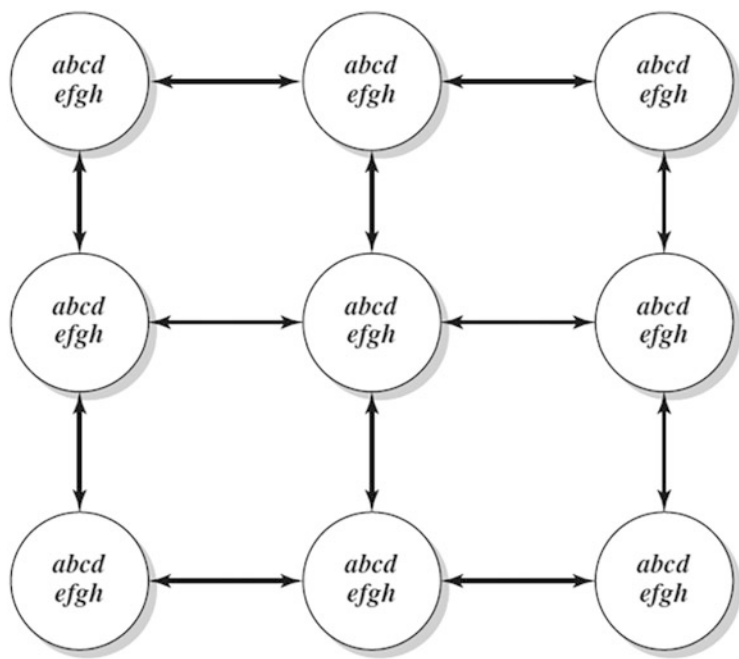


Fig. 1.12 Cellular layout

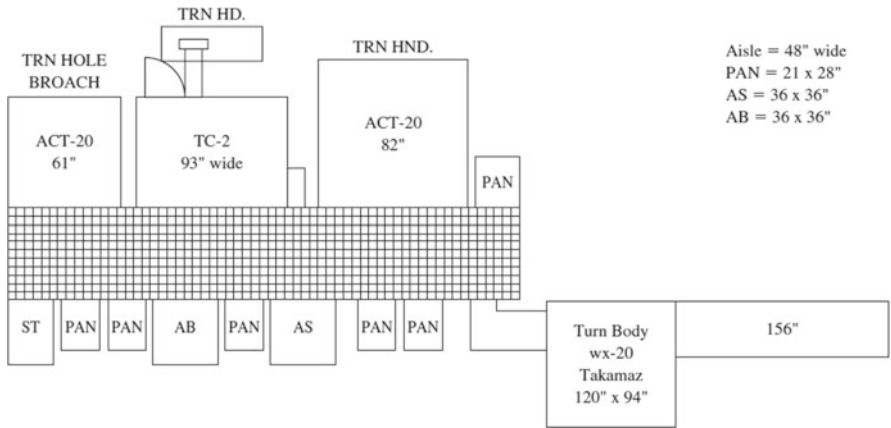


Fig. 1.13 Single-cell layout for manufacturing a small hand tool

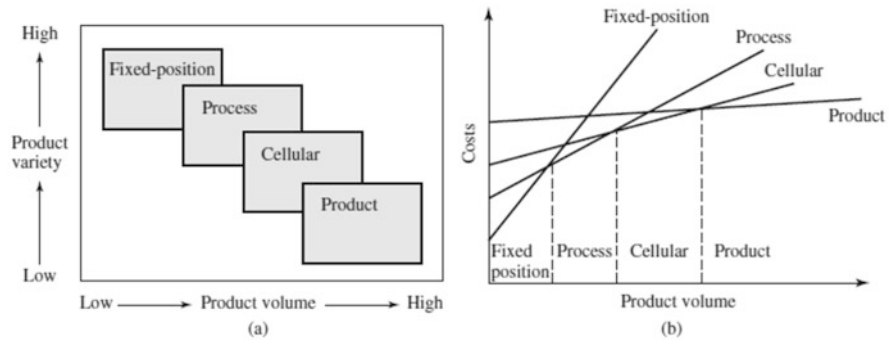


Fig. 1.14 (a) Product variety-volume and (b) cost-volume breakeven analysis

tools (clamps and pliers), striking tools (sledges and hammers), measuring tools, metal-cutting tools (reamers, files and drills), grinding tools, and sharpening tools.

From the point of view of product types and production volumes, the following generalizations are valid: (a) the production line layout is especially suitable for cases where the number of part types is low and the production volume for each type is high; (b) the process layout is especially suitable for cases where the number of part types is high and the production volume for each type is low; (c) the cellular layout is especially suitable for cases where the number of part types is neither low nor high and the production volumes are in the middle (between low and high).

A graphical breakeven-point comparison between the fixed-position, process, cellular, and product layouts is shown in Fig. 1.14. In part (a) of the figure, both product-variety relationships and product costs are compared with product volume. In part (b) we consider production volumes, costs (fixed and variable), and revenues. We show the total-cost lines, the revenue lines, and the break-even points for the four

layouts. As can be seen from this graph, the product layout is preferred for high-production volumes and the fixed-position layout for low-production volumes.

If F is the fixed cost, v the variable cost per unit, and r the selling price per unit, the production level Q corresponding to the breakeven point can be determined from the relationship $F + vQ = rQ$. This relationship states that the total cost is equal to the revenue from selling the product. Solving for Q , we get the breakeven quantity:

$$Q = \frac{F}{r - v}$$

1.7 Service Systems

Service systems include many different building types. The listing below is not exhaustive but indicates the range and variety of building types in the service arena.

Industrial Commercial industrial parks, public utility buildings, and nuclear power plants.

Cultural Courthouses, municipal facilities, police and fire stations, detention and correctional facilities, art museums, houses of worship, water parks, and aquariums.

Commercial Office buildings, banks, credit unions, department stores, shopping malls, art galleries, and boutiques.

Recreational Regional and urban park facilities, stadiums, arenas, dance halls, and nightclubs.

Educational College campuses, research laboratories, high, middle, and elementary schools, and day-care centers.

Medical Public hospitals, teaching hospitals, medical office clinics, nursing homes, and pharmacies.

Residential High-rise apartments, condominiums, duplexes, single-family residences, campgrounds and trailer parks.

Transportation Airports, railway terminals, bus stations, truck transit terminals, and shipping port terminals.

Notice that we have left out most of the infrastructure, which includes roads, bridges, walkways, utility systems, water reservoirs, tunnels, and the like. Some civil and mechanical engineers would refer to these as facilities, but we do not include them under our rubric of facilities planning.

Many detailed design problems within these building types go beyond the scope of this book. For instance, we could write an entire book on hospitals, which are among the most complicated facilities to plan and design, owing largely to their myriad building and service system requirements and sanitary concerns. Even art museums entail special considerations for lighting, heating, and ventilation, such that expert consultants often assist in their planning and design. Rather than treat

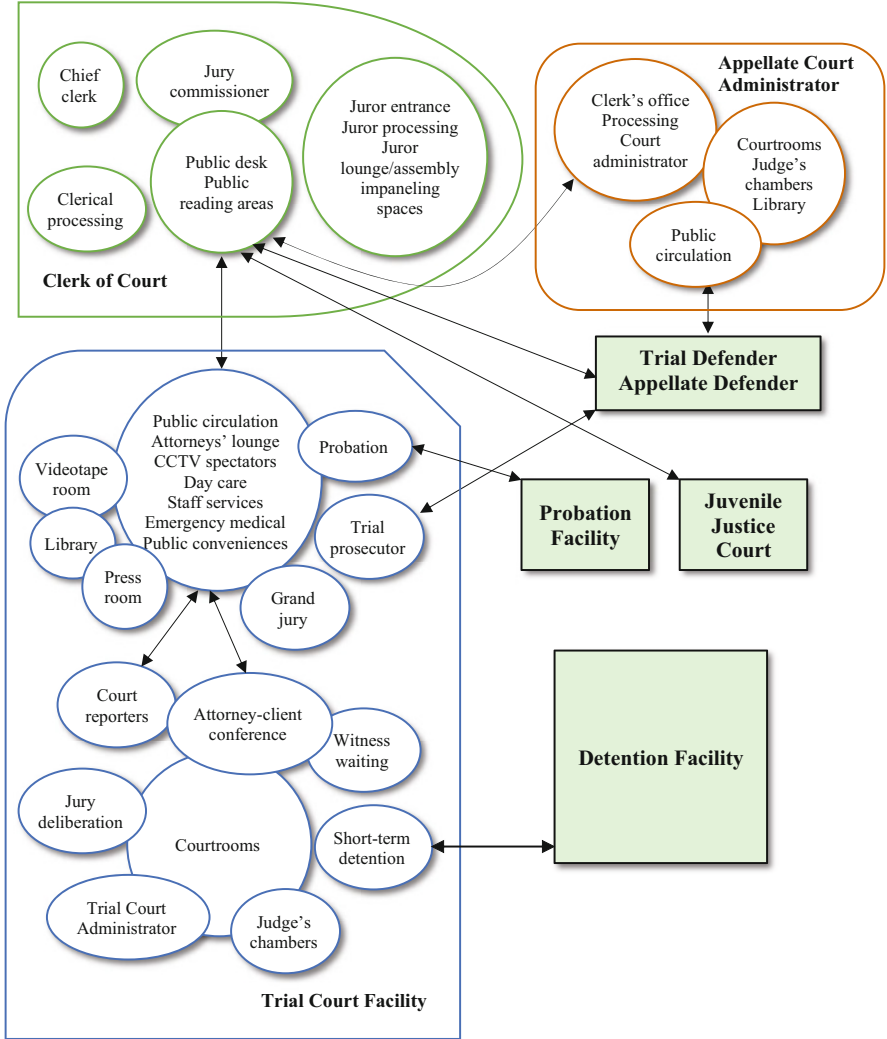


Fig. 1.15 Typical trial courts complex of buildings

each building type in detail here, we will focus on the general principles and fundamental methodology used in designing such buildings.

In the design of service facilities, while one may apply the notions of job shop or product layout, unfortunately there are no standard layout types as there are for manufacturing facilities. This is simply because of service facilities' broad scope and diversity of functions. One convenient categorization in the service sector is public vs. private, yet that does not provide a useful functional dichotomy.

Figure 1.15 is a planar graph of activities of a public trial courts complex, where the key activities involved in trial courts planning have been identified [9]. The

planning problem is very complex because of the number of people who use the facility.

As in a manufacturing facility, once the key activity vector $\mathbf{a} = (a_1, a_2, \dots, a_n)$ is identified, one has significant idea of the organization and eventual layout plan for the facility.

1.8 Renovated or Reengineered Facilities

Often a brand-new facility is not warranted; a remodeled or renovated facility is more appropriate (see Chap. 12). Often, too, a new facility is appended to an existing one. Reengineered facilities can become more difficult to design than a brand-new facility because of the constraints imposed by the existing facility (e.g., existing locations of columns, walls, stairwells, and so on). Sometimes the problems of reengineering are such that it is simply easier to construct a brand-new facility from scratch. Often, too, the building codes that applied to the older facility are outdated and the new building codes must be respected, which compounds the design problems of reengineered construction. For further details about reengineering and remodeling existing structures, see Chap. 12.

1.9 Facilities Planning and Design Constraints

In the creation of a facility, many external factors come into play, including the following ones:

- Building codes and zoning ordinances.
- Fire, health, and safety considerations.
- Structural and environmental constraints.
- Utility systems (heating, power, water, and light).
- Environmental and energy system constraints.

Rule books provide explicit constraints on the sizes and shapes of elements within and outside a facility. Some of these constraints are very helpful, while others are severely limiting. We shall have more to say about these concerns in Chap. 12.

1.10 Summary and Conclusion

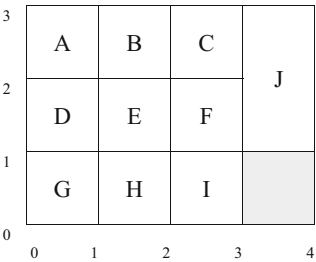
This chapter has provided a brief overview of the fundamental principles, concepts, definitions, and basic design processes of facilities planning. In summary, some fundamental principles are:

1. Design is an activity.
2. Design problems are wicked problems.
3. The activities of a facility and its graph realization $G(N,A)$ form the foundation of the facility layout.
4. The design process has three fundamental hierarchical stages: conceptual design, parametric design, and detailed design.
5. A design system is basically an issue-based information system (IBIS).
6. The facility plan depends on the dynamic resolution of the IBIS planning issues over time.
7. Most manufacturing layouts are either a product, process, fixed-position, or cellular layout, or a combination of these.

In Chap. 2, we illustrate the detailed process of designing a manufacturing facility and its material handling system—the factory project—which is the integrating and unifying concept of the book.

1.11 Exercises

- 1.1 Give a definition of *design* (in your own words) as it relates to your factory design project.
- 1.2 List and explain (in your own words) the ten key characteristics of *wicked problems*. Relate these characteristics to your own factory design layout problem.
- 1.3 What are the basic objectives of *facilities planning*?
- 1.4 What are the four different types of layouts for a factory? Visit a local manufacturing facility, take a plant tour with your classmates (if possible), and try to characterize the layout into one of the four basic layout types. If it does not exactly fit one of these types, describe the differences and similarities to the four basic types of layouts.
- 1.5 For the factory project, what type of layout discussed in this first chapter do you think would be most appropriate for your factory?
- 1.6 Visit a local fast-food restaurant, coffee shop, or donut and pastry shop. What are some design, contextual, and performance variables that underlie the design of the service enterprise? List at least seven items in each category.
- 1.7 An example layout of a factory plant with ten departments (A, B, C, . . . , J) is shown. Each department occupies one cell except department J, which occupies two cells. Draw the planar graph representation of the layout, then develop a new layout alternative by moving department J in such a way that no arcs cross one another. Then generate a new plant layout. This is referred to as “topological juggling” of the planar graph. Disregard the scale and size of the areas of the departments.

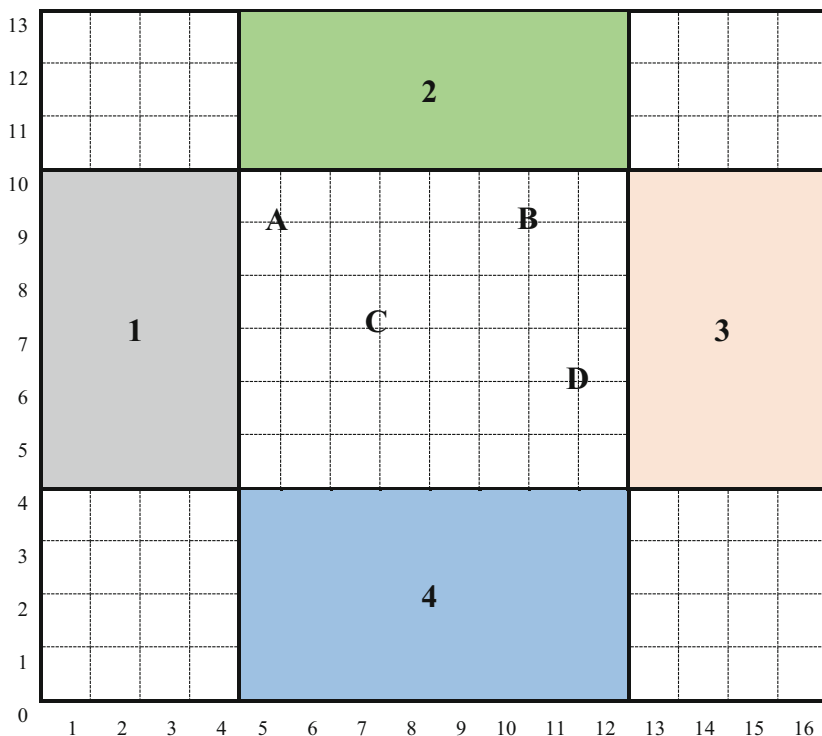


- 1.8 Visit a local post office or fast-food restaurant and identify the way customers enter and leave the facility and interact with the service staff. Create a process flow diagram “planar graph” and identify any problems that occur in the service process—unusually long delays, excessive queuing, crossing of traffic patterns, backtracking, and the like. Suggest some simple improvements to the layout by moving certain stations or changing the way people move through the facility and interact with the staff. Propose a revised layout based on your analysis.
- 1.9 Make a floor plan of your dorm room or apartment on a scale of $\frac{1}{4}$ inch = 1 foot. Use AutoCAD or a similar layout tool. Use a suitable grid to help you to scale the plan and make sure the dimensions are correct. Identify and make paper cutouts of movable furniture and equipment. Identify the design, contextual, and performance factors that you consider crucial to the success of the layout, and develop at least two alternative arrangements. Based upon your analysis choose the recommended plan.
- 1.10 A small factory makes 1000 units of a certain product per day. This product has five parts A, B, C, D, E. One unit requires the assembly of 4A’s, 3B’s, 2C’s, 1D, 1E. The sequence of departments (1, 2, 3, 4, 5) for the production of each part are: Part A: 1-2-3-5, Part B: 2-5-2-3-4, Part C: 1-3-3-4-3, Part D: 4-3-5-1-2, Part E: 3-4-5. The following matrix shows the volume of parts as they flow through the plant:

Department	1	2	3	4	5	Total	Area (ft ²)
1		AD 5000	C 2000			7000	1500
2			AB 7000	C 2000	B 3000	12,000	2000
3		C 2000		BE 4000	AD 5000	11,000	3000
4			CD 3000		E 1000	4000	2000
5	D 1000	B 3000				4000	1500
Total	1000	10,000	12,000	6000	9000	38,000	10,000

Suggest two alternative layouts, using cutouts of the departments (as square as possible) and a grid layout on a sheet of paper. Based on the data given and your analysis, justify your layout. (More about from-to matrices will be discussed in Chap. 4.)

- 1.11 Shown below is a grid layout of a facility complex where there are four existing departments around a central courtyard or circulation space area for material handling and setup and storage. A new facility to service the four departments is going to be located at one of the four points on the grid in the courtyard.



You wish to find the location of the new facility {A, B, C, D} that minimizes the total distance traveled in *two-way* trips to and from the existing departments. The number of two-way trips per day is (10, 20, 15, 30) in that order, respectively. Assume that travel is initiated from the central location of the departments, as indicated by their numerical location in the grid. If you wish to minimize the total distance traveled for all departments, which alternative location is the best one?

- 1.12 In Exercise 1.11 if you want to find the grid-point location within the courtyard that minimizes the total number of two-way trips for all departments, which location is the best? (More will be discussed about this type of location problem in Chap. 5.)

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Chapter 2

Factory Layout and Material Handling Project



2.1 Introduction

This chapter presents a factory design project that will serve as a unifying concept for the organization of the book and as a connector of the topics typically covered in a course on facilities planning and material handling. The factory design project has been extensively tested at Texas A&M University, the University of Massachusetts at Amherst, and the University of Tennessee at Knoxville. It is developed within a conceptual approach that emphasizes the use of information-based manufacturing strategies.

Students are required to design a plant layout for the production of some mechanical device. In order to promote the team approach, groups of three to four students will be allowed for each project. The selection of the device is up to the students, although it requires the approval of the instructor. Suitable devices typically chosen include staplers, tire pumps, master brake cylinders, popcorn poppers, desk fans, desk lamps, and the like. Each group will assume responsibility for the development of the entire laboratory design project. Although this project is in reality a *simulation exercise on facilities design*, it is intended to prepare students for work after graduation.

The use of computers and analytical procedures during the development of the design project is highly encouraged—not only for putting together the documentation reports and project presentation, but also, more significantly, for drafting, conducting computer simulations, solving mathematical models, and other procedures found to be necessary or desirable to support the proposed design. The general scope of all available relevant computer codes will be briefly described and their use demonstrated in lab sessions.

AutoCAD must be used to prepare all required drawings—for two reasons. First, although most companies have a specialized person to do all the drafting needs, normally it is difficult to convey a design concept to this individual. Second, many companies complain about their engineers' lack of drawing and printing skills.

Most if not all the laboratory work required can and should be done during the laboratory sessions. The overall project process will be divided into six sections, each one requiring a report to be reviewed and graded. After each section report is returned to each team, it must be revised according to the requirements and suggestions identified in the review process.

Besides the introduction, this chapter has seven sections and an appendix. Section 2.2 provides a project overview. Section 2.3 identifies the main activities related to product design in the overall project. Section 2.4 gives fundamental directions about parts manufacturing. Section 2.5 focuses on layout planning. Section 2.6 addresses the general aspects of personnel planning. Section 2.7 offers an overview of office layout planning. Section 2.8 provides directions on how to recommend the final layout. The Appendix at the end of the book describes the computerized decision-support methodology used in the calculation of the unit cost of the product in the factory design project.

2.2 Project Overview

This chapter provides an integrated conceptual view of facilities planning and material handling. A hypothetical project will be used as the spine or interconnector of the various models and procedures studied in this book.

Designing a manufacturing facility layout may become a complex undertaking, depending on the number of factors affecting the performance of the facility, as well as the variability of relevant data required to conduct a sound, logical, and systematic study. This complexity, however, can be reduced somewhat by breaking down the overall project into sections or tasks that are more easily managed. Our factory layout and material handling design project is divided into six sections:

Section I: Product design

Section II: Process design

Section III: Layout planning and material handling

Section IV: Personnel requirements and calculation of product's total unit cost

Section V: Office layout

Section VI: Plant layout

Following a well-defined approach, the information from these sections, once completed, will be synthesized and integrated into a final layout.

The purpose of Section I is to provide a fundamental understanding of the product or products that will be manufactured at the plant. Without such knowledge, any further work will be shadowed by uncertainty concerning the feasibility or desirability of a proposed layout. Four information components provide the essential knowledge required in Section I: production drawings, assembly drawing, parts list, and assembly flowchart. Production drawings document the shape and dimensions of the specific parts to be manufactured. They shed light on actual manufacturing operations required. Assembly drawings show the relative position of the individual parts in the final assembly. The parts list indicates which parts are purchased or

manufactured and summarizes the quantity of each part in the final product. It may also include special remarks relevant to a specific part (for example, weight, material, or special fabrication processes). The assembly flowchart documents how the individual parts are linked together as subassemblies, and how the subassemblies and major assemblies become the final product. Inspections are also usually indicated in this chart.

Once the essential information on the product is obtained from Section I, decisions must be made on how to actually manufacture each part chosen for fabrication. The purpose of Section II is to document the corresponding operational sequence required to manufacture each part. The document summarizing this information is known as a production route sheet. For each operation listed on a route sheet—one sheet for each part or subassembly—specific machine types, brands, models, and capacities need to be determined and indicated. Additionally, where appropriate, the specific type of material required and the corresponding quantity needed in each operation must be documented. Evidently, machine and material requirements depend upon a predetermined capacity at which the plant is expected to operate.

After it has been decided what product or products will be manufactured and which operational sequences will be required, Section III focuses on how the parts and materials will be moved within the plant. The required material handling system can be identified with the aid of layout planning charts and material requirements tables. Layout planning charts document fabrication operations, moves between manufacturing departments or to individual workplaces, storage operations, and inspections. For fabrication operations (either treating or assembling operations), these charts also summarize relevant information, such as standard times, machine types and quantities, manpower requirements, and material handling equipment. Since the layout planning charts force a detailed analysis of every move of each individual part, the task of selecting material handling systems that will effect a good material flow throughout the plant is made easier.

As decisions concerning machines, materials, and handling systems are made, the associated costs are also computed to aid in estimating the total operation cost of the proposed plant. An important variable cost not yet considered is the personnel cost. Specifically, the purpose of Section IV is to identify the type of personnel required along with the corresponding cost. It should be remembered that production personnel (mostly machine operators and assembly workers) are only a portion of the total plant staffing requirement. Indirect costs, such as those associated with management and office personnel, can be established on the basis of an organization chart. Support personnel, such as janitors and nurses, should also be included. Once the staffing requirements are completed, expected salaries can be determined, as well as benefits besides the salaries. The total personnel cost can then be computed.

Once Sections I through IV are successfully accomplished, there is enough information to begin developing an actual layout of the plant. This is the most important phase of the entire planning function, since the layout determines the following critical elements of the overall facility design: (a) how much space will be allocated to each planning department; (b) relevant material flow or closeness relationships between different departments; (c) location of manufacturing

equipment and personnel. This is also the stage where all final details, such as restrooms, office equipment, and shipping and receiving areas, are established. As a check to determine the suitability of the proposed layout, a material flow overlay should be made to trace the path of the individual parts throughout the plant. This chart will highlight any major problems with the material flow.

Determination of the physical arrangement of workstations and the associated material flow overlay will bring the layout process to conclusion. The resulting layout provides an effective picture of what the plant will be like and can be used to communicate a wide variety of manufacturing information. At this point, both the total annual cost of the plant and the per-unit cost can be calculated in order to provide input for deciding whether to build the plant.

Section V focuses on the office layout for the personnel identified in Section IV. Finally, Section VI generates the final total layout for a factory.

In summary, this is a design course where the knowledge learned in a number of engineering courses, especially those in the area of industrial engineering, can and should be integrated to develop an effective and efficient plant layout. The factory project can be accomplished by groups of three to four students. It is a factory design simulation exercise that includes all significant phases of a real-life process. Students are expected to apply some analytical techniques and computerized procedures discussed in the course to enhance their decision-making process and justify some of the most challenging courses of action.

2.2.1 Computerized Format Files

The following files are available for documenting the results obtained in the project. Each file has a name consisting of (a) project section number after the initial letter *s*, (b) initials of document name, and (c) MS Word document extension.

Section I

s1pl.docx: parts list

Section II

s2rs.doc: route sheets (production routings)

s2mrt.docx: machine requirements table

s2mct.docx: machine costs table

s2mmr.docx: material requirements table

Section III

s3lpc.docx: layout planning charts

s3mht.docx: material handling requirements

Section IV

s4prc.docx: personnel requirements and costs

The format and organization of each document can be seen by opening the corresponding file. A brief description of each document is provided in Sects. 2.3, 2.4, 2.5 and 2.6 of this chapter.

2.2.2 Basic Documents

In the first session of the laboratory factory design project, each group of students disassembles the device for which a facility layout is going to be designed. All parts are identified and enumerated in the parts list provided by file **s1pl.docx**. Most of the parts are manufactured and a few of them will be purchased.

The route sheets for the parts to be manufactured in the facility are prepared and documented in the **s2rs.docx** template. These sheets contain the standard times for performance of each manufacturing operation or process. These standard times enable us to estimate the machine requirements, which will be documented using the **s2mrt.docx** template. The necessary equipment will be purchased after a careful review of possible vendors. The costs for the machinery will be tabulated using the **s2mct.docx** template. The materials required for the fabrication of various parts are documented in the **s2mmr.docx** template.

Layout planning charts are detailed documents that contain essential information on various steps followed in the manufacturing or assembling of parts. These charts are prepared using the **s3lpc.docx** template. They identify material handling requirements and costs documented in the **s3mht.docx** template.

The factory direct and indirect personnel along with the associated salary information will be documented using the **s4prc.docx** template.

The plant layout summary template (**summary.docx**) is designed for documenting all cost components of the project. It is useful in analyzing total annual costs, unit costs, and profit margins. The **Unit Cost Template.xlsx** calculates the cost per unit of the product selected for the factory design project. Instructions for using this template are given in Section IV of the project (Chap. 11).

2.2.3 Project Report

A report documenting all procedures and findings must be written using a word processor, such as MS Word. A template document (file **template.docx**) and templates for all required tables will be provided in computer files that can be easily accessed by the students. These templates have been designed using MS Word and can be efficiently modified by the students to include specific relevant information on their application.

The report must include a title page (see the document template), a summary sheet (file **summary.docx**), an introduction section, and additional sections to document the specific achievements of each of the six sections of the factory layout design

project. A final section of the report should be devoted to an overview of work done, conclusions, and recommendations. Sample calculations as well as additional relevant material should be placed in an appendix. After each section of the project is finalized, the report should be submitted for grading and recommendations on how to improve it.

2.3 Section I: Product Analysis

- Production drawings
- Assembly drawing
- Parts list
- Assembly flow charts

The design project begins with the collection of information that will serve as the foundation for any future analysis in the factory layout design process. This section of the project aims to provide adequate answers to the following four questions: (1) What product will be manufactured? (2) What parts does the product have? (3) Where are these parts obtained? (4) How will the parts be used to manufacture the product? The required relevant information will be classified as production drawings for individual parts, an assembly drawing for the product, the corresponding parts list, and an assembly flowchart.

The production drawings provide essential information about the shape, dimensions, materials, and other relevant manufacturing-related aspects on the parts to be produced. Often this information can provide details that help in the selection of manufacturing processes and operations. The assembly drawing shows an exploded view of the product. It helps us to visualize how the individual parts are put together in the final assembly.

The parts list provides a summary of all the parts needed for an assembly. It shows manufactured parts as well as those purchased, along with the required quantity of each. It also includes special remarks, if any, relevant to specific parts.

The assembly flowchart serves as a graphic representation of how to assemble the entire product. It shows how the individual parts are linked in subassemblies and major assemblies as the final product is put together. Usually it shows inspections.

As the above information is obtained, it develops a broader understanding of the product, serves as a knowledge base for the layout designer, and can be used to proceed effectively into the initial stages of the desired factory layout design.

2.3.1 Production Drawings

There is no realistic way to design the layout of a plant without knowing the product in detail. As a growing number of factors enter into the decision-making process to

the specific operational sequences required to manufacture each individual part, the production drawings become more and more valuable to the layout designer. Besides detailing the physical dimensions of the parts, these drawings also give information on materials, tolerances, and surface finishes.

The assembly drawing, while not showing how the product is put together, does show the relationship among the parts. It will be useful later on when decisions are made about specific ways to assemble the final product.

At this stage of the project, each team—consisting of three to four students—should have a mechanical device disassembled. The decision must be made, and verified by the instructor, as to which parts will be manufactured and which ones purchased. Only 20 parts need to be considered individually, with all other parts regarded as a kit. Each team must manufacture 12 parts and purchase 8. Once this decision has been made, each team is required to make detailed sketches of the parts to be manufactured, with each team member drawing an equal number of parts on AutoCAD. The sketches must show all the dimensions with accuracy within one-hundredth inch. They may not be to scale but must be proportional.

2.3.2 Parts List and Identification System

The parts list not only indicates which parts are to be manufactured or purchased, but also provides the quantity needed, types and quantities of materials required, and special manufacturing-relevant remarks for each specific part. Each part is listed along with an identification code, which can be useful in finding more detailed information. The cataloging, storing, and manufacturing routings (machining sequences) information can be enhanced through the use of this coding system.

The parts list is essentially a table with a heading including the name of the product and one row for each part. Typically, a parts list table has the following entries on each row: part identification code, part name, quantity, material, weight, and whether the part is manufactured or purchased. The identification system must be designed and fully explained. File **s1pl.docx** contains the format of the parts list.

2.3.3 Assembly Flowchart

The assembly flowchart provides a graphical representation of how to assemble the entire product. It helps us to visualize the flow of components entering into a product and shows the logical sequence of assemblies, subassemblies, and inspection stations. Assembly stations are usually denoted by circles labeled A1, A2, A3, and so on. Similarly, subassembly stations are denoted by smaller circles with labels SA1, SA2, SA3, and so on. Finally, inspection stations are represented by squares labeled I1, I2, I3, and so on.

The basic function of an assembly flowchart is to show the sequence of operations and inspections in an assembly process. One of the parts must be chosen and designated as the base part. This should be the one that logically would be picked up first, and to which all other parts are sequentially attached. The assembly chart graphically depicts the sequence of assembly operations and inspections from start to finish, including packaging and shipping. It includes the company name and product and each individual part name and number. The assembly flowchart is drawn using AutoCAD on 10" × 16" paper.

2.4 Section II: Parts Manufacturing

- Manufacturing route sheets
- Machine requirements table and costs
- Material requirements table and costs
- Machine drawings

The design of a manufacturing facility can be viewed as a logical progression of steps. After the initial planning of what parts are to be produced in the plant, the production drawings and the assembly flowchart are studied in detail to determine how to best produce the parts. Specific manufacturing processes and operations must be identified in an efficient sequence to produce each part. These sequences are documented in route sheets.

The layout designer needs to determine the specific type and capacity of every machine required for conducting the operations listed in the route sheets. Once the machine requirements are consolidated by type, specific machine brands and models are selected that best suit the plant's expected needs.

Using information from both production sketches and production routings, we can assess the material requirements for the plant. In this assessment any losses due to scrap should be included, since the cost of the scrap contributes, sometimes significantly, to the overall cost of the product. Usually, the material requirements and associated per-unit material cost are expressed on a weight basis.

Both the machine and material requirements are contingent upon the capacity at which the plant expects to operate. These data, along with a good approximation of the future cost involved, will bring the plant layout one step closer to reality.

2.4.1 *Route Sheets*

The format for the route sheets is available in file **s2rs.docx**. Each sheet shows the sequence of fabrication and assembly operations required to manufacture a particular part. The route sheet for the base part includes the entire assembly process. However, the sheets for the other parts do not need to show the entire assembly process

because, typically, parts are taken to storage facilities after being manufactured and are later on retrieved to form subassemblies.

Route sheets are important because they contain critical information required to perform further analyses, such as the determination of machine and material requirements. Typically, route sheets contain the following information:

- Part name and number
- Drawing number and lot size
- Operation number
- Operation description
- Jigs, fixtures, or tools required for operation
- Machine type
- Standard time and machine capacity/hour
- Material requirements (type and quantity)

2.4.2 Machine Requirements and Costs

This information is summarized in a table, which lists the total number of machines required, by type, to manufacture each part. Specific machine brands and models are indicated, along with their costs and space requirements.

The total cost of the machines represents the initial capital investment, while the annual cost reflects the depreciation of the machines over a specified multi-year period. The expected salvage value of all machines is usually expressed as a percent of the initial cost. In the calculation of the total cost per machine all shipping and handling charges, installation fees, and all other costs associated with making the machine operational must be included.

2.4.3 Machine Requirements

The format for the machine requirements table is available in file **s2mrt.docx**. This format is designed for detailing and summarizing the number of machines required by part number and operation number. Machine requirements will be calculated on the basis of an availability percent, a specified number of setups per day along with the corresponding setup times, required production volume, the length of the daily production period, and the standard time of the machining operation.

The availability percent indicates the fraction of a production period during which the machine is up for working on a particular part of the given product. In the absence of a more accurate figure, it can be assumed that machines will be available to do work 90% of the time, with the remaining time being required for maintenance and repair work. In the layout design project, each group will assume that one daily

setup taking 0.20 hours will be required per machine. Additionally, if not specified otherwise, the plant will be assumed to operate 8 hours on each work day.

The fractional number of machines needed can be calculated using the expression

$$N = \frac{Pt}{(H - s)p}$$

where

N = number of machines

P = daily production volume

t = standard time

H = available time

s = setup time per day

p = availability factor (as a decimal fraction)

As a sample calculation, assume that the production rate is 1600 pieces per day and the standard time of a particular machining operation is 0.015 hour per piece. Using the above formula, $N = \frac{1600 \times 0.015}{(8 - 0.20) \times 0.90} = 3.41$. If an integer number is required, $N = 4$ machines must be purchased.

2.4.4 Machine Costs

The general format of the machine cost table is provided in file **s2mct.docx**. This format allows the listing of each machine along with a short description, the number of identical machines required, space requirement per machine, purchase cost per machine, and the total cost of identical machines. The overall annual depreciation cost for all machinery will be computed using the straight-line technique, although other techniques will be acceptable. If not specified otherwise, it will be assumed that the service life of the manufacturing equipment is 15 years and the salvage value is 10% of the purchase cost. As a sample calculation, if the total machine cost is \$1,200,000, the annual depreciation cost will be estimated as $N = \frac{1,200,000 - 120,000}{15} = 72,000$.

2.4.5 Material Requirements

The format of the material requirements table is provided in file **s2mmr.docx**. The table shows the amount and type of each material used to manufacture each part. Material requirements and material costs are given on a weight basis. The total amount of each type of material should include the corresponding scrapped quantity. As an example, material requirements for parts cut from sheet stock must allow for

the blank size and the quantity scrapped. Whenever appropriate, purchased items are given on a cost per unit basis.

2.4.6 Machine Drawings

Layers are an important and necessary component of AutoCAD drawing. The machine drawings for this project must be done and plotted using a $1/4'' = 1'$ scale and must include the following layers:

- Layer #1: Outline of machine
- Layer #2: All text
- Layer #3: Cross-hatching of machine
- Layer #4: Operators figure
- Layer #5: Work area of machine (usually 4' around machine)
- Layer #6: Dimensions of machine

2.5 Section III: Layout Planning

- Layout planning charts
- Material handling requirements
- Material handling costs

After determining in Sections I and II what products will be manufactured and how they will be manufactured, respectively, we now emphasize how to efficiently move parts and materials within the plant. Material handling is basic to all manufacturing processes. Raw materials must be delivered to the places where they will be processed, and the final products must be stored and then distributed to the customers. This is a function that cannot be avoided, but can always be improved.

The specific purpose of this section is to generate three types of documents: layout planning charts, material handling requirements, and material handling costs. The layout planning charts allow an integrated analysis of every operation, move, storage, and inspection that take place in the process of transforming raw materials into components of the product to be manufactured. Once the material handling requirements have been established, specific equipment and accessories need to be identified. At this time, the cost due to material handling can be determined. The specific material handling systems and associated costs can be summarized in tabular form along with a total material handling cost figure.

2.5.1 *Layout Planning Charts*

One of the most important tools the designer uses in defining the material handling requirements of a plant is the layout planning chart, available in file **s3lpc.docx**. This chart documents the sequence of operations performed on a particular part. In this sequence the following operations are considered:

- Fabrication (F)
- Move (M)
- Storage (S)
- Inspection (I)

Along with each operation, the chart specifies the time per piece required for the action, the machine type and required number of machines, the manpower requirement, and the material handling requirements.

By analyzing each operation in the sequence documented on a layout planning chart, the designer is forced to determine how often a type of operation (F, M, S, I) takes place, the most effective type of facility for the operation, and the associated manpower requirements. In particular, the information on type of moves, frequency of moves, origins and destinations of moves, quantities being moved, and time required by each move is essential in selecting the most effective and efficient material handling system, as well as in balancing machine utilization and manpower.

2.5.2 *Material Handling Requirements and Costs*

One of the most important decisions made during the design of a plant is the selection of material handling systems to provide a good material flow throughout the plant. The layout planning charts are useful in determining what methods might best be used. Typical material handling equipment can be classified as conveyors, hoists/cranes, and industrial trucks.

A preliminary sketch of the proposed layout often helps to clarify specific requirements of the material handling system. For example, it helps the designer to better visualize machine interactions and provides a basis for later on selecting the specific type of equipment needed, its size, its capability, and so on. The costs of individual components of the material handling system are itemized in the material handling requirements and costs table, available in file **s3mht.docx**. The total cost of each piece of equipment should include shipping and handling charges, installation fees, and all other costs required to make the equipment operational. The table also shows the annual cost (depreciation) of each piece. The material handling cost per unit of product is determined by dividing the total resulting from the consolidation of all equipment annual costs by the annual production volume. If not otherwise specified, in this project it will be assumed that the service life of the material handling equipment is 10 years, and the salvage value is 10% of the purchase cost.

As an illustration of the computation of the material handling cost per unit, let us consider a towline. Assume that the required length is 900 feet. Moreover, the cost per foot is \$210, and the installation cost per foot is 40% of the purchase cost. As can be verified, this results in a total cost equal to \$264,600. The salvage value can be estimated as 10% of the purchase cost, \$18,900. On the basis of this, assuming a straight-line depreciation model, the annual cost is calculated as $\frac{264,600 - 18,900}{10} = 24,570$. If, after proceeding in this manner, the total cost for all equipment (including installation) is \$1,130,460 and the total salvage value is \$80,747, the corresponding material handling cost per year will be equal to $\frac{1,130,460 - 80,747}{10} = 104,971$. Moreover, if the annual production volume is 260,000 units, the corresponding cost per unit will be $\frac{104,971}{260,000} = 0.40$.

2.6 Section IV: Personnel Planning

- Personnel requirements and costs
- Corporate structure
- Unit cost

This section of the project will estimate personnel requirements and costs and calculate the cost per unit for the first operating year. By using the layout planning charts developed in Section III, we can determine the number of people directly necessary to produce the required units of finished product each week. The production personnel, however, are only a portion of the plant's total staffing requirements. It is recommended to use the corporate structure or organizational chart of the company to aid in the determination of indirect (management and office) personnel needed. This includes the plant manager, supervisors, engineers, accountants, maintenance staff, salespersons, and so on.

As various stages of the plant design are completed, the corresponding cost components are identified and quantified. Still, questions concerning the profitability of a product cannot be answered until the entire cost per unit has been calculated. The cost per unit for the first operating year is based upon material, material handling equipment, machine requirements, and personnel costs.

2.6.1 *Personnel Requirements and Costs*

The personnel requirement costs table is provided in file **s4prc.doc**. The exact number of people required to achieve the desired production level as determined in Section II must be established at this stage of the project. All personnel requirements documented in the layout planning charts of Section III are consolidated by type. It is noted that this total does not include any indirect labor, such as supervision, engineering, personnel management, payroll and accounting, medical services,

sanitation, and maintenance. The costs (salaries) for all personnel should be estimated based on current day wages, cost of living, and inflation rate.

2.6.2 *Unit Costs*

The labor cost per unit can be calculated by dividing the total labor cost per year by the annual production volume. This can then be added to the cost per unit of machines, materials, and material handling equipment, all of which have been previously determined. The cost per unit for the first operating year is a very useful piece of information, because it is the basis on which the selling price can be determined after adding the desired profit per unit. The cost per unit can also serve as an index that management can use to track the cost components of the product.

2.7 Section V: Office Layout

- Activity relationship chart
- Alternative office layouts
- Selected office layout

This section will determine how the offices should be physically arranged to efficiently accommodate the personnel identified in Section IV, according to the relative importance reflected by the closeness codes of the relationship chart.

After determining several alternatives to link workstations into offices, a recommended office layout must be generated using AutoCAD. Each member of the project team must propose an alternative office layout. Each drawing should be done using a $\frac{1}{4}'' = 1'$ **scale** and should represent a $50' \times 60'$ area (approximately). Interior wall partitions should be 6" thick. The **minimum** items required for the office layout are:

- Offices
- Furnishings
- Door swings
- Conference room
- Reception area
- Restrooms
- Workroom with storage and copying capability
- Identification of equipment, areas, and offices

2.8 Section VI: Recommended Plant Layout

- Systematic layout planning
- Proposed plant layout
- Material flow for selected parts

A substantial number of hours of planning and analysis go into the design of a manufacturing facility. One of the final stages before the construction phase is the development of a plant layout showing a material flow overlay. This allows the planner to see how the plant will actually look, and to make adjustments and last-minute changes before it is built.

Perhaps to a greater degree than any other engineering discipline, industrial engineering means the *reengineering of the factory floor*. Indeed, the development of an effective and efficient floor plan for the proposed facility is usually considered the most important step in the plant layout process. This is because the layout defines how much space area will be allocated, the physical relationships between different areas, and where each piece of equipment and each person will be located. This is a time-consuming task, since the optimal location for each department or each piece of equipment is often not readily apparent. Additionally, the size or shape requirements of the building might have to be taken into account.

Some details that have to be accounted for and have not been previously planned are desks and office equipment, first aid, lunch facilities, and restrooms. The number of fire extinguishers and water fountains needed and their location must be chosen.

Chapter 3

Product Design and Process Planning



The facility design process is usually complex enough as to require a very significant amount of information before it is actually started. Critical information including the types of products to be manufactured, quantities to be produced, specific manufacturing processes, and corresponding sequences of manufacturing operations markedly impact product and process design. This chapter provides an introduction to the activities of market research, forecasting, product design, and process design, also known as *process planning*, that precede the facility design process and provides the data for analysis.

Several typical *internal functions* influence the process of facilities planning because they define the environment in which a company operates. The following internal functions serve as the platform on which facilities planning strategies are developed and coordinated to reach the company's goals:

1. Marketing study (*why* a product is going to be manufactured)
2. Product design (*what* is going to be manufactured)
3. Process planning (*how* it is going to be manufactured)
4. Schedule design (*when* and how much is going to be manufactured)
5. Finance and administration (core values, leadership, vision, resources)

An integrated *strategic plan* is a document that formulates functional courses of action (*strategies*) that will be consistent with and supported by the internal functions of an organization. These *functional strategies* are specific means by which the objectives of facilities planning are reached in consistency with the main goals of the organization. Functional strategies are needed for the following activities:

1. Selling the product
2. Manufacturing
3. Distribution
4. Purchasing
5. Inventory and production control
6. Facilities design

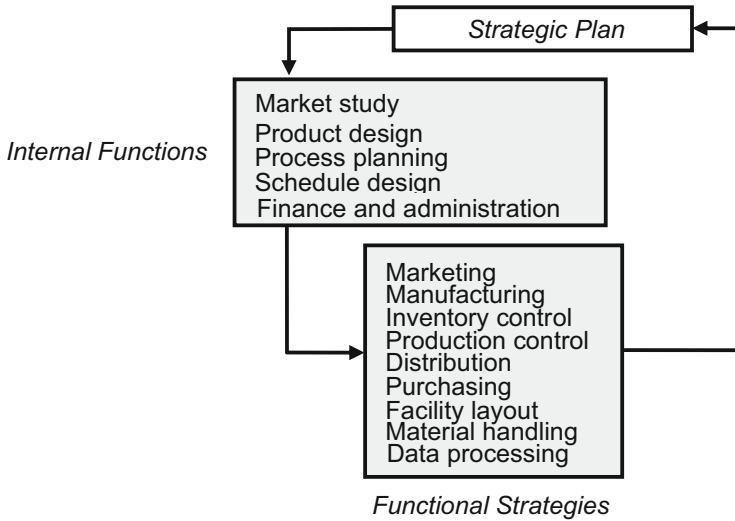


Fig. 3.1 Strategic facilities planning

7. Material handling
8. Data processing/information

The schematic representation in Fig. 3.1 shows that the overall process of integrating the internal functions, formulating the specific strategies, and coordinating the entire plan is iterative in nature. The goal is to converge to or arrive at a facilities design and location plan that supports the objectives of the organization.

3.1 Market Research

Consumers want products that are functional, reliable, economic, and aesthetically pleasing. Market research surveys are often used for estimating the market demand for new products, as well as for assessing or validating demand estimates for existing products. Typically, to design a product that will be well received in a highly competitive market environment, a company needs advance knowledge of new market opportunities, buyers' attitudes, and consumers' behaviors. Market research is vital in the facility design process because it provides information on customer response to the product, sales forecast, possible product models, advertising, cost estimates, and production schedules, among other aspects. All of these play a major role in the facility design process.

3.1.1 *Types of Market Research*

Market research surveys can be generally classified as either qualitative or quantitative. *Qualitative* market research measures the depth and range of buyers' attitudes and beliefs, instead of focusing on estimating the demand for a product. It is designed to contact or interact with relatively few people in the target audience of interest. Popular methods in this category include focus-group discussion studies, ethnography or photo-ethnography (here customers record actual behaviors and participate in follow-up interviews), depth interviews, observational techniques combined with interviews, and store exit interviews of customers.

Quantitative methods focus on measuring the demand existing in the market for a given product. Using a range of sampling strategies, quantitative market research studies often project results that can be extended not just to portion but to an entire market. Popular quantitative market research methods include online surveys, personal quantitative interviews, mail surveys, telephone surveys, and a variety of hybrid methods resulting from the combination of two or more of these.

The reliability and validity of market surveys depend on a number of factors, such as the design itself of the survey, the experience of interviewers, and the ability of the analysts to interpret results.

Forecasting is a process to calculate, estimate, or predict some future event or condition, usually based on a rational study and analysis of available pertinent data. Every industry needs to predict the market demand for its products or services. The estimate of the market demand is perhaps the most critical of all informational items required for the effective planning of facilities layout, production scheduling, production control, and inventory management. Both short-range and long-range plans depend on the ability of forecasting methods to provide reliable estimates of product demand.

Forecasting techniques are generally classified as either qualitative or quantitative. Those in the first category primarily involve judgment, while those in the second one primarily involve historical data and statistical models.

3.1.2 *Qualitative Forecasting Methods*

Qualitative methods are typically used when formal mathematical (statistical) models are not available or cannot be used due to lack of relevant data. Often the available data are not thought representative of the future, creating a need to either collect relevant useful data or use qualitative techniques. These techniques factor subjective or personal experiences into their models and are particularly useful in long-term forecasting. Some of the commonly used qualitative methods are described below.

- A. **Delphi Method** The Delphi method [5, 6] of market forecasting uses a preselected panel of geographically dispersed experts interacting through a

multistage process designed for collecting and extracting knowledge by means of a series of questionnaires. At each stage, a new questionnaire is developed based on analysis of the answers provided at the previous stage. Comments, forecasts, and relevant feedback are presented to the group without identifying their originators. By promoting a group discussion and analysis of results in a creative and systematic manner, this method develops a reliable consensus concerning the market forecast. In general, the Delphi method is applicable to long-range forecasting and new product sales. Its major disadvantage is that it may become quite time consuming and expensive.

- B. **Market Research** The market research technique is generally applied when a firm introduces a new product into the market and is interested in estimating its sales forecast. This technique may be very informal, utilizing the sales force to estimate the extent of the market, or it may be systematically conducted using special mathematical tools. Typical tools used to collect data in this technique are questionnaires, test markets, panels, and surveys.
- C. **Product Life-Cycle Analogy** This is a useful method of making forecasts for a new item, when there may be a shortage of historical data. It is based on the assumption that what happened in the past may be expected to happen in the future. Forecasts are based on *life cycles* (design, introduction, growth, maturity, and decline) of similar products, services, or processes. If the related products exhibit a great deal of similarity, quantitative techniques may be used. Otherwise, it may be more appropriate to relate the products in a qualitative fashion to acquire a view of possible patterns of demand. For example, the seasonal demand pattern for an established product such as baseball bats may be used to estimate the expected demand pattern for baseball gloves. Although the actual demand level and trends for gloves cannot be determined precisely in this manner, the seasonal pattern may be expected to be similar.
- D. **Sales Force Composite** This method is frequently used in large organizations that have a limited number of products and a few large customers. It is based on the principle that the persons in contact with the market have the best knowledge about future market trends. It combines the forecasts of sales representatives for their particular regions and comes up with a composite forecast for a product.

3.1.3 *Quantitative Forecasting Methods*

Quantitative methods are mostly used for medium-time and short-time range forecasting and can be generally classified into two categories: time series (or historical data) analysis and causal methods.

- A. **Time Series Forecasting Methods** These methods are based on analyses of historical data including observations measured at successive times or over successive periods. It is assumed that past patterns in demand data can be used to forecast future demand. Some of the well-known time series methods are briefly described below.
1. **Moving Average.** The forecast for a period is provided by the arithmetic average of a given number of past period demand values, all having equal weights. As an alternative, the demand points may be assigned weights that are not all equal.
 2. **Exponential Smoothing Model.** This model uses a weighted average of past data and current values, adjusting the weight on current values to account for the effect in data fluctuations, such as seasonality. Exponential smoothing techniques assign exponentially decreasing weights as the demand values get older. The technique is oftentimes used in large-scale applications because of its robustness and simplicity.
- B. **Causal Methods** Causal methods attempt to define relationships between the variable of interest and the values of a group of related explanatory variables. Some of the best-known causal methods are briefly described below.
1. **Regression Method.** A statistical model relates a dependent variable to one or more independent variables believed to influence it. In general, there are two main types of regression models, known as linear and nonlinear models.
 2. **Econometric Method.** A system of interdependent regression models that describe some sector of economic activity.
 3. **Input-Output Method.** Formulations describing the flows from one sector of the economy to another are used to predict the inputs required to produce outputs in the second sector.

3.2 Product Design

The fundamental purpose of the product design phase is to answer the question “*What is going to be made?*” It could be a product or a group of products in a manufacturing setting, or a service or a diversity of services in a service business environment. In either case, a product development process is required to accommodate the sequence of all relevant steps or activities needed from initial conception through a final product. In this chapter, the manufacturing of a product (or group of products) will be exclusively considered. The design of a new product starts with idea generation and continues through various development and testing phases to culminate with a detailed set of product specifications and a final product.

3.2.1 Product Design Process

A typical product design or development process is shown in Fig. 3.2. This product was selected by Brown et al. (M. Brown, J. Clepper, R. Green, C. Kubesch, and D. Sanchez) for their *Factory Layout Design Project* at Texas A&M University [3].

This process focuses on functional requirements and manufacturability of the product. It can be started once a great idea on a new product is available. The new idea can come from a variety of sources such as customers, employees, and competitors. A great idea by itself is still insufficient to proceed to the manufacture phase.

A list of product attributes and product requirements should be prepared to address relevant features such as service life, functionality, reliability, performance, looks, cost, and usability (user-related features, such as safety). Most of these aspects are covered by three essential considerations in the idea-generation phase: the product should be functional, reliable, and economic.

All these considerations in one way or another are closely related to the level of technology available. For example, the development of semiconductors and

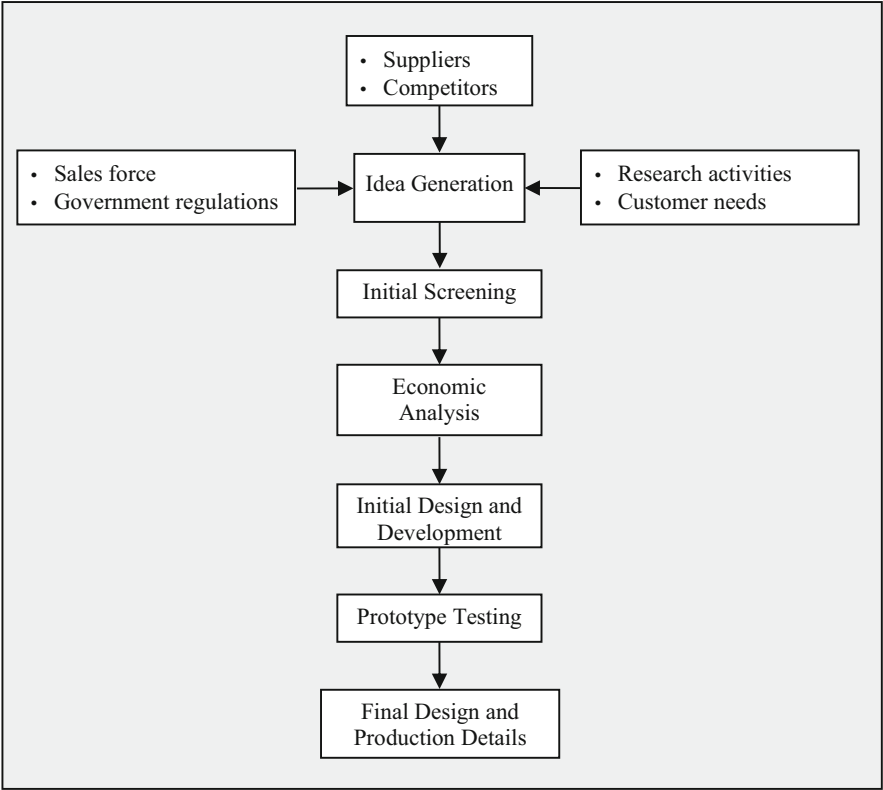


Fig. 3.2 Product design process

microchips has led to many improvements in a number of products, such as computers and television sets. These innovations have completely replaced older products manufactured on the basis of earlier technologies.

The idea-generation phase is progressive; it includes working out details, thinking through adaptations, and defining specifics such as how the product may be manufactured, what materials can be used, possible failure modes, required regulations, and so on.

In the initial screening phase, all fundamental and sweeping ideas are evaluated. The aim is to eliminate ideas that do not appear to have high potential for success. Both market criteria and technical criteria are used to evaluate the feasibility of potential products. Market criteria determine whether there is a market for the product, whether this market is expected to grow and by how much, and what is the size of competition in the market. Technical screening determines the feasibility of a product from the point of view of manufacturability.

The economic analysis phase encompasses a diversity of financial and engineering economy calculations to evaluate the product proposal from an economic point of view in which the time value of money is usually considered. In an engineering study, we must decide how the physical environment will be altered to produce services and goods in a way that is considered attractive from the economic environment point of view. The total cost of a product includes direct costs (labor, materials, equipment) and indirect costs. Distribution costs should not be ignored. The designer must consider all relevant costs in the design phase in order to perform a valid analysis of the product proposal. The economic study will tell the final word about the feasibility of the intended project.

In the initial design and development phase, all details of the product are composed. Three main factors that should be taken into account during this phase are: (a) product functionality, (b) technical requirements and specifications, and (c) economics of production and distribution. Typically, this phase includes work in all the areas of the project by several individuals or teams, depending on size and complexity. Design review meetings are interspersed at appropriate intervals. In order to be commercially successful, the product must perform its intended function at a competitive cost. Relevant design features related to product functionality include size, weight, quality and reliability, product life, ease of use, and maintenance. Technical requirements in the product design include selection of materials, parts, and manufacturing processes. Materials should be easy to work with, satisfy functional requirements, and promote low product costs. In order to assure a safe product deployment, areas of technical innovations should be evaluated carefully and often prototyped ahead of time to determine if the proper level of technology available is used to accomplish the goal of designing the product.

The initial design and development phase is often iterative. First designs and prototypes usually show the opportunities for improvement and serve as input to a second design cycle.

Prototyping is the design verification phase of product development and is used to demonstrate or prove aspects of a design. Prototyping takes the design from the virtual and imaginary realm to the physical world. Once a product has been

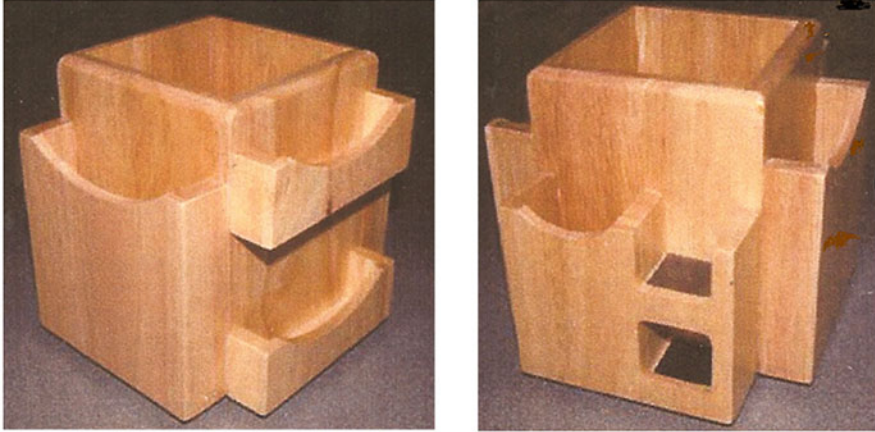


Fig. 3.3 Revolving desktop organizer [3]

designed, a prototype model is constructed to test its physical properties and functioning under actual conditions. Although the design phase may involve a substantial amount of calculations and analytical modeling, physical testing is important in order to uncover any problems. Typical prototyping models include clay models (initial phase), fabrication and machining models (functional versions), and rapid prototyping models (computer aided prototyping).

In the final design and production details phase, all the deficiencies identified during prototype testing are removed and appropriate changes and modifications are incorporated in the design. The last step in this phase is to thoroughly document the design. This means preparation of detailed drawings for some parts and thorough model construction for others. This documentation usually includes:

- Bill of materials (or part list)
- Component part drawings
- Assembly drawing

The *bill of materials* is in essence a *structured part list* that indicates the level of assembly at which each part joins the product being assembled. Component *part drawings* provide important information for fabrication, including shape, dimensions, and specifications. An *assembly drawing* or *exploded view diagram* of the product shows its parts separately but in positions that indicate their proper relationships to the whole.

A distinctive feature of this textbook is the illustration of all relevant steps of the overall layout design project by means of a sample product. Figure 3.3 shows two views of the particular type of a revolving desktop organizer chosen as the sample product. The use of this product can result in the elimination or significant reduction of such problems as declining productivity, increased stress levels, and reduced profitability caused by the state of disarray characteristic of many desks. As can be

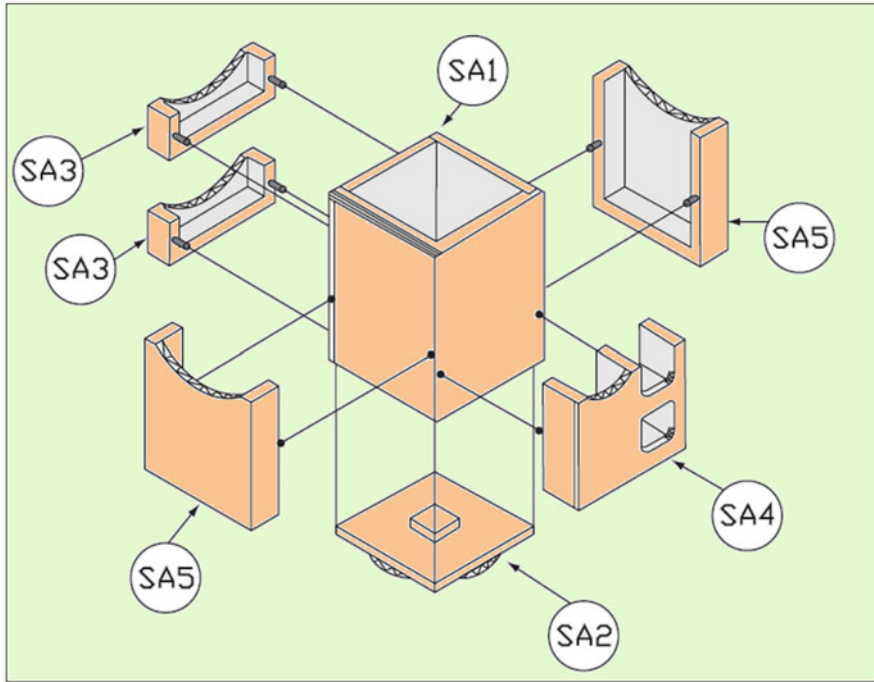


Fig. 3.4 Exploded assembly drawing [3]

appreciated in the figure, this is a product with a rather simple design and low costs associated with machines and materials.

Figure 3.4 shows an exploded assembly drawing showing the main five sub-assemblies of the revolving desktop organizer:

- SA1. Main subassembly
- SA2. Main bottom assembly
- SA3. Card holder assembly
- SA4. Pen holder assembly
- SA5. Paper holder assembly

3.2.2 Bill of Materials or Part List

This document consolidates basic information on the various parts composing a product, typically including standard sizes, part identification, materials specification (type and amount), and whether the parts are to be made in the facility or provided by outside vendors. Any relevant references (such as drawing references once they become available) are also included.

Table 3.1 Parts list

Company name:						
Product name:						
Date:						
Item number	Part code	Part description	Qty.	Material	Weight (lb)	Made or bought
1	1A-01	Main side A	1	Ash	0.24	Made
2	1B-01	Main side B	1	Ash	0.22	Made
3	1C-01	Main side C-01	1	Ash	0.215	Made
4	1C-02	Main side C-02	1	Ash	0.225	Made
5	1AS-01	Card holder front	2	Ash	0.025	Made
6	1AS-02	Card holder right side	2	Ash	0.01	Made
7	1AS-03	Card holder left side	2	Ash	0.01	Made
8	1AS-04	Card holder bottom	2	Ash	0.025	Made
9	1BS-01	Pen holder front	1	Ash	0.065	Made
10	1BS-02	Pen holder right side	1	Ash	0.045	Made
11	1BS-03	Pen holder left side	1	Ash	0.04	Made
12	1BS-04	Pen holder bottom	1	Ash	0.04	Made
13	1BS-05	Pen holder horizontal divider	1	Ash	0.015	Made
14	1BS-06	Pen holder vertical divider	1	Ash	0.035	Made
15	1BS-07	Magnetic tape	2	Ash	0.015	Bought
16	1CS-01	Paper holder front	2	Ash	0.095	Made
17	1CS-02	Paper holder right side	2	Ash	0.035	Made
18	1CS-03	Paper holder left side	2	Ash	0.035	Made
19	1CS-04	Paper holder bottom	2	Ash	0.035	Made
20	1Z-01	Main assembly divider	1	Plywood	0.045	Made
21	1Z-02	Screw backing support	1	Ash	0.01	Made
22	1Z-03	Main assembly bottom	1	Ash	0.1	Made
23	1ZR-01	Plastic base	1	Plastic	0.045	Made
24	1ZR-02	Rolling assembly	1	Plastic	0.025	Bought
25	1ZR-03	Screw	1	Steel	0.005	Bought
26	1D-01	Wooden dowel	10	Pine	0.0007	Bought
27	1D-02	Wood glue				Bought
28	1D-03	Wood varnish				Bought

Table 3.1 shows an example of a part list. The item number is the counter of parts. The part code is an alphanumeric reference that allows a quick identification of a part. The part description is a word or phrase used to name a part. The part quantity is the number of units of each part required in the product. This information along with information on material each part is made of and the weight of each part allow the facility planner to estimate the amount required of each type of material.

Finally, the part list indicates which parts are manufactured in the facility and which ones are bought from an external source. This information is essential to

Table 3.2 Bill of materials

Company Name:
Product Name:
Date:

Item Number	Level	Part Code	Part Description	Qty.	Material	Weight (lb)	Made or Bought
1	I	1A-01	Main Side A	1	Ash	0.24	Made
2	I	1B-01	Main Side B	1	Ash	0.22	Made
3	I	1C-01	Main Side C-01	1	Ash	0.215	Made
4	I	1C-02	Main Side C-02	1	Ash	0.225	Made
5	I	1AS-01	Card Holder Front	2	Ash	0.025	Made
6	I	1AS-02	Card Holder Right Side	2	Ash	0.01	Made
7	I	1AS-03	Card Holder Left Side	2	Ash	0.01	Made
8	I	1AS-04	Card Holder Bottom	2	Ash	0.025	Made
9	I	1BS-01	Pen Holder Front	1	Ash	0.065	Made
10	I	1BS-02	Pen Holder Right Side	1	Ash	0.045	Made
11	I	1BS-03	Pen Holder Left Side	1	Ash	0.04	Made
12	I	1BS-04	Pen Holder bottom	1	Ash	0.04	Made
13	I	1BS-05	Pen Holder Horizontal Divider	1	Ash	0.015	Made
14	I	1BS-06	Pen Holder Vertical Divider	1	Ash	0.035	Made
15	I	1BS-07	Magnetic Tape	2	Ash	0.015	Bought
16	I	1CS-01	Paper Holder Front	2	Ash	0.095	Made
17	I	1CS-02	Paper Holder Right Side	2	Ash	0.035	Made
18	I	1CS-03	Paper Holder Left Side	2	Ash	0.035	Made
19	I	1CS-04	Paper Holder Bottom	2	Ash	0.035	Made
20	I	1Z-01	Main Assembly Divider	1	Plywood	0.045	Made
21	II	1Z-02	Screw Backing Support	1	Ash	0.01	Made
22	II	1Z-03	Main Assembly Bottom	1	Ash	0.1	Made
23	III	1ZR-01	Plastic Base	1	Plastic	0.045	Made
24	III	1ZR-02	Rolling Assembly	1	Plastic	0.025	Bought
25	IV	1ZR-03	Screw	1	Steel	0.005	Bought
26	IV	1D-01	Wooden Dowel	10	Pine	0.0007	Bought
27	IV	1D-02	Wood Glue				Bought
28	IV	1D-03	Wood Varnish				Bought

identify the manufacturing processes and manufacturing requirements to be available in the facility.

Table 3.2 shows a bill of materials corresponding to the part list given in Table 3.1. A new column has been added to document the level of assembly at which a part joins the product. Four levels of assembly have been identified for the parts listed in Table 3.1.

Make-or-Buy Decision Manufacturing capabilities are typically assessed based on their strategic value and economic impact. Processes that add capability in an efficient manner during a reasonably long period should become in-house, while nonessential or inefficient processes can be contracted out. The following factors affect the make-or-buy decision in an organization. Usually, a single factor should not trigger the decision, but rather the joint consideration of all of them.

Production Capacity If capacity is available, it can be used to manufacture additional parts. Otherwise, a firm can buy the parts.

Product Quality Firms having a high degree of specialization generally can offer higher quality than those with low levels of specialization.

Demand Nature When demand is high and stable over a long period, it is reasonable to invest in facilities to satisfy the demand. If the demand is low or unsteady, it is often economically advantageous to outsource part of the work.

Facility Utilization The ability of a firm to match facilities to business is a key factor in deciding if parts should be manufactured internally or externally.

Skill and Materials When the parts require special manufacturing skills or materials not readily available, it is reasonable to consider an external provider.

Suppliers The availability, reliability, and location of suppliers may restrict the make-or-buy decisions.

3.2.3 Component Part Drawings

Component *part drawings* or engineering drawings are detailed line drawings of each part of the product, showing its shape, dimensions, tolerances, and surface finish. These drawings convey essential information for fabrication. As an illustration, Fig. 3.5 shows the top, front, bottom, and side views of the main sides of the revolving desktop organizer, part 3 (part code 1C-01) in Table 3.1.

3.2.4 Assembly Drawing

An *assembly drawing* shows how each part is related to the other parts and provides an insight into how to assemble the parts to make the final product. Figure 3.6 shows the assembly drawing for the paper holder of the revolving desktop organizer. This subassembly consists of parts 16, 17, 18, 19, and two units of 26 in Table 3.1.

3.3 Product Design Tools

The various tools used to aid product design are concurrent engineering, quality function deployment, and value analysis. A brief description of each is provided below. Some documented benefits of these tools are reduced product design time, reduced time to market, reduced design and manufacturing costs, increased product quality, and increased customer satisfaction.

3.3.1 Concurrent Engineering

Replacing the traditional view of product design, concurrent engineering is a systematic approach that develops products and their related manufacturing and support

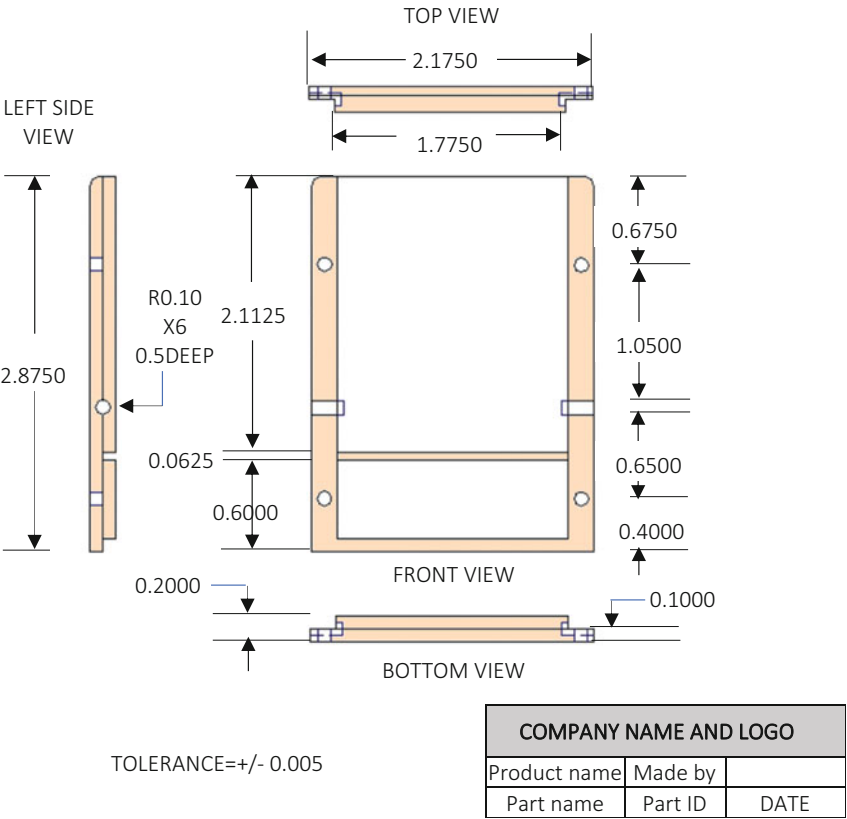


Fig. 3.5 Part drawing [3]

processes in parallel (simultaneously). It promotes an early consideration of all activities related to manage, develop, manufacture, verify, test, deploy, operate, support, train people, and eventually dispose off the product. This is a crucial decision because the majority of costs associated with design and development of a product occur rather early in the process. Since it depends on continuous review and improvement, the concurrent engineering process requires significant involvement, resources, and time to refine its final implementation.

3.3.2 Quality Function Deployment

Quality Function Deployment [1] identifies and links customer requirements to a diversity of functions, including design, development, engineering, manufacturing, and service. Customer requirements can be identified by means of direct discussion or interviews, surveys, focus groups, customer specifications, observation, warranty

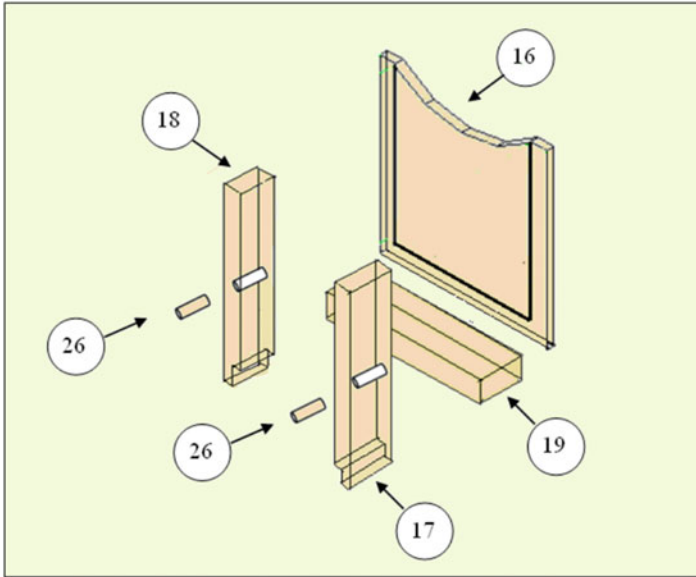


Fig. 3.6 Subassembly drawing [3]

data, field reports, and so on. Once obtained and properly understood, customer needs are summarized and documented in a product planning matrix or *house of quality*, shown in Fig. 3.7, consisting of the following six major components:

1. *Customer requirements* stated by customers.
2. *Technical requirements* or product characteristics.
3. *Planning matrix* to quantify customer priorities on product requirements observed through market surveys, and adapt the relative importance of these priorities to issues related to product design.
4. *Relationship matrix* to quantify, using a suitable symbolic or numerical scale, interrelationships between technical and customer requirements.
5. *Correlation matrix* to check the degree to which technical requirements support (or do not support) each other in the product design process.
6. *Technical priorities, benchmarks, and targets* to document priorities assigned to technical requirements by the matrix, measures of technical performance achieved by competitive products, and the degree of difficulty involved in developing each requirement. The final output is a set of target values for each technical requirement to be met by the new design.

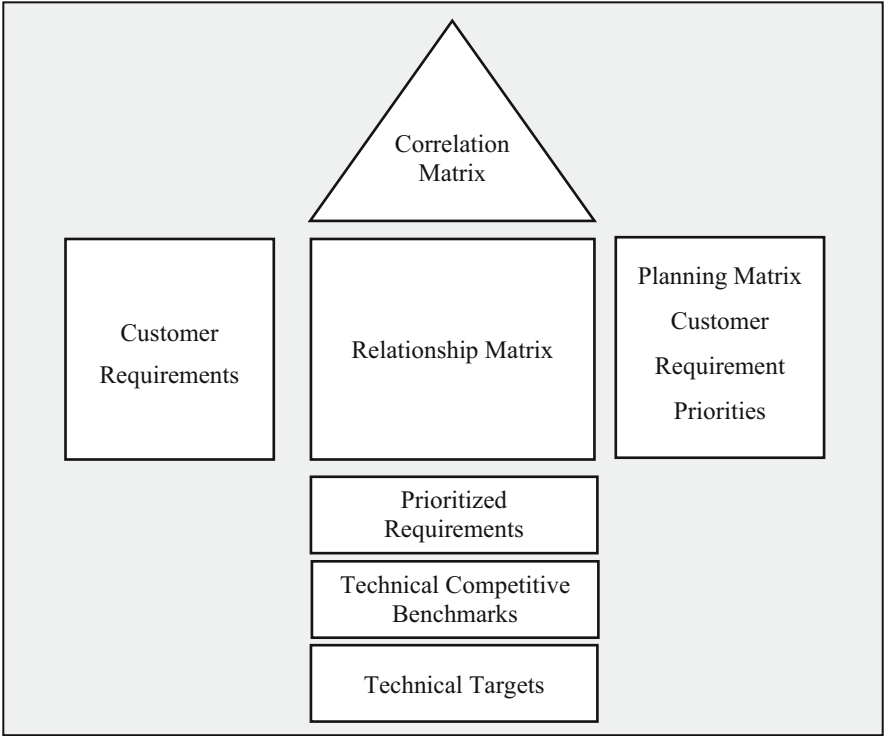


Fig. 3.7 House of quality

3.3.3 Value Analysis

The value analysis technique establishes a relationship between the cost of each component and its functional role in the product. Product functions are classified as either *basic* or *secondary* functions. A basic function makes the product work and makes it marketable. A secondary function describes the manner in which basic functions are implemented. As defined, basic functions cannot be changed, but secondary functions, also known as *supporting function*, can be modified or eliminated to reduce product cost.

A cost function matrix or value analysis matrix is prepared to identify the cost of providing each function by associating the function with a mechanism or component part of a product. Product functions with a high cost/function ratio are identified as opportunities for further investigation and improvement. Improvement opportunities are then brainstormed, analyzed, and selected. As value analysis progresses to larger and more complex products and systems, emphasis is shifted on *upstream* product development activities.

3.4 Factory Design Project: Section I. Product Design

Chapter 2 presented an overall view of the factory design project and serves as the unifying document for the various sections of the project. We now summarize relevant aspects and guidelines for the development of the product design phase.

The designer's primary goal of Section I is to become familiar with each part and the way the parts come together as a final product. Additionally, it is decided how each part will be secured (either purchased or manufactured) as a first step to identify the manufacturing processes that will be needed in the factory. A final objective in Section I is to visually grasp the completed product.

In summary, Section I focuses on appropriate and precise answers to the following four questions:

What product is going to be manufactured?
What parts compose the product?
Where are the parts secured from?
How are the parts used?

3.4.1 *What Product?*

Basic information on the product to be manufactured should be conveyed using one or more of the following options:

- A working model
- A prototype production model
- Drawings
 - (a) Product drawings (important for fabrication) should show dimensions and specifications.
 - (b) Assembly drawing.
 - 1. Exploded view of the product
 - 2. Exploded photograph

In combination, the detailed product assembly and exploded drawings, adequately dimensioned, define the shape and size of the product.

3.4.2 *What Parts Compose the Product?*

Basic parts information identifies all parts and provides details including standard sizes, part number, basic materials specification, and whether the parts are to be made in the facility or provided by outside vendors. This section provides complete information relative to design, construction, specifications, and manufacturing tolerances.

Which parts are manufactured or purchased? This information must be documented on the part list. A bill of materials can be done instead of a part list.

How are the parts used?

- Develop proper sequence of operations in which individual parts should be combined to form the desired product.
- Provide an *assembly chart*—a one-sheet graphical representation of the sequence and steps by which the individual parts can most effectively be combined into proper subassemblies and assemblies. Inspections are also shown. This chart provides the basic flow diagram for plant layout.

3.4.3 Guidelines¹

- Prototype or working model of mechanical device must be easy to disassemble.
- The product must require several manufacturing and assembly processes.
- The product should have at least 20 parts: 12 parts to be manufactured, 8 parts to be individually purchased, and all others to be purchased as a kit.
- Part drawings on AutoCAD—three per student.
- Assembly flowchart—show inspections in addition to assemblies.
- Assembly drawing—sketch or photograph (exploded view).
- Sketches must show at least three major dimensions in thousandth-of-inch accuracy.
- Sketches need not be to scale but must be proportional.
- Parts list should show: (a) quantity per product, (b) materials, (c) size and weight information, (d) make-or-buy decision, and (e) useful remarks.
- See checklist for grading Section I in Fig. 3.8.
- Chapter 2 contains the relevant information and files for the report.

3.4.4 Report Organization

- Introduction: relevant background, objectives, and organization of the report.
- Sections documenting the main results of the report. Each of these sections should have its own introductory paragraphs and discussion. The following four sections must be included:
 - (a) Production Drawings
 - (b) Assembly Drawings
 - (c) Parts List or Bill of Materials
 - (d) Assembly Flowchart

¹These guidelines are based on the authors' experience based on regularly teaching a course on facilities planning for over 15 years.

Group No _____	Product Description	Grade _____	Date _____
Names 1. 2. 3. 4.			
Organization and style			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Introduction of report is lacking ☐ Technical English style can be improved ☐ Organization can be improved			
AutoCAD drawings			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Drawing software was not used ☐ Drawings are not complete ☐ Neatness of drawings can be enhanced ☐ Dimensions are not correctly specified ☐ Material identification is inadequate ☐ View projections (top, side, front, others) are not clear			
Parts list			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Introduction needs to be improved ☐ Material identification inadequate ☐ Weights are not listed ☐ Purchased/manufactured not indicated ☐ Part numbers are inadequate or missing			
Assembly flow-chart			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Introduction missing ☐ Neatness can be enhanced ☐ Assembly logic can be improved			
Assembly drawing (or photograph)			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Introduction missing ☐ Minimum effort			
Comments			

Fig. 3.8 Checklist for grading report for Section I

- Summary, conclusions, and recommendations.
- Appendix (if needed, to illustrate calculations or add important supporting material).

3.5 Process Planning

The fundamental purpose of the process design phase or *process planning* is to answer the question “*How is the product going to be made?*” Production methods are the most fundamental factor affecting the plant’s physical layout, for they ultimately determine the type of machinery and equipment to be physically arranged. The term *process planning* is synonymous with process design, design for manufacture, design for production, and design for assembly, among others. *Traditionally, design efforts account for only 5% of the total product cost but influence 70% of the manufacturing cost* [7].

Process planning decisions begin after the product design decisions are made. The output of product design and the demand forecast obtained from market surveys are the two most important inputs to process planning. The product design affects the type of equipment, and the demand forecast (for a stipulated time period) affects the quantity of equipment needed. The major activities of process planning or process design are:

1. To select the manufacturing processes that are required to transform raw materials into final parts and products.
2. To sequence the manufacturing processes in the most appropriate order according to resources available and scope of the manufacturing enterprise.
3. To determine the appropriate type and quantity of equipment and machinery pieces required by the chosen manufacturing processes.
4. To determine the types and amounts of material required to perform the chosen manufacturing processes.
5. To arrange manufacturing facilities in production departments.

3.5.1 Process Planning Procedure

Process planning is the intermediate stage between product design and manufacturing. Its main objective is to achieve a desired product output and quality level at minimum cost. The selection of process and equipment directly affects the rate of output achieved and amount of capital investment required. Process planning essentially decides how the product will be manufactured. A typical process planning process is described in Fig. 3.9. The most important input to this procedure is the demand forecast per year, a quantity presenting significant challenges to market estimators.

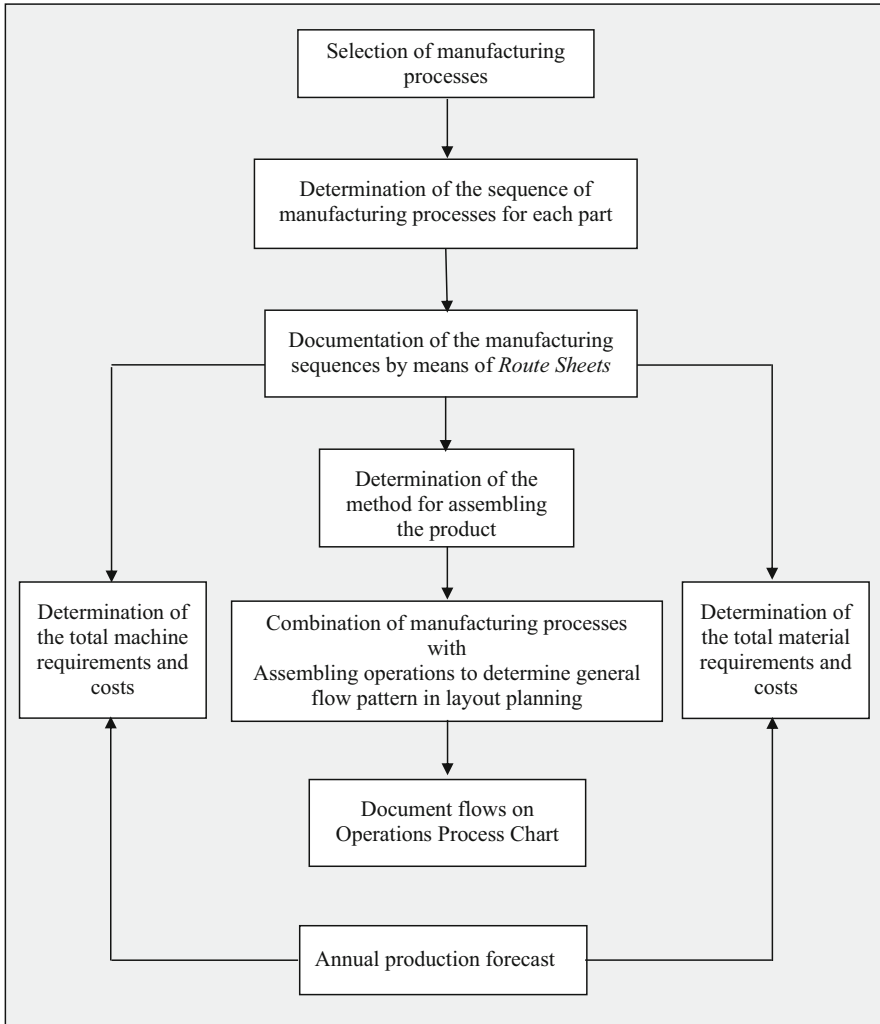


Fig. 3.9 Process planning

3.5.2 Selection of Manufacturing Processes

Each manufacturing process has its own functional, machine, and labor requirements. Before sequencing the processes needed to convert raw materials into final parts, those individual manufacturing processes that are most appropriate for the manufacturing operations of a given firm must be carefully selected. In more specific terms, the manufacturing planners should select the most economical processes that satisfy product specifications and are consistent with the level of mechanization and

automation desired, as well as with the production volume anticipated for the product.

The initial step of the process summarized in Fig. 3.9 focuses on the identification and selection of suitable manufacturing processes. In general, most manufacturing processes can be classified in one of the following categories:

- Processes used to change shape of material
- Processes used for machining parts to specified dimensions
- Processes for obtaining a surface finish
- Processes used for joining parts or materials
- Processes for changing physical properties
- Plastics processing (injection molding)

As implied by the popular adage, “*There’s more than one way to skin a cat,*” alternative manufacturing processes are available to perform each operation. These processes, depending on the level of mechanization and automation, have varying facilities and installation requirements, as well as varying production capabilities. As previously indicated, manufacturing processes should be selected in a manner consistent with a desired level of mechanization and automation compatible with the scope of the manufacturing enterprise.

The following general suggestions may help simplify the often arduous and difficult task of selecting manufacturing processes.

1. List all manufacturing operations (manufacturing capabilities) to be required to provide all design features of the product or the parts chosen for fabrication.
2. Identify a list of manufacturing processes and the group of operations it can perform. When selecting potential manufacturing processes, the desired level of automation and mechanization and the scope of the manufacturing enterprise should be considered.
3. Select a list of comparison factors, such as costs, automation and mechanization levels, capability and production capacity of equipment, installation requirements, and manpower requirements. This will require visualization of each individual operation, estimation of manpower, and a rough estimate of necessary layout provisions.
4. Perform a careful step-by-step comparison between the alternative processes using the comparison factors identified above. If desirable, a point system could be used.

3.5.3 Sequencing of Manufacturing Processes

Determining the most efficient and cost-effective sequence of manufacturing operations

is a key step in process planning. This sequence directly affects product quality, production time, and product cost. Obviously, different operational sequences will result in different operational timings, material handling times, tooling requirements,

material specifications, manpower requirements, and different devices of several types. Also, machining operations cannot be necessarily performed in any arbitrary order for a given part. For example, both geometric and technological constraints may require that some operations be performed before or after other operations.

The following general rules can aid decision-making concerning the sequencing of manufacturing processes, once all relevant *precedence constraints* have been established.

1. Critical operations to establish the *locating surfaces* are performed early in the sequence.
2. Rough work involving heavy cuts should be performed early in the sequence.
3. *Internal operations* are performed in advance of *external operations*, because internal surfaces are less likely to be damaged during the handling and movement of the part.
4. *Protective operations* (for example applications of protective coatings, inspection and testing, and packaging for shipment), generally nonproductive in nature, are placed at different times in the sequence.
5. Critical operations involving *close dimensional tolerances* and *surface finishes* are done late in the sequence.
6. The physical location and capability of production and material handling facilities should be taken into consideration when deciding on the final sequence.
7. Nature of tools and fixtures may influence the sequence of operations. Once a part is loaded on a fixture, as much work as possible should be done on the part.

Route Sheets All information that is essential for fabricating the parts of the product is recorded on *route sheets*, one sheet per part. A route sheet documents the sequence of operations needed to transform raw materials into a finished part or component. For each of these operations the route sheet documents machine requirements, material requirements, standard times, and, if necessary or desirable, drawing references. When the departmental organization of the layout is completed, the route sheet can indicate the department where each operation takes place. A typical route sheet contains the following information:

A. Heading of Route Sheet

- Component name and part identification (part code)
- Drawing reference number
- Lot size

B. Body of Route Sheet

- Operational sequences with descriptions and operation identification numbers
- Equipment requirements (type of machine, tools, jig, fixtures, etc.)
- Standard times
- Machine capacity per hour
- Material requirements (type and quantity)

ROUTE SHEET						
PART NAME	Paper Holder Front	DATE	02-14-07	DRAWING NUMBER		11
PART NUMBER	1CS-01	PREPARED BY	Marcus Brown	LOT SIZE		125
MATERIAL	Natural Birch					
OPERATION NUMBER	OPERATION DESCRIPTION	MACHINE NAME	JIGS, TOOLS, FIXTURES, ETC.	STD. TIME (sec)	MACHINE CAPACITY PER HOUR	MATERIAL REQUIRED QUANTITY
010	Cut to size	10" Table saw	Table fence	8	450	0.13 lb.
020	Route outside edges	Wood shaper	Straight bit, D=13/32"	15	240	
030	Route arc	Portable router	Straight bit, D=1/5"	20	180	
040	Sand all cut edges	Combination sander		10	360	
050	Lacquer all surfaces	Sprayer		5	720	
060	Dry lacquer	Drying oven		600	6	

Fig. 3.10 Route sheet for the paper holder front of the revolving desktop organizer

Jigs, fixtures, and inspections gauges are supporting devices that are necessary for efficient operations and help in reducing cost of production per piece by allowing higher production rates. Figure 3.10 shows the route sheet for the paper holder front (part 1 CS-01 in Table 3.1) of the revolving desktop paper holder [3]. As noted in this figure, there are six operations performed to manufacture the part.

Assembly Chart Route sheets provide information on production methods to manufacture each part, and the *assembly chart* indicates how these components are put together into a finished product. The assembly chart is a schematic diagram that represents the sequence of operations required to assemble the final product providing an early view of the operational flow of each subassembly and final assembly. It usually shows how and where individual components become sub-assemblies and how the various components are produced, and when and where these are put together to make the final assembly. This chart also shows when and where in the production process certain support activities like inspection and packaging will occur. Figure 3.11 shows the sequence of operations for the assembly of the revolving desktop organizer [3].

Operation Process Chart The combination of the route sheets and the assembly chart results in the *operation process chart*. This chart is helpful for visualizing and comprehending the full process that will be performed on the factory floor. It is the first step taken in the direction of configuring a facility layout.

Operation process charts are often used for operation analysis in order to investigate the shortcomings of the existing methods and improve them. It helps in deciding whether some elements should be eliminated or combined or their sequence be altered in order to obtain the maximum utilization of the system. Figure 3.12 shows the operation process chart for Subassembly SA1 of the desktop organizer [3].

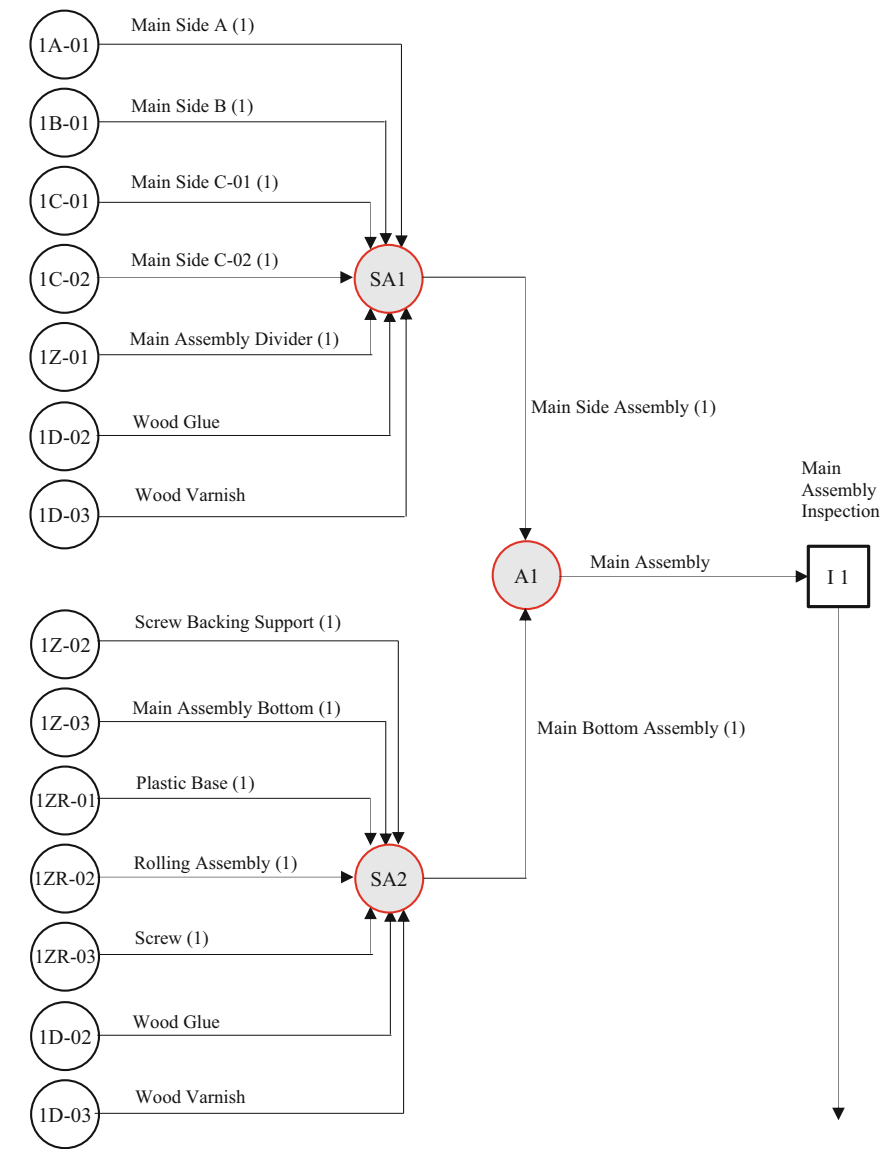


Fig. 3.11 Assembly chart for desktop revolving organizer

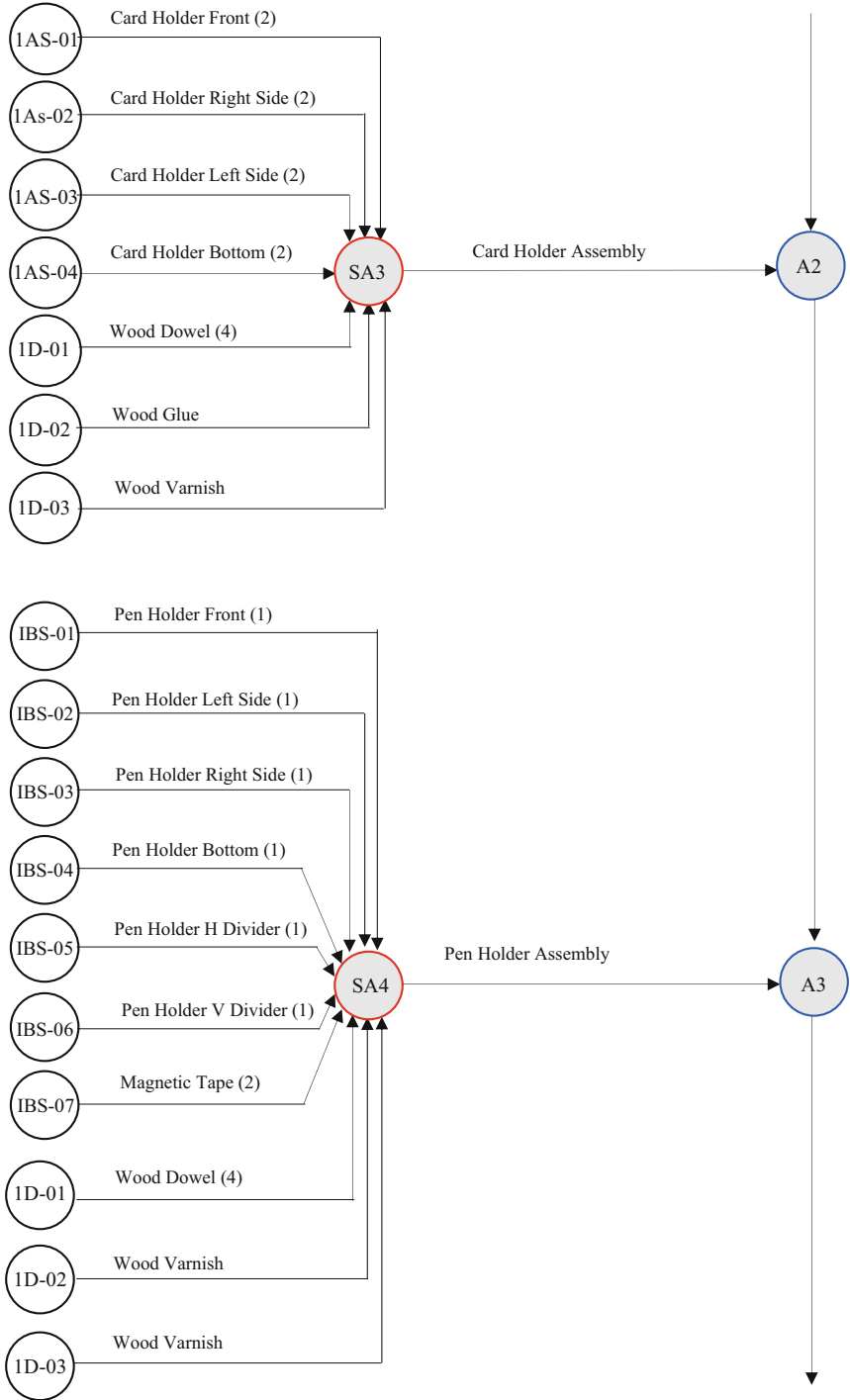


Fig. 3.11 (continued)

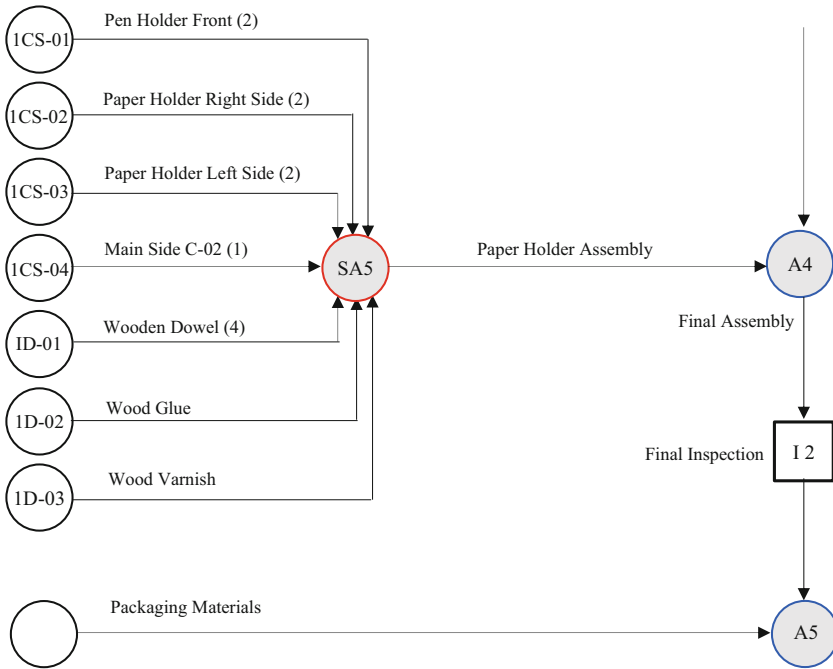


Fig. 3.11 (continued)

3.6 Types of Process Planning

Planning procedures are classified as either *manual process planning*, which is based on the experience and knowledge of the process planner, or *computer aided process planning*, which focuses on eliminating the process planner from the planning function. Automated process planning of machined parts is a key element in integrating design and manufacturing. The two traditional types of approaches to computer-aided process planning are the *variant approach* and the *generative approach*.

Usually, the task of process planning involves a number of interdependent activities. Most of them cannot be performed independently. Generation of the optimal process plan usually requires several iterations. Although significant progress has been made in automated process planning, the complexity and size of the process in real-life large-scale applications makes it virtually impossible to achieve a system that will automatically perform the complete task. Usually, instead of including all aspects of the process, automated procedures limit themselves to those steps that are relevant to manufacturability analysis.

For details and literature survey on the complete plan generation steps, readers are referred to work by Altling and Zhang [2], Chang [4], and Wang and Li [8].

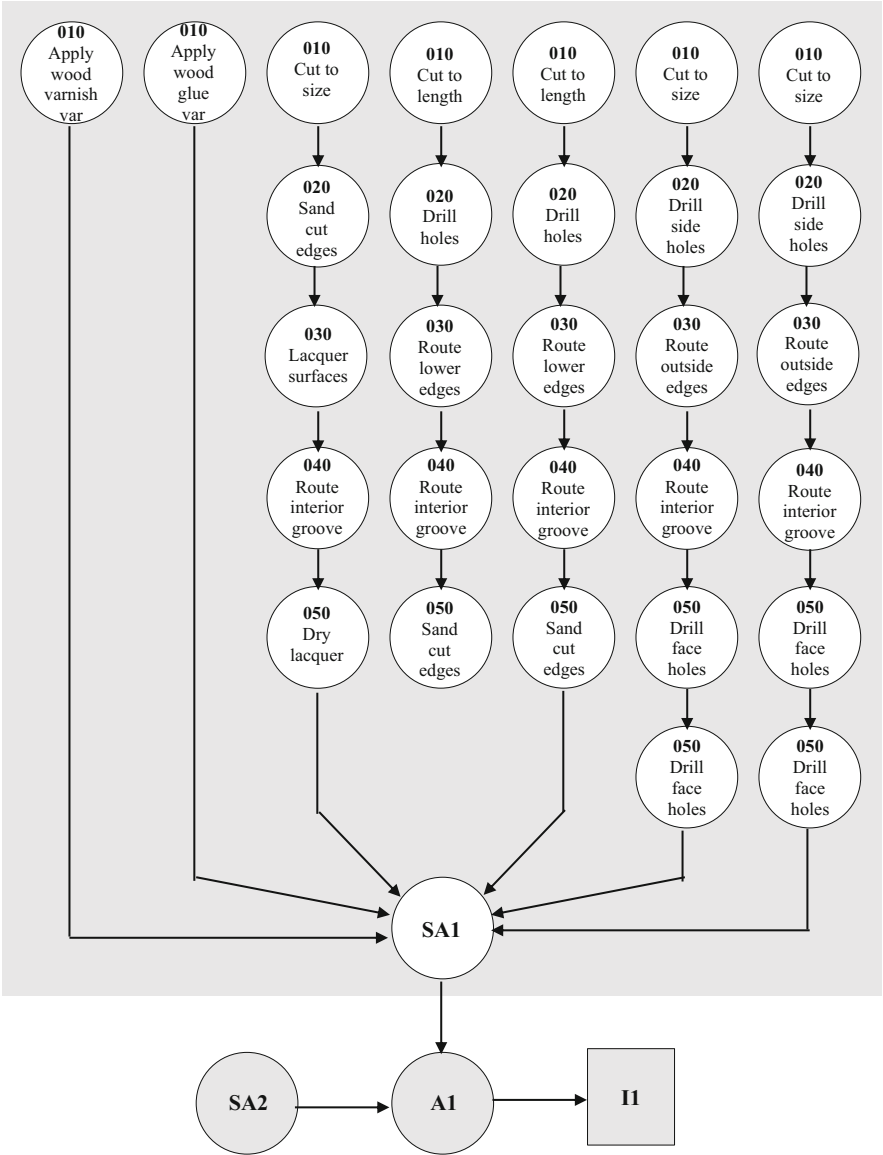


Fig. 3.12 Operations process chart for subassembly SA1

3.6.1 Manual Process Planning

Manual process planning is based on a manufacturing engineer's experience and knowledge of production facilities, equipment, their capabilities, processes, and

tooling. It is very time consuming, and the results vary based on the person doing the planning. Planning of the operations to produce a part requires knowledge of:

- The part requirements (as indicated by the part drawings).
- The available machines and processes and their respective capabilities.

Given this knowledge, the planner selects a combination of processes required to produce a finished part. Both production cost and production time are usually the dominant criteria, although machine utilization and the part routing are often significant factors as well.

3.6.2 Variant Process Planning

The variant approach involves retrieving an existing plan for a similar part and adjusting it to the requirements of a new part. The principle is that similar parts require similar plans. The process requires a human operator to classify a part, input part information, retrieve a similar process plan from a database (which contains the previous process plans), and edit the plan. Planning for a new part involves retrieving and modifying an existing plan.

In comparison to manual process planning, the variant approach is highly advantageous in increasing information management capabilities and reducing time and labor in complicated activities and decisions. However, as a result of the need to accommodate various combinations of geometry, size, precision, material, quality, and shop loading, there are difficulties in maintaining consistency in editing practices. The biggest limitation is that the quality of the process plan still depends on the knowledge of a process planner. The computer is just a tool to assist in manual process planning activities.

3.6.3 Generative Process Planning (GPP)

The generative approach creates new process plans by integrating decision logic, formulas, manufacturing rules, and geometry-based data to determine the processes required to convert the raw materials into finished parts. It develops a new plan for each part based on input about the part's features and attributes. It is the only approach that allows the development of a process plan at the early design stage where manufacturability evaluation is most effective. Also, it does not keep the designer tied to earlier process plans and allows the development of alternative process plans for the same design.

The variant systems are better developed and more mature than generative systems; they are suitable for planning processes in large-scale production. However, the generative systems are much more suitable for planning processes for a discrete number of manufacturing products exhibiting a great level of diversity.

3.6.4 Semigenerative Process Planning

The semigenerative method can be viewed as an enhanced application of variant technology having generative features. It can be used in the following ways:

- Use the variant method to develop the general process plan and then use the generative method to modify it.
- Use the generative method to create as much of the process plan as possible and then use the variant method to fill in the details.
- Use the generative method for complicated part features and the variant method for fast process plan generation.

3.6.5 Computer Aided Manufacturing

In modern manufacturing environments, it may not be efficient or profitable to make everyday products manually. However, using numerically controlled machines, it is possible to make hundreds or even thousands of units of the same part in a day. Manufacturers are increasingly using programmable numerically controlled machine tools.

The system that makes all this possible is known as computer-aided manufacturing (CAM), a system of computer-controlled production machines. The use of CAD/CAM (computer-aided design and manufacturing) significantly decreases design and production times, with productivity gains.

CAM systems prepare and coordinate programs designed for numerically controlling manufacturing equipment. This allows for automated production of the mechanical parts, subassemblies, assemblies, and final products. The system needs to know the physical shape of the product (CAD model) before it can compose a proper set of fabrication instructions to a production machine. This information is obtained either from CAD, which involves the use of computer hardware and graphics software to generate design drawings, or directly from the machinist in charge of the operation. In the latter case, information is transferred from a blueprint, a part or assembly drawing, or a sample of the part, using, for example, a keyboard, mouse, or digitizer.

The computer analyzes the geometry of the part and calculates the tool paths that will be required to machine the part. Each tool path is translated into a detailed sequence of machine axes movement commands. The computer-generated instructions control the operations of a machine tool, such as movement, drilling, cutting, and tool changes, and can be stored in a central computer's memory, or on a disk.

There are two primary types of numerical control systems, which differ by program storage method:

1. Computer numerical control (CNC)
2. Direct numerical control (DNC)

In CNC the control system is directly connected to a local control computer where the actual program is saved. In DNC a more modern method permits a flexible distributed control of several production machines from a common center. If the DNC system is combined with an automated material handling system, it usually is known as a flexible manufacturing system (FMS).

CAD/CAM software programs are continuously being upgraded and made more user friendly. The main advantages of using the CAM system include the following:

- Faster turnaround of new products.
- Reduced waste as a result of more efficient use of raw materials.
- More precise estimation of manufacturing cost.
- CAM can be viewed as a *fixed* cost that reduces *variable costs*.
- CAM allows for cost savings that can be passed on to the final consumer. It utilizes human resources more efficiently to minimize labor costs.

3.7 Schedule Design

The fundamental question in the schedule design phase is, *How many parts are going to be made in a specified time period?* To answer this question, it must first be decided if parts are going to be fabricated one by one or in batches. Schedule design determines the process requirements in terms of the number of units of each type of equipment needed to meet the production schedule. This can be accomplished by means of the following activities:

1. Determination of the quantity to be manufactured for each component (including scrap estimates) for a specified time period.
2. Identification of equipment required by each operation.
3. Consolidation of all equipment requirements.

The basic scheduling process is described in Fig. 3.13. The major demand inputs are customer orders, delivery dates, demand forecasts, and production plans. Other factors such as scrap and rejection estimates must be considered before estimating the overall demand. The production lead-time constraint accommodates the time required to purchase raw materials and supplies, as well as the time for assembly, subassembly, and fabrication. Production capacity is one of the major constraints in the scheduling process, since it is affected by several factors, including the number of working days per period, number of shifts planned, manpower levels and their skills, overtime policy, and available equipment. Other factors such as absenteeism, machine breakdown, or unavailability of materials tend to reduce the firm's production capacity.

The expected number of units P_1 to start into production for a part having a specified sequence consisting of n operations can be calculated as

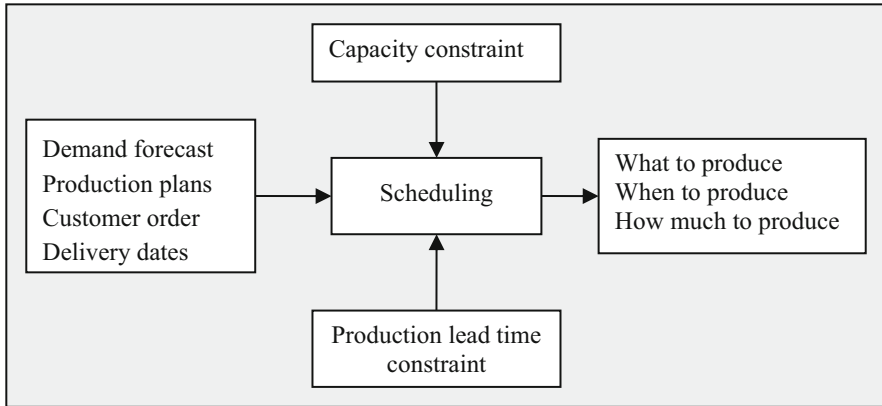


Fig. 3.13 Schedule design function

$$P_1 = \frac{O_n}{(1 - \delta_1)(1 - \delta_2) \dots (1 - \delta_n)} \quad (3.1)$$

where O_n is the market estimate for a part after the n th operation, and δ_i is the percent defective on the i th operation.

The general formula for computing the *decimal number* (either a fraction or a mixed number) of machines is shown below:

$$N = \frac{Pt}{(H - s)p} \quad (3.2)$$

In the above formula, P is the daily production, H is the number of hours per day, t is the *standard time* in hours per piece, s is the daily setup time in hours, and p is the fraction of the time the machine is up.

Example

Assume that $P = 1600$ pieces per day, $t = 0.004$ hours per piece (250 pieces per day), $H = 8$ hours per day, $s = 0.2$ hour, and $p = 0.90$. Find the fractional machine number.

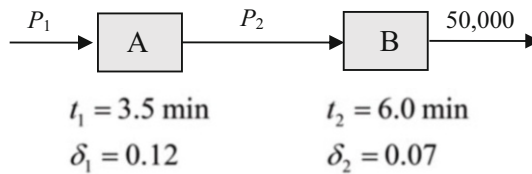
Solution

$$N = \frac{1600(0.004)}{(8 - 0.2)(0.90)} = 0.912$$

Based on this result, it is concluded that no more than one machine will be needed. If there are several products requiring this type of machine, typically all fractional numbers are added if the required work is performed at different times and in the same general location, before deciding on the number of machines to be bought (an *integer* number).

Example

A product requires two sequential machine operations. The first takes 3.5 minutes and its defect percentage is 12. The second takes 6.0 minutes and its defect percentage is 7. Assuming 250 workdays per year and a daily shift of 10 hours, it is desired to determine the minimum fractional number of machines to manufacture 50,000 units per year. In another similar plant, past annual data on identical operations and working conditions indicate that 10 machines were out of production a total number of 2198 hours due to setup and 2052 hours due to machine unavailability (for instance, maintenance needs).

Solution

- (a) The number of parts processed in the machines are equal to $P_2 = \frac{50,000}{1-0.07} = 53,764.4$ and $P_1 = \frac{53,764.4}{1-0.12} = 61,096$.
- (b) The daily setup time in hours is $s = \frac{2198}{250 \times 10} = 0.88$.
- (c) The fraction of time each machine is up is equal to $p = 1 - \frac{2052}{250 \times 100} = 0.918$.
- (d) The number of machines is $N = \frac{P_1 t_1 + P_2 t_2}{60(H-s)p} = \frac{61,096(3.5) + 53,764.4(6.0)}{60(10-0.88)0.918} = 4.3$.

It is noted that the fifth machine will not be fully used to manufacture this product, and that, on the other hand, four machines will not be sufficient.

3.8 Factory Design Project: Section II. Process Design

In this section of the project, we need to determine the best way to manufacture the parts. Section II deals with the entire production process and details how each part of the final product is produced and how it flows through the factory. It is important to identify the proper manufacturing sequence for each piece in order to maintain efficiency and meet the company's goals. The objectives of Section II of the factory design project are:

- To determine how to make the parts
- To determine machine requirements and costs
- To determine material requirements and costs

3.8.1 Guidelines

- Follow the procedure outlined in Fig. 3.14.
- Develop route sheets for all manufactured items and assemblies.

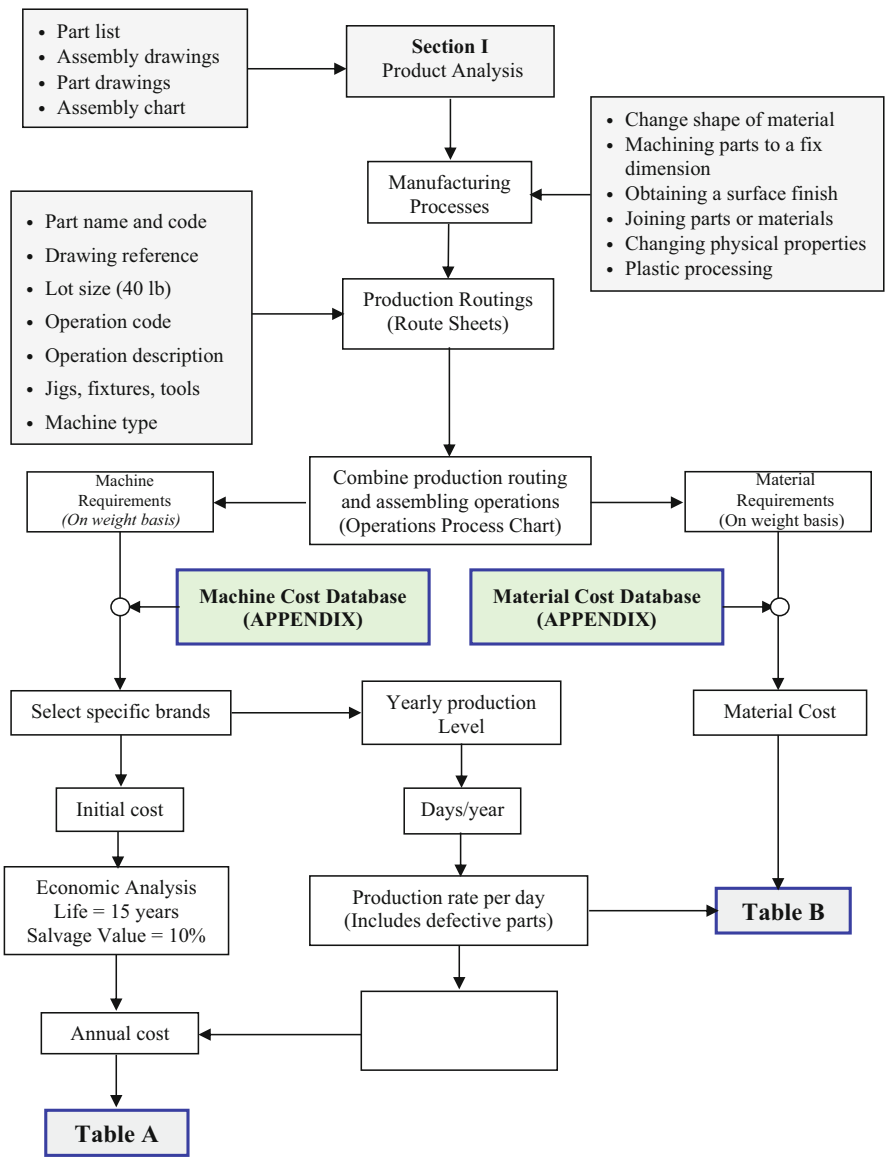


Fig. 3.14 Conceptual procedure for Section II

- Determine machine and material types and costs. The Decision Support Methodology (Appendix) assists in the accomplishment of this task.
- Consolidate machine requirements and costs (Table A in Fig. 3.11).
- Consolidate material requirements and costs (Table B in Fig. 3.11).
- Machine drawings (one or two per student) using AutoCAD.
- Perform economic analysis, assuming a life span of 15 years, a salvage value equal to 10%, and straight line depreciation.
- The grading checklist to be used is shown in Fig. 3.15.

3.8.2 Organization of Report

1. Introduction: Relevant background, purpose, and report organization
2. Manufacturing operation
 - Introduction
 - Route sheets and operations process chart
 - Discussion
3. Machine requirements and cost
 - Introduction
 - Machine requirements and costs (Table A)
 - Discussion
4. Material requirements and costs

3.9 Summary

In this chapter, we have discussed the importance of market research and forecasting, and product design and process design in facility layout planning. Market research and forecasting are used for long-term sales forecast, product models, advertising and brand positioning, cost estimates, and so on.

Product development has much implication for facility layout planning. It determines what is to be made. The product design process consists of idea generation and screening on the basis of market criteria, technical criteria, financial criteria, and principal design; modeling and prototyping; and final design. The results of this process are thoroughly documented in detailed drawings of the parts, assembly drawings, and the bill of materials. Use of various tools, such as quality function deployment, value analysis, and concurrent engineering, can greatly improve the quality and reduce cost and time in marketing the product.

Process design determines the processes and type of equipment to be used and the location of the production departments, material handling equipment, and other auxiliary units. Process planning requires a thorough analysis of the product to be

Group No _____	Product Description	Grade _____	Date _____
Names 1. 2. 3. 4.			
Organization and style			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Introduction of report is lacking ☐ Technical English style can be improved ☐ Organization can be improved			
Route Sheets			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Missing information ☐ Standard times are unrealistic ☐ Operation descriptions are inadequate ☐ Sheets are not complete (at least 3 per student)			
Machine requirement and Cost			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Machine fractions not calculated ☐ Machine choice can be more specific ☐ Unrealistic costs ☐ Annual cost analysis not documented			
Material Requirement and Cost			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Quantities not calculated ☐ Amounts of material are unrealistic ☐ Wrong calculation of material requirement ☐ Material choice can be more specific			
Machine Drawings			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Incorrect scale ☐ Incomplete ☐ Neatness of drawings can be enhanced			
Comments			

Fig. 3.15 Check list for grading report for Section II

made in order to choose the proper technology and equipment, and decide whether to make the product in-house or buy it from a vendor. Commonly the product is described through engineering drawings, parts or material lists, assembly drawing, exploded view diagrams, and exploded view photographs. Other tools used are assembly chart, operation process chart, and flow process chart. Results of the planning are route sheets that specify operations, operation sequences, work centers,

standard times, tooling and fixtures; and process plans that typically provide more detailed, step-by-step work instructions. Process planning is either manual, which is based on the planner's experience and knowledge of process planner, or computer aided, which is focused on eliminating the process planner from the planning function. Computer-aided process planning is highly advantageous in increasing information management capabilities and requiring less time and labor.

3.10 Exercises

- 3.1 What is strategic planning? What are the internal functions and functional strategies that must be properly integrated in successful strategic planning?
- 3.2 Outline the product development process, explaining the purpose of each step. Provide an example to illustrate this process.
- 3.3 Describe the Quality Function Deployment (QFD) process. Illustrate the steps of the process with an example related to the manufacturing of the product being considered in the factory design project.
- 3.4 Describe the part list and the bill of materials emphasizing the main difference between these two documents. When is one document more appropriate than the other?
- 3.5 What are the main types of market research? Make a meaningful comparison of these methods.
- 3.6 Describe the typical qualitative forecasting methods. Provide examples of situations where these methods can be applied. Outline their main advantages and disadvantages.
- 3.7 Describe the typical quantitative forecasting methods. Provide examples of situations where these methods can be applied. Outline their main advantages and disadvantages.
- 3.8 A plant manufactures three parts, A, B, and C, to be assembled into a product. Turret lathes are required for one operation on each of the three. For planning purposes it is assumed that plant personnel work at 70% of normal and lathes have a utilization probability of 0.90. Policies establish that no run will be for less than the monthly production requirement. The plant works an 8-hour, 5-day week and setup is carried out during the regular work shift. The required production is 10,000 per month (4.2 weeks/month). It is desired to determine: (a) the number of lathes; (b) the number of turret lathe operators; and (c) the number of turret lathe setup workers. The following data are given (including setup time per machine):

Product	Operation	Time (h)	Defective (%)	Setup time (h/month)
A	A-747	0.083	3.4	10
B	B-214	0.031	2.6	14
C	C-103	0.117	1.5	12

- 3.9 In which charts and/or drawings do you document the information for product design and process design? Summarize the content of each chart or drawing.
- 3.10 Consider the following list of factors:
- A. Parts (names and codes)
 - B. Quantity for each part
 - C. Make/buy
 - D. Assembly level for each part
 - E. Part materials
 - F. Machine type and fraction
 - G. Sequence of operations (flow)
 - H. Crew size (manpower)
 - I. Inspections
 - J. Assemblies and subassemblies
 - K. Material handling requirements
 - L. Operation number and description
 - M. Standard times
 - N. Planning departments

It is desired to identify those in each of the following documents: (a) the parts list, (b) the bill of materials, (c) the route sheet, (d) the assembly chart, (e) the process chart, and (f) the layout planning chart. Indicate your answer in the following table, where an **X** mark indicates that a factor is included in a document:

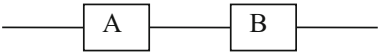
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Part list														
Bill of materials														
Route sheet														
Assembly chart														
Process chart														
Layout planning chart														

- 3.11 Describe the typical content of a layout planning chart. Explain the relevant balancing considerations necessary to develop the chart.
- 3.12 What is *quality function deployment*? Describe the way to summarize and document customer requirements.
- 3.13 A six-stage process goes through the sequence of machines 1-2-3-4-5-6. Each machine discards 7% scrap. The current demand is 2000 good units per day.
- (a) Determine the number of units per day started in the *third stage* (machine 3).
 - (b) The standard time per part processed at the *third stage* is 2.5 minutes. The corresponding machine requires a 15-minute setup every day. Assuming one daily 8-hour shift, and a machine availability factor equal to 0.85, find the fractional number of machines required in the *third-stage* operation.

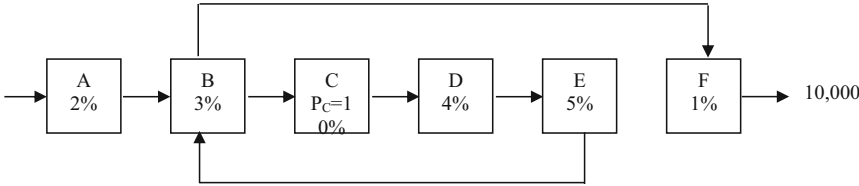
3.14 Find the machine fractions for the following case. Part X is routed from machine A to machine B and then back to machine A, and has an annual production volume of 150,000 units. Part Y is routed from machine B to machine A and its annual production volume is 120,000. Assume the following data:

	Machine A	Machine B
Standard time (hr) for part X		
First operation	0.10	0.01
Second operation	0.07	
Standard time (hr) for part Y	0.06	0.06
Scrap estimate (%) for part X	6.00	3.00
Scrap estimate (%) for part Y	6.00	3.00
Historical efficiency (%)	95.00	90.00
Reliability factor (%)	94.00	97.00
Hours available per year	2000.00	2000.00

3.15 Two machining operations A (3 minutes per part) and B (10 minutes per part) are performed sequentially to manufacture a part. Machines A and B produce 5% and 6% defective items, respectively. The factory operates 8 hours each day, 5 days per week, 4.2 weeks per month. Every day each machine needs 0.30 hours for being set up. Find the machine fraction for each type (A and B) if we need to handle a demand of 1000 items per month? Use a machine-up factor equal to 85% for each machine.



3.16 Consider the given sequence of six operations A, B, C, D, E, and F with the defective product percentages shown in the diagram.



Determine the number of parts to be manufactured at the beginning of the sequence. (a) Assume that the sub-sequence B-C-D-E-B is performed once. (b) Assume that this sub-sequence is repeated twice.

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Chapter 4

Layout Planning Procedures



Given similar production resources, including labor, material, and machines, a factor that contributes significantly to economic success or failure in an extensive range of production systems is the factory layout. To be effective and allow for smooth and efficient operation of a factory, the physical arrangement of equipment and machinery must take account of a number of complex and complicating factors affecting product design and process planning.

A systematic planning approach must be followed to collect data, develop alternatives, and choose the final layout. Clear objectives should be defined and proper input data collected. Obviously, even when the systematic approach is comprehensive and correct, the final output cannot be better than the input data. Furthermore, meaningful evaluation criteria should be identified, including the economics (investment return, operational costs, construction and services costs), the process (effectiveness, parts flow, equipment balancing), and adaptability (flexibility, future modifications, and expansions).

The field of facilities planning has significantly evolved during the last four decades. Modern facilities planning has its roots in pioneering work on *plant layout* by Richard Muther [10], the developer of *systematic layout planning (SLP)*, a *conceptual* systematic approach that provides a process for layout design. The SLP design process is best utilized when integrated with specific analytical methods for product-mix segmentation and department planning in designing factory layouts. In particular, this chapter will address the combined approach of SLP integrated with *production flow analysis (PFA)*, discuss fundamentals of space and flow planning, and introduce the decision-support methodology to be used in the lab factory layout project.

Chapter 4 has nine sections. Section 4.1 is an introduction to layout planning focusing on a conceptual view of the overall layout process. Section 4.2 summarizes the steps of the systematic layout planning approach. Section 4.3 describes a computerized procedure to obtain a flow matrix from the route sheets and production volumes for all parts. Section 4.4 summarizes the production flow analysis (PFA) process and shows an integration of SLP and PFA. Section 4.5 provides flow

planning principles and patterns, and Sect. 4.6 introduces the layout-planning chart, a document containing fundamental data for planning layouts. Space requirements are considered in Sect. 4.7. A basic procedure that underlies the fundamental steps of layout planning methodologies is described and illustrated through a numerical example in Sect. 4.8. Section 4.9 describes the computerized procedures used in the factory layout project. Section 4.10 closes the chapter with a brief summary of the material presented therein.

4.1 Introduction

Planning departments are groups of workstations put together in a facilities layout. A workstation consists of fixed assets needed to perform specific operations. It can be considered as a facility itself. It includes space for equipment, materials, and personnel. Chapter 1 presented the basic layouts for a group of facilities, such as a factory or a single production or planning department. Depending on the basic layout of their facilities, planning departments can be subdivided as follows:

- (a) Product or production-line departments
- (b) Fixed materials location departments
- (c) Product family departments
- (d) Process departments

Layout planning in facilities design essentially means *space planning*. Layout planning is the main focus of facilities design. As indicated by Lee [10], every layout has four fundamental elements: *space planning units (SPUs)*, *affinities*, *space*, and *constraints*. Conceptually, a layout is the result of arranging the space planning units on the available space with the goal of accommodating the closeness relationships indicated by the affinities without violating any of the relevant important constraints. The generation of a final layout is the result of an iterative progressive process that starts with an initial plan, goes through a revision and improvement methodology, and ends with a recommended layout.

Space planning units (SPUs) are separate physical components to be arranged on a layout. Typical examples are a production or service department, a warehouse, a building feature, or a single workstation requiring a fixed location.

The ***affinities*** represent relationships that demand closeness among the space planning units. All these relationships fall into five general classifications:

- Organizational relationships
- Flow relationships (either physical or nonphysical flows, such as communication flows)
- Control relationships
- Environmental relationships
- Process relationships

If the SPUs are represented by *nodes* or *circles* and the affinities by *arcs* or *lines* joining the related SPUs, the resulting graphical representation is generally known as

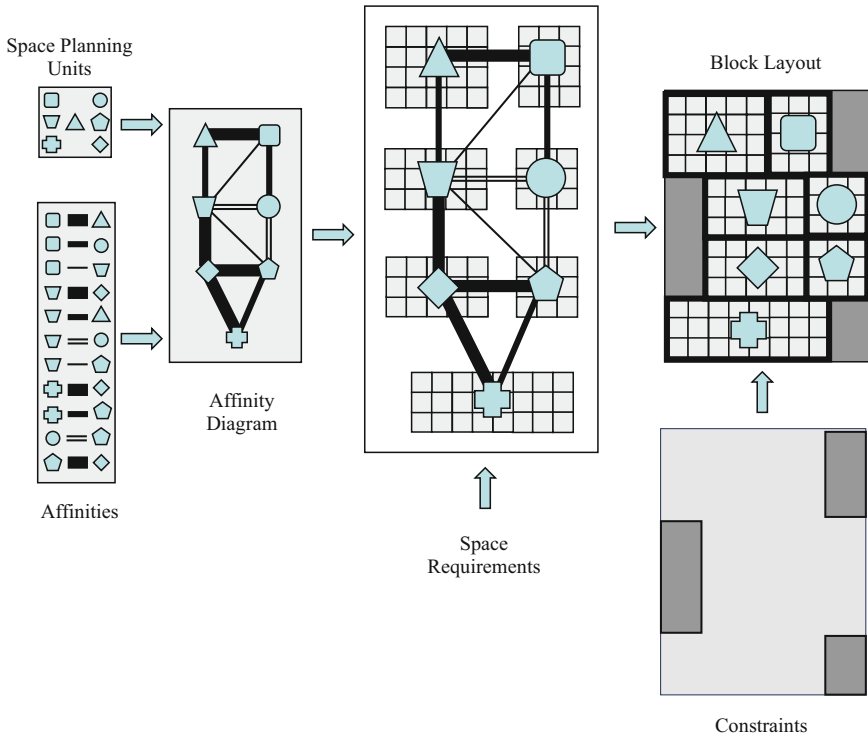


Fig. 4.1 Conceptual illustration of layout procedure

an *affinity diagram* or *relationship diagram*. To convey the relative importance of the relationships, several types of lines of varying thickness can be used. The relationship diagram is actually an idealized *spatial arrangement*.

Each SPU has its own unique *space* requirement. When space is added, it transforms the relationship diagram into a *preliminary space plan* or *space relationship diagram*.

The **constraints** are conditions, assumptions, policies, or requirements that restrict a physical arrangement or space plan. Typical constraints are floor loading, columns in a building, and a predetermined location of the receiving and shipping areas in a factory layout. The constraints transform the preliminary space plan into a final *space plan*.

Figure 4.1 provides a conceptual illustration of the overall procedure. Seven SPUs are represented by geometric symbols with different shapes. In the affinity diagram, thicker lines represent stronger relationships. Furthermore, relevant constraints preclude three areas of the factory floor from being used as departmental space. In essence, this chapter presents fundamentals of layout planning as well as procedures for supporting the decision-making process necessary to implement the conceptual approach shown in Fig. 4.1.

4.2 Systematic Layout Planning

Systematic layout planning (SLP), developed by Richard Muther in 1961 [12], is arguably the best-known, most widely used, and best-coordinated methodology for layout planning. In essence it is an *approach* to develop a feasible layout through a multistep procedure that uses the following types of input information:

- A. List of products to be manufactured, production quantities, routing sheets for all products, list of supporting services, standard times for all operations, and all manufacturing activities grouped into planning departments.
- B. Relationships between the various departments.

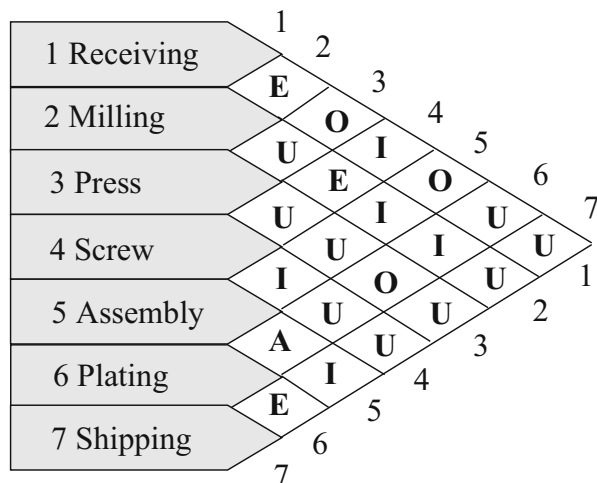
From the above input, two intermediate outputs are established:

- A. Flow of materials.
- B. Activity relationships.

The flow of materials between departments is a direct result of the manufacturing operations sequence (documented in the route sheets) and the production volume for a specified planning period. The flow can be consolidated into a *square* matrix, known as the *from-to* chart. In this chart, departments correspond to rows and columns, and each *entry* is equal to the material flow *from* the department corresponding to the *row* to the department corresponding to the *column*. Since not all products have the same handling requirements, a standard unit must be chosen to measure the flows as equivalent numbers of trips for a specified time period.

A second type of chart (developed by Muther) provides a visual representation of the closeness relationships; it is known as the *activity relationship chart* (Fig. 4.2). The chart represents the relationships *qualitatively* using the following letters: A = absolutely necessary; E = especially important; I = important; O = ordinary closeness acceptable; U = unimportant; and X = not desirable to be close. An illustration of this chart is given in Fig. 4.2 for seven departments [7].

Fig. 4.2 Sample activity relationship chart



A properly developed activity relationship chart is helpful in deciding on the location of facilities related to:

- Work centers or departments in an office/layout
- Activities in a service business
- Work centers in a maintenance or repair operation
- Service areas within a production facility

Based on either the from-to chart (a quantitative flow measure) or the relationship chart (a qualitative flow measure), the SLP approach generates the *relationship diagram*, which, as indicated earlier, places activities spatially. From the information on this diagram plus that from space requirements along with space available, the *space relationship diagram* is obtained. Now modifying considerations and practical limitations are combined with the space relationship diagram to develop a set of alternative layout plans. Finally, each plan goes through a systematic, objective, and consistent evaluation to select the one that is most attractive. A short description of the overall process follows.

In essence, the entire process consists of six major steps:

- Establish the relative degree of closeness among departments. Useful factors to be considered are: (a) flow of material, and (b) functional and service interaction.
- Establish space requirements given the quantity, kind, and shape of the facilities included in the layout.
- Create an *activity relationship chart*.
- Generate a space relationship diagram.
- Develop and evaluate alternative arrangements using factors such as ease of future expansion, flexibility, effectiveness of flow, material handling ease, material handling cost, safety, ease of supervision, and appearance.
- Select final layout accommodating the material handling system, storage facilities, and amount of personnel required, building features, and utilities.

Figure 4.3 outlines the main steps of the SLP approach.

It is noted that the SLP design process, being a conceptual approach, does not actually describe specific methods for product-mix segmentation, department planning, and developing alternative layouts. It provides a systematic and structured procedure to guide layout planners through a sequence of steps. A strategy to eliminate the limitations of SLP is to combine it with another technique known as production flow analysis (PFA).

Example 4.1

A factory has four planning departments (1, 2, 3, 4). **Product A** is manufactured according to the sequence 1-2-3-4 and **product B** according to the sequence 3-4-2-1-2. Daily production volumes of A and B are 10 and 20 parts, respectively. Both products have similar sizes, shapes, and material handling requirements. (a) Construct the from-to chart indicating the number of trips *from* one department *to* another. (b) Develop a relationship chart following these rules: “A” for any two

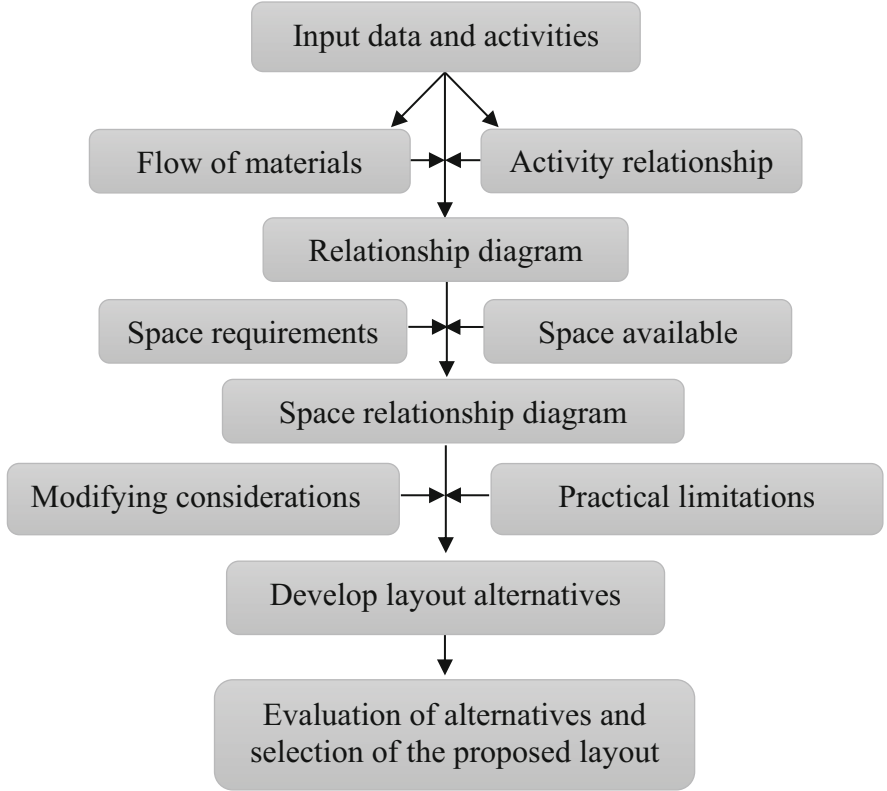


Fig. 4.3 Systematic layout planning

departments with a total number of trips (including both directions) equal to 40 or more; “E” for 30 or more but less than 40; “I” for 20 or more but less than 30; “O” for 10 or more but less than 20; “U” for less than 10.

Solution

Figure 4.4 shows the paths corresponding to the interdepartmental flows.

(a) The from–to chart for the given data is shown below:

From/To	1	2	3	4
1	-	10+20=30	-	-
2	20	-	10	-
3	-	-	-	10+20=30
4	-	20	-	-

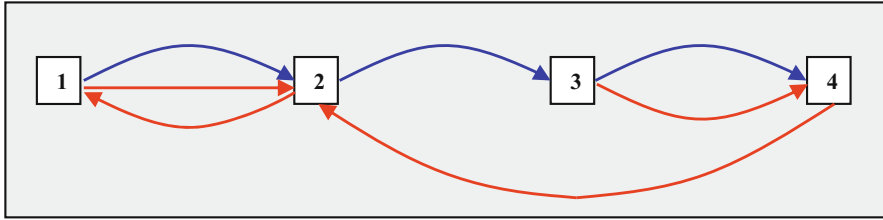
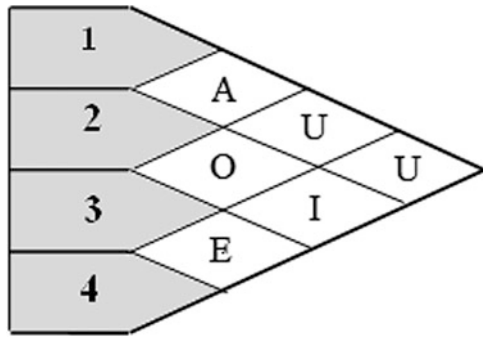


Fig. 4.4 Interdepartmental flows for Example 4.1

Fig. 4.5 Relationship chart for Example 4.1



(b) The relationship chart obtained from the specified rules can be obtained as follows. First, calculate the number of trips between any two departments:

- Between departments 1 and 2: 50 trips
- Between departments 1 and 3: 0 trips
- Between departments 1 and 4: 0 trips
- Between departments 2 and 3: 10 trips
- Between departments 2 and 4: 20 trips
- Between departments 3 and 4: 30 trips

From the specified rules, the relationship chart shown in Fig. 4.5 is obtained:

Example 4.2

In Example 4.1 assume that moving 2 units of component A is equivalent to moving 1 unit of component B as a result of B being twice as large as A. Find the from-to chart using component A as the reference product.

Solution

Using component A as the reference product, the following results are obtained:

From/To	1	2	3	4
1	-	10+40=50	-	-
2	40	-	10	-
3	-	-	-	10+40=50
4	-	40	-	-

4.3 From–To Chart Program

The input data required for the generation of a from–to chart consist of the production volume and the sequence of manufacturing processes for each part. Product is moved from a machine to the following one in batches of known size. We will consider two cases:

- No machine performs defective operations resulting in defective product. The number of parts processed in each machine is equal to the required output value of good parts. The FROMTO-1.xlsm program is used for this case.
- Some or all machines perform defective operations resulting in defective product. The number of parts processed in a machine is higher than the required output volume of good parts. The FROMTO-2.xlsm program is used for this case.

4.3.1 From–To Chart for Machines Without Defective Item Probabilities

An XLSM file is a macro-enabled spreadsheet created by Microsoft Excel. It contains worksheets of cells arranged by rows and columns as well as embedded macros programmed in the Visual Basic for Applications (VBA) language. The FROMTO-1.xlsm program contains six worksheets labeled as MENU, OPERATION, Sheet 1, INPUT, Sheet 4, and Sheet 5. The instructions for the from–to program are given in Table 4.1.

The MENU worksheet consists of two sections. The top section has the eight numbered red buttons (steps) used to input the data for an application. The bottom section shows the from–to chart for the given data. Following the instructions in Table 4.1 for Example 4.2, Fig. 4.6 shows the top section of the MENU worksheet along with the table of operational sequences displayed after clicking on button 7.

Table 4.1 Instructions for FROMTO-1.XLSM program

Button No.	Initial Steps
8	To reset all the values in the program, click on this button once at the start only.
1	Provide the total number of different parts to be produced (at most 15), and the number of departments (at most 20 machines).
2	Click on this button to reset all the values from the previous run of the program.
Button No.	Repetitive Steps for Each Part
3	Yellow cells are the input cells. Clear all the old values in the yellow cells before starting with the sequence of departments for the <i>first</i> part. Provide the part index (counter of parts) and the quantity of the part to be produced in the time period under consideration. Also, set the batch size that is going to be used for moving that part between departments. When the batch size is defined, the program computes the number of trips by using the formula $Number\ of\ trips = Quantity / Batch$.
4	Enter the sequence in which this part moves through the different departments in the yellow cells. Once the sequence is finished click on button 4.
5	Click on the “Total Part” button corresponding to the current part. For part number 1 click on “Total Part 1” and so on.
6	Click on the button labeled “Total”. The from-to chart is updated when you click on this button.
7	This step is optional. Click on the button “View Table” if it is desired to view the input provided for the current part. This input is shown on the “Operation Worksheet” To return to the input or main menu, then click on the “Menu Worksheet”. Once in the Menu Worksheet follow the steps 3 to 7 to input details for the remaining parts.
Steps	Creation of From-To Chart
(a)	Scroll down the “Menu Worksheet” until the from-to format is shown on the screen.
(b)	Choose the number of departments previously defined.
(c)	Click on the “Reset Value” after pressing the “Choose Department Number” button.
(d)	Choose the number of departments again.
(e)	Click on the “Show From-To Chart” button. This will update the chart for the given data.
(f)	Click on “Create From-To List for MCRAFT” and “Data File” buttons.

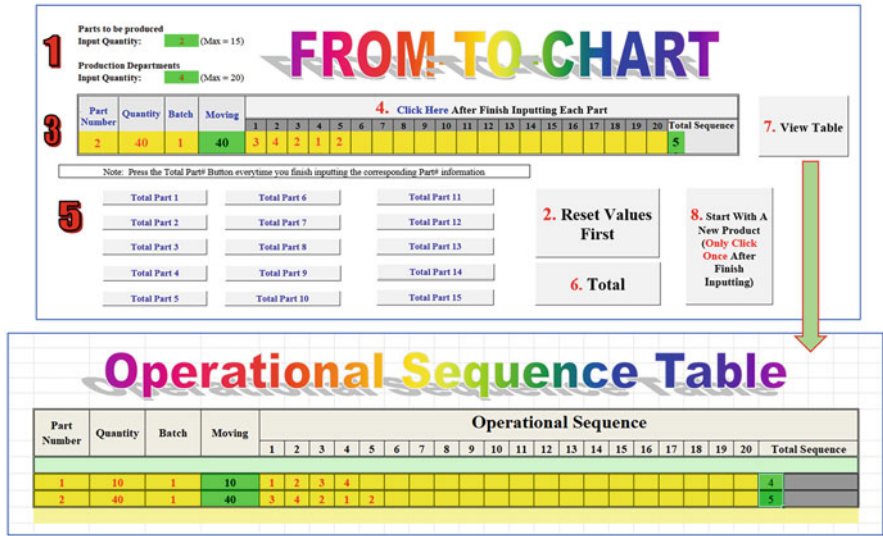


Fig. 4.6 FROMTO-1.xlsm program buttons

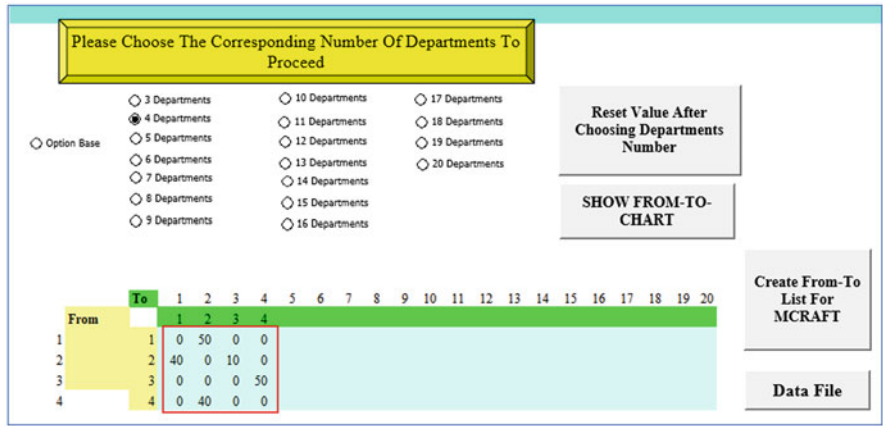


Fig. 4.7 Results from FROMTO-1.xlsm for Example 4.2

Figure 4.7 shows the bottom section with the corresponding From-to chart. This section has two buttons labeled “Create From-to List for MCRAFT” and “Data File” for generating data files used by CRAFT (Computerized Relative Allocation of Facilities Technique). This program is described in Sect. 4.9.

4.3.2 From-To Chart for Machines with Defective Item Probabilities

It is assumed that the machines performing manufacturing processes produce a fraction of defective items. The FROMTO-2.xlsm program is used for this option. This program is an extension of the FROMTO-1.xlsm program in which a new worksheet (Sheet 2) is created. Sheet 2 is a *template* that can be used for applications having up to 10 parts and 10 machines, although it can be modified to have more parts (up to 15) and machines (up to 20). A probability of defective product is assigned to each machine. Currently the sheet contains default probabilities that can be easily changed depending on the application.

- A. **Description of Sheet 2** As an illustration, the Worksheet 2 for Example 4.2 is shown in Fig. 4.8. This example considers two parts and four machines. The parts are numbered as 1 and 2; similarly, the machines are numbered as 1, 2, 3, and 4. The sheet has four sections. Each section is described as follows.

The **top section** contains the batch size and manufacturing process sequence for each part. This information is automatically copied from the OPERATION worksheet. To facilitate the building of the from-to chart, the operation sequences are expressed as connected moves through machine pairs. For example, the operation sequence 1-2-3-4 is expressed as 1 2 - 2 3 - 3 4 - 4. This sequence indicates that there are no part moves after 4.

The **second section** has the default defective item probabilities for the process machines shown in Table 4.2. Although the program allows up to 20 machines, the current template has been designed for 10 machines only. From the defective probabilities, shown below in cells with blank background, the worksheet calculates the probabilities of non-defective items, shown in the cells with yellow background.

The **third section** shows the from-to chart consolidating all parts. This chart is the result of adding the entries of all individual from-to charts associated with up to ten charts (found in the bottom section of the worksheet). The rows and columns of the chart are labeled with the corresponding machines (processes) numbers. For Example 4.2, the first four rows and first four columns are assigned the labels 1, 2, 3, and 4, respectively. Rows 5-10 and columns 5-10 are assigned the label #/NA, which indicates that the row and column numbers are not applicable. The result is shown in Fig. 4.8.

The **bottom section** shows the individual part from-to charts consolidated in the third section. The worksheet first calculates the number of batches of parts moved from one machine to another, as illustrated in Table 4.3 for part 1 in Example 4.2.

The sequence row in Table 4.3 indicates that part 1 initially moves from machine 1 to machine 2; then it moves from machine 2 to machine 3; finally, it moves from machine 3 to machine 4. Considering these moves in reverse order, the entry in the from-to chart for part 2 corresponding to the row 3 and column 4 is equal to $10/0.96 = 10.42$. Similarly, the entry for row 2 and column 3 is equal to $10.42/0.95 = 10.96$, and for the entry for row 1 and column 2 is equal to $10.96/$

FROM-TO CHART WITH DEFECTIVE ITEM PROBABILITIES FOR EACH MANUFACTURING PROCESS (MACHINE)

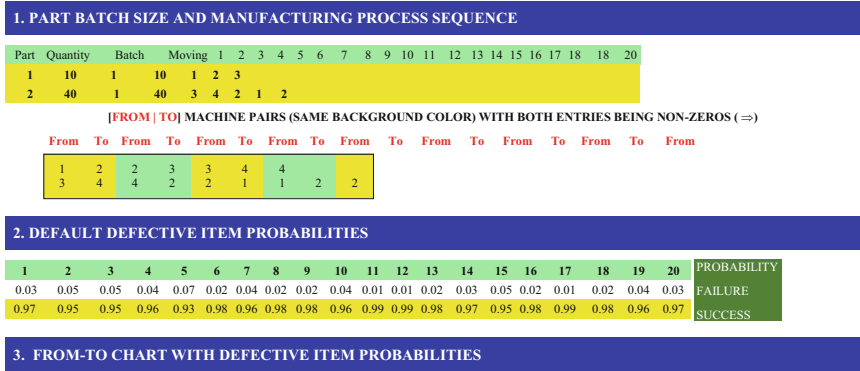


Fig. 4.8 Worksheet 2 of FROMTO-2.xlsm for Example 4.2

Table 4.2 Default defective item probabilities for process machines

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0.03	0.05	0.05	0.04	0.07	0.02	0.04	0.02	0.02	0.04	0.01	0.01	0.02	0.03	0.05	0.02	0.01	0.02	0.04	0.03
0.97	0.95	0.95	0.96	0.93	0.98	0.96	0.98	0.98	0.96	0.99	0.99	0.98	0.97	0.95	0.98	0.99	0.98	0.96	0.97

Table 4.3 Part 1 batches moved through the operational sequence in Example 4.2

Machine	1	2	3	4	5	6	7
Probability	0.97	0.95	0.95	0.96	0.93	0.98	0.96
Sequence	1	2	2	3	3	4	4
Batches Moved		11.54		10.96		10.42	
Output Value	10		0.95		0.95		0.96

Part	Quantity	Batch	Moving	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
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#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!

Fig. 4.9 Array formula for Example 4.2

Part	Quantity	Batch	Moving	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	10	1	10	1	2	3	4																
2	40	1	40	3	4	2	1	2															

Fig. 4.10 Content of array formula for Example 4.2

0.95 = 11.54. All other entries are equal to 0. The result for part 1 is shown in Fig. 4.8.

B. Instructions for Sheet 2

- This sheet is generated according to the following instructions:
1. Go to the MENU worksheet and click on button 8 twice.
 2. Go to Sheet 2 and clear the #REF! entries in the from–to charts of all parts.
 3. Return to the MENU worksheet and proceed as in the case of non-defective items to complete both top and bottom sections of this sheet (see Table 4.1). Furthermore, click on the “Create From–To List For MCRAFT” and “Data File” buttons.
 4. Go to Sheet 2. When clicking on the cell right below the Part heading, the formula bar at the top of the screen shows the array formula {=OPERATION!B8:Z8} of Fig. 4.9. By extending the cell containing the array to the right and then to the bottom of the yellow area, the screen shows the array given in Fig. 4.10.

4.4 Production Flow Analysis

Production flow analysis (PFA) is a technique that consolidates all relevant material flow information and alternative production routings to form manufacturing groups of facilities that can manufacture compatible groups of parts or components of a product based on the resources included in each facility group.

4.4.1 Overview of Conceptual Approach

Depending on the scale of the undertaking, the PFA logic can be applied at varying levels—an entire company, a factory, a portion of a factory, a production line, and a single tooling facility. In general, the procedure consists of the following steps:

- Identify and classify all production resources, machines, and equipment.
- Document all product designs and corresponding production routings for their components.
- Analyze part flows generated by the majority of parts.
- Develop alternative production routings and facilities groupings to obtain a simplified material flow system.
- Further study exceptional parts not fitting into the grouping of production resources.
- Validate and implement the new material flow system.

When properly designed and implemented, the PFA approach can identify causes of delay in material flows such as complex production sequences, high volume and variety of parts, variety of machines, ineffective facility layout, and inappropriate assignment of machines for operations, among others. In the case of a single factory, the overall process reduces itself to four stages:

- Factory flow analysis
- Group analysis
- Line analysis
- Tooling analysis

Factory flow analysis identifies significant material flows and their corresponding paths. Through minor redeployment of equipment, paths are redesigned to make them as much as possible direct and progressive (no backtracking).

Group analysis focuses on the flows in each of the shops. Operation sequences of the parts being produced are analyzed to identify manufacturing facilities groups (cells) in each shop. Loads are determined for each group (family) of parts to obtain equipment requirements for each cell. Although each cell usually contains all the equipment necessary to manufacture its part family, some intercell material flow may be allowed due to shared resources and nonavailability of equipment.

Line analysis generates a linear or U-layout for the machines contained in each cell.

Part routings and part volumes are used to develop a cell for efficient transport as well as minimum material handling and travel by operators.

Tooling analysis integrates the results obtained from group analysis and linear analysis with data on parts including shape, size, material, tooling, fixturing, and other relevant part attributes. Tooling analysis helps to schedule the cell by identifying families of parts with similar operation sequences, tooling, and setups. It seeks to sequence parts on each machine and to schedule all the machines in the cell to reduce setup times and batch sizes. This increases available machine capacity on bottleneck work centers in the cell.

4.4.2 Integration of SLP and PFA

SLP, being a conceptual rather than an algorithmic approach, lacks the ability to plan departments depending on the type of layout desired. More specifically, two limitations of SLP are the use of a from-to chart instead of the production routings (route sheets) and the inability to generate hybrid layouts that combine features of the process and cellular layouts. An integrated approach known as *production flow analysis and simplification toolkit (PFAST)* can overcome these two limitations, as a result of the algorithmic nature of PFA. This section provides a cohesive *conceptual* view to this integrated approach, based on work by Huang [4]. More details on the use of PFAST to design hybrid cellular layouts are found in the book by Irani and Huang [5].

A fundamental requirement for the design of modern facility layouts is the distribution of identical machines at multiple locations in the facility. The material flow network in any facility layout can be decomposed into a network of layout modules, with each module representing a portion of the entire facility.

A layout module is defined as a group of machines connected by a material flow network that exhibits a flow pattern characteristic of a specific type of layout, such as the product, cellular, or process layout. The concept of layout modules extends current thinking on input data requirements and methods for facility layout and supports the need for a new generation of facility layouts beyond the three traditional ones. Figure 4.11 shows the overall conceptual approach for integrating SLP with PFA.

The initial steps of the integrated approach are those of SLP. All relevant data to be collected can be classified into three categories. Facility-related data include size, manufacturing equipment, support services, and life cycle. Product data include product mix, quantities, revenues, demand information, growth patterns, frequency of orders, degree of demand stability, setup times, and standard times for all operations. Additional data are related to material handling and storage characteristics.

Now the PFA procedure is used, starting with the analysis for product-mix segmentation considering the number of part types to be manufactured and the

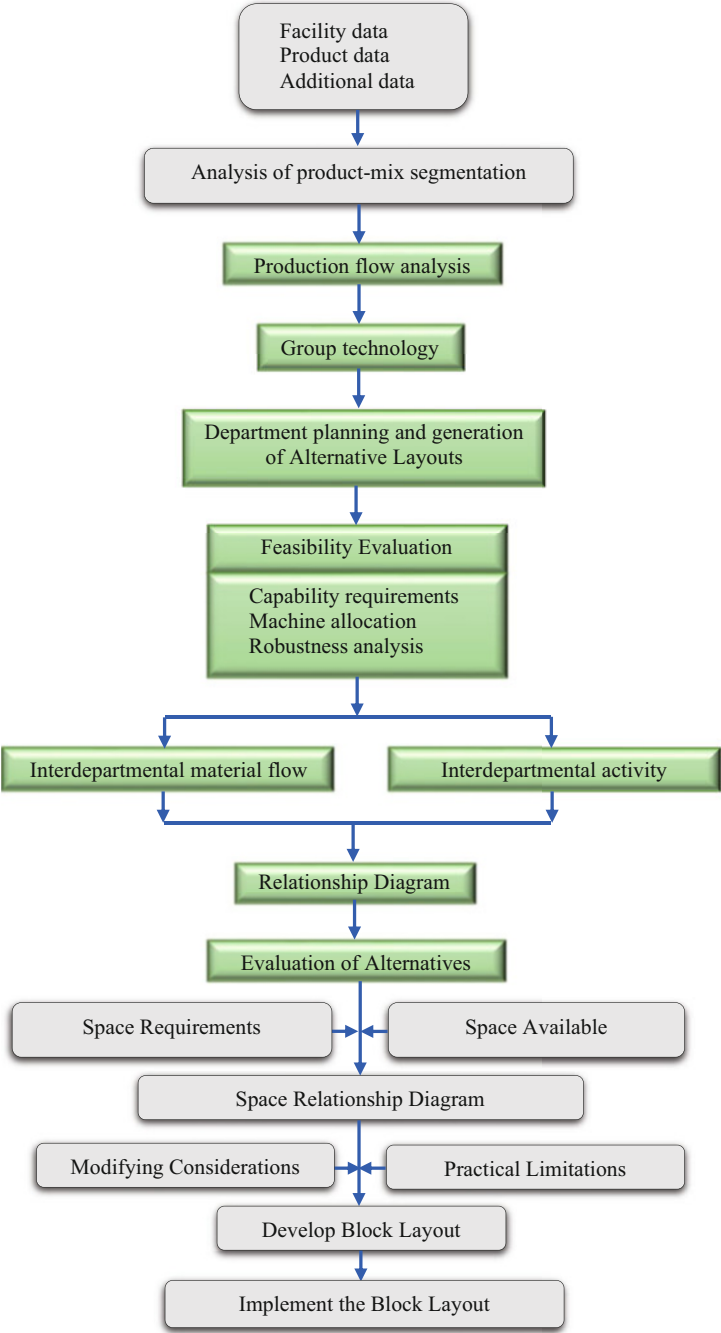


Fig. 4.11 Integrated systematic layout planning [4]

corresponding production flow analysis. This information along with a group technology procedure will result in the generation of production departments and layout alternatives for different types of manufacturing environments. Once the feasibility of the alternative layouts is checked with respect to capacity requirements, machine allocation, and sensitivity analyses for changes in product mix and demand, quantitative flow measurements and qualitative flow relationship are determined for each feasible alternative layout. After this step, relationship diagrams (for flow and for non-flow relationship) are determined.

The evaluation of feasible alternative layouts to select the final layout is performed by means of a series of analyses including closeness scores, material handling costs, activity-based costs, throughput estimation, inventory models, queuing theory, scheduling, and simulation.

From this point on, the SLP approach is used one more time to establish a space relationship diagram for the final layout on the basis of both space requirements and space available. The inclusion of modifying considerations and practical limitations will transform the space relationship diagram into a block layout. After this, the recommended block layout is implemented.

4.5 Flow Planning

Modern manufacturing techniques require a flexible approach to facilities planning. The first principle of plant layout continues to be *flow*, or more simply, “*the best flow is no flow*.” Manufacturing has become increasingly cellular in nature, with U-shaped flow patterns that allow adjacent input and output areas, so that operators can tend more than one machine efficiently. The spine concept for services and traffic aisles is quite compatible with cellular manufacturing. As the need for long aisles continues to be diminished, the spine becomes more likely to be U-shaped. The spine contains the central electricity, compressed air, heating, plumbing, telephones, and other systems as well as service facilities, such as maintenance, offices, personnel, and material handling.

The material flow pattern becomes the foundation not only for the basic design of the facility but also for the overall efficiency of the entire operation [1]. Material flow in a typical manufacturing facility is a critical activity in accomplishing timely product deliveries, since it may be affected by a number of dynamic factors, most importantly by delivery schedules, availability of material handling equipment, routes of movement, and aisle widths. Patterns of flow exist within workstations, within departments, and between departments.

Flow planning results from an efficient integration of *flow patterns* and *adequate aisles* to provide smooth and progressive movement of people, materials, and equipment.

Essentially, three principles or guidelines can be used to promote effective flow patterns:

1. Increase direct flow paths by designing paths with no intersections and no backtracking. A direct flow path has uninterrupted flow from origin to destination. Congestion and undesirable intersections may occur when flow paths are interrupted.
2. Reduce flow by applying principles of work simplification. Motion studies and ergonomic considerations are important in establishing the flow *within workstations*, which should be simultaneous (coordinated use of hands, arms, and feet), symmetrical (coordination of movements about the center of the body), natural (movements are continuous, curved, and make use of momentum), as well as rhythmical and habitual (flow allows a methodological and automatic sequence of activities, reducing mental, eye, and muscle fatigue). The reduction of flow can be achieved by work simplification strategies, including:
 - Eliminating flow by planning for the delivery of materials, information, or people directly to the point of ultimate use, eliminating intermediate steps.
 - Minimizing multiple flows by planning for flow between two consecutive points of use to take place in as few movements as possible.
 - Combining flows and operations whenever possible by planning for the movement of materials, information, or people to be combined with a processing step.
3. Reduce flow costs. Strategies that reduce or minimize flow costs lower handling times, travel distances, and handling operations, especially expensive manual operations. Manual operations can be generally replaced by means of mechanization and automation of the handling process.

Concerning aisles on the layout, the following factors are relevant in the determination of proper widths.

- Use of the aisle: material, personnel, handling equipment, machinery, and other equipment
- Frequency of use: volume of traffic (at peak loads)
- Speed of travel permitted or desired
- One-way traffic or both
- Future conditions (type and frequency of movements)

Table 4.4 summarizes standard aisle widths for typical use in manufacturing factories using trucks, stock trucks, and several types of fork trucks.

Flow patterns *within departments* depend on the type of departments planned for a layout. In product and product family departments the flow pattern is the one followed by the product, as parts move along the sequence of workstations or machines that perform the operations transforming the raw material and intermediate material into a final product. Furthermore, in a process department there should be

Table 4.4 Aisle widths

Type of use	Suggested aisle widths
For personnel only (2 persons to pass)	30 inches minimum
For two-wheel hand truck (no passing or turning with load)	30 inches minimum
For stock truck (where trucker must pass around it)	20 inches plus width of truck
For stock truck (where other trucks and workers must pass)	38 inches plus two times width of trucks
For hand-operated fork truck, pallet transporter, semi-live skid, and jack	5–8 feet, depending on the nature of load
For 2000-pound fork truck type	8–10 feet
For 4000-pound fork truck	10–12 feet
For 6000-pound fork truck	12–14 feet

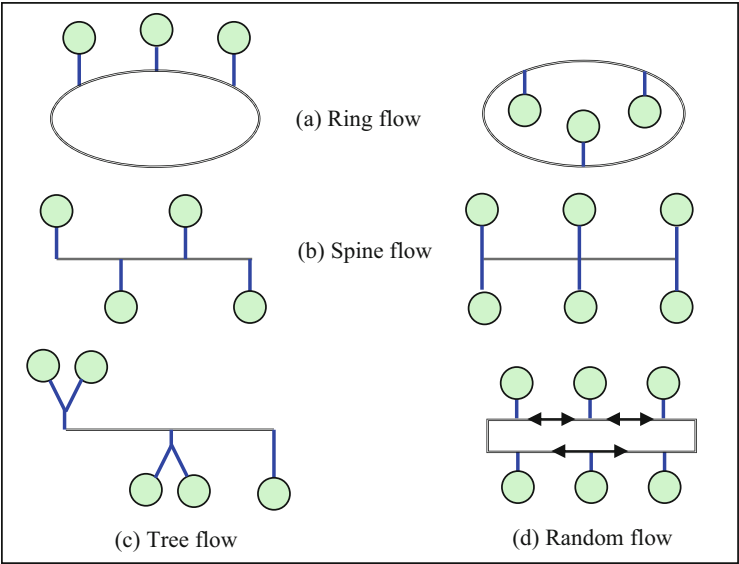


Fig. 4.12 Flows within departments

rather low flows between workstations or machines. Flow within a department can be classified into the patterns illustrated in Fig. 4.12.

Flow *between departments* is a criterion often used to evaluate flow within a facility. The between-departments flow typically is a combination of the basic horizontal flow patterns shown in Fig. 4.13. An important consideration in combining the flow patterns is the location of the entrance (receiving department) and exit (shipping department).

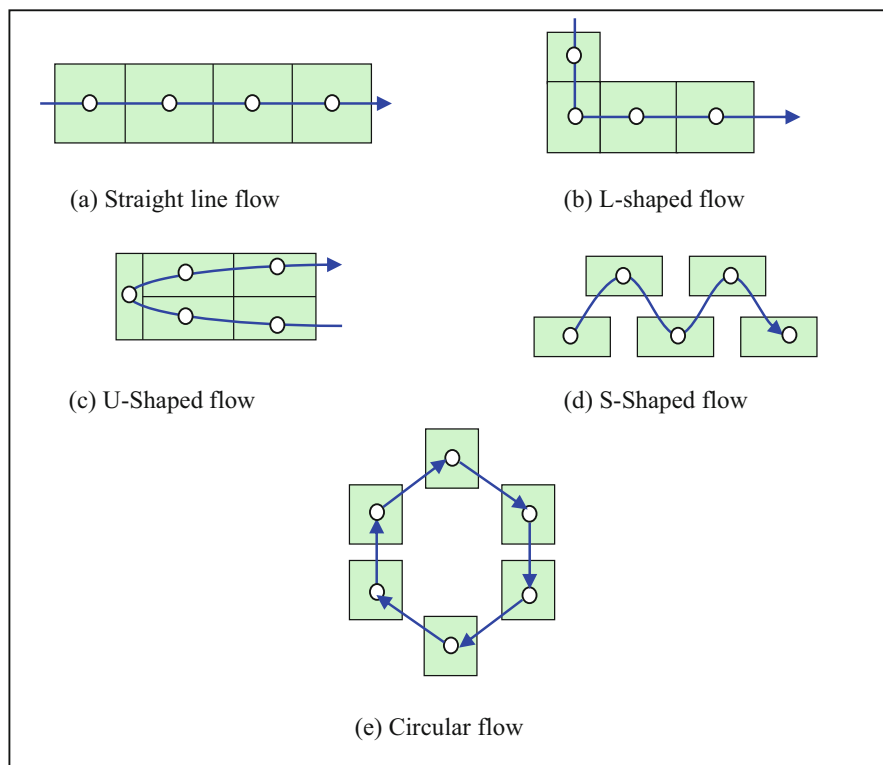


Fig. 4.13 Flows between departments

4.6 Layout Planning Chart

This chart documents the entire *sequence* of activities required to transform raw materials into subassemblies and assemblies resulting in a part of component of a product. Once workstations are grouped into planning departments, and storage areas and their requirements are identified, along with proper aisle widths, the information on all layout planning charts can be *converted* into a preliminary physical arrangement of the facilities on the available area.

The layout planning chart consolidates process information, available work period, and production quantity requirements to generate data upon which to estimate manpower and machine requirements, as well as material handling and storage methods. The *heading of the layout planning chart* provides the following information:

- Part name and identification code
- Assembly name and identification code
- Material type and quantity

- Pieces per assembly (for the assembly containing the part being documented)
- Assemblies per product
- Daily production
- Production hours per day
- Part size or weight
- Lot size

The part identification code and its name, the assembly identification code and its name, and the material type and quantity are obtained directly from the corresponding route sheet. The *body of the layout planning chart*, one for each part, documents the following:

- Flow process in terms of the *sequence* of the activities needed to manufacture a part: **fabrication (F)**, **move (M)**, **storage or delay (S)**, and **inspection (I)**
- Standard time for each *fabrication* operation
- Machine selection
- Machine balance
- Manpower requirements
- Manpower balance
- Material handling (load, method, equipment)

For each fabrication (manufacturing or assembly) operation, the chart specifies the standard time per piece or per lot (when appropriate), machine type and required number of machines, the manpower requirement, and the material handling requirements. By analyzing each operation in the sequence documented on a layout planning chart, the designer is forced to determine how often a type of operation (F, M, S, I) takes place, the most effective type of facility required by the operation, and the associated manpower requirements. In particular, the information on type of moves, frequency of moves, origins and destinations of moves, quantities being moved, and time required by each move is essential to decide what is the most effective and efficient material handling system, as well as to balance machine utilization and manpower by distributing work among machines of the same type and operators (individual operators or crews) in a manner resulting in uniform workloads.

Table 4.5 shows the layout planning chart for the paper holder front, part 1CS-01, of the revolving desktop organizer [3]. The following symbols are used in the chart:

- ◊ Fabrication operation (F)
- Move (M)
- △ Storage (S)
- Inspection (I)

Table 4.5 Layout planning chart

TABLE 4.5 Layout Planning Chart																
LAYOUT PLANNING CHART																
PART No <u>1CS-0P</u>					CS/ASSY <u>1</u>					PCS REQD/HR <u>128</u>						
PART NAME <u>Paper Holder Front</u>					ASSY/PRODUCT <u>2</u>					PROD HRS/DAY <u>8</u>						
ASSEMBLY No <u>SA5</u>					PCS/DAY <u>1500</u>					LOT SIZE <u>1 (SA5)</u>						
MATERIAL <u>Natural Birch</u>					SIZE <u>0.1282 lb</u>					PAGE <u>15 OF 28</u>						
PREPARED BY <u>Marcus Brown</u>										DATE <u>03/04/03</u>						
STEP No.	F M S I	DESCRIPTION	TIME PER PIECE (sec)	MACHINE OR EQUIPMENT	MACHINE REQUIRED			TOTAL MANPOWER				HANDLING REQUIREMENTS			REMARKS	
					MACH FRAC	COMB WITH	MACH REQD	CREW FRAC	MAN FRAC	COMB WITH	MEN REQD	HOW MOVED	CONT TYPE	LOAD SIZE (LB)		DIST MOVED (ft)
1	△△△	From material storage						0.9658	0.0015	A	1	Forklift	Pallet	500 32.03	26,9387	
2	△△△	Cut to height	8	10" Table Saw	0.5292	Alt TS (5.1930)	6	1.0095	0.2646	C	1					
3	△△△	To wood shaper						1.0095	0.0021	C	1	By hand	Cart		20,0459	
4	△△△	Route outside edges	15	Wood Shaper	0.9923	Alt WS (6.8518)	7	0.997	0.1323	S	1					
5	△△△	To portable router						0.997	0.0025	S	1	By hand	Cart		29,7046	
6	△△△	Route arc	20	Portable Router	0.6615	Alt PR (4.6307)	5	0.9957	0.6615	U	4					
7	△△△	To combination sander						0.9957	0.0067	U	4	By hand	Cart		61,5795	
8	△△△	Sand all edges	10	Combination Sander	0.6615	Alt CS (8.7322)	9	0.9762	0.6615	AE	2					
9	△△△	To sprayer						0.9762	0.0047	AE	2	By hand	Cart		30,7168	
10	△△△	Lacquer all surfaces	5	Sprayer	0.3307	Alt S (1.000)	1	0.9921	00.3307	AD	1					
11	△△△	To drying oven							NA			Conveyor	Pincher		NA	
12	△△△	Dry lacquer	600	Drying Oven	33.69	Alt DO (476.3)	1		NA							
13	△△△	To sub-assembly						0.9762	0.0048	AE	2	By hand	Cart		NA	

4.7 Space Requirements

After the activity relationships have been decided, a proper amount of space must be determined for each one. Space planning involves arranging the elements of a plan in response to the functional requirements of the programmed activities. The interrelationships of the activities themselves are the most variable factors in the interpretation of the program. Planning, however, must take into account the likelihood of changes in future space requirements.

Most buildings incorporate two types of space: committed and uncommitted. Committed spaces, because of specific requirements or spatial configuration, are designed or used for only a particular activity. Committed space is difficult to adapt to new uses. Uncommitted spaces have no definite character, allowing their use for many unspecialized functions, multiple use, and flexibility for change. Space allocation in a facility bears a close relation to the equipment, material, personnel, and activities carried on in a department.

Activities to be considered in determining space requirements are: offices, receiving and shipping operations, storage, production, tool rooms, maintenance, warehouses, material handling, parking, and various service activities. Three widely applied methods for determining space requirements are described by Konz [8]:

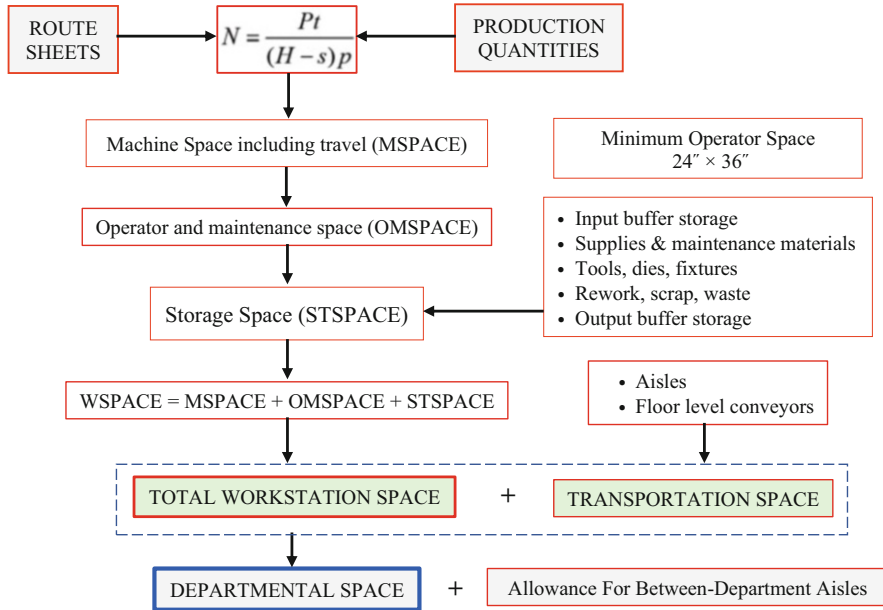


Fig. 4.14 Calculation of space requirements

A. **Calculation Method:** Each workstation is a manufacturing facility having its own receiving and shipping, production, and storage areas. The workstation space is equal to the machine space, including travel, operator and maintenance space, and storage space. For each department the space is equal to number of workstations multiplied by the average workstation space plus transportation space. Transportation space is primarily for aisles but can include space for material handling equipment such as floor-level conveyors. In addition to within-department space, we can add an allowance (e.g., 10%) for between-department aisles. Figure 4.14 shows the steps for calculating space requirements.

As can be seen in Fig. 4.14, workstation space merges machine space including travel, operator and maintenance space, and storage space. Space may need to be allocated on one or more sides of the machine for a seated or standing operator. When the operator obtains and disposes off items, in addition to processing items, space should be planned for reaching the machine from an aisle; for this reason, the required space may exceed the minimum of 24" × 36". Furthermore, maintenance and service space allows access to machines that usually are not movable. Storage space is typically calculated based on input buffer storage of product; supplies and maintenance materials; tools, dies, fixtures; rework, scrap, waste; and output buffer storage of product. Supplies include empty containers, packaging materials, tool bits, and so forth. Finally, it is noted that when multilevel storage is used, floor space may be saved for other activities.

- B. **Conversion Method:** This method estimates the new space from the present space. This should be done department by department, instead of directly for the entire facility.
- C. **Space Standards Method:** This method is most appropriate for service and storage areas. Using standards, we can estimate the amount of space. Chapter 11 provides standards for office space planning.

4.8 A Closeness Relationship Procedure for Layout Planning

The procedure presented in this section can be viewed as an expanded adaptation of an earlier program developed by S. Khator and C. Moodie [7]. The program was originally intended to assist in layout planning using a relationship chart as input, but lacked the ability to perform the placement of departments on the factory floor to generate a layout. We have significantly modified it to include algorithmic steps for placing departments on a layout.

4.8.1 Description of Procedure

The procedure accepts input in the form of a relationship matrix. Then, using the closeness codes A, E, I, O, U, and X, it determines a *closeness rank* and a *selection order of departments*. After a numerical value is given to each closeness code, the departments are placed on the *layout* according to the predetermined selection order, in such a way that the *score* of the layout will be as high as possible.

Closeness ranks are determined on the basis of the number of A, E, I, O, and X closeness relationships. A method for doing this is to consider first the departments having A relationships, then those having E relationships, and so on. The department having the largest number of A relationships is assigned rank 1. In case of ties, the rank will be decided by the largest number of E relationships; if ties continue to exist, they will be broken by the largest number of I relationships, and so on. If two departments have the same number of A, E, I, and O relationships, the one having the lowest number of X relationships will be chosen first. Once all departments having A relationships are assigned closeness ranks, those departments having E relationships are considered, and so on. At the end of this procedure, each department is assigned a rank, rank 1 for the most important, rank 2 for the one next in importance, and so on.

The *selection order* of departments is determined according to the following procedure. The first department is that assigned rank 1. The second department is one having an A relationship with it; in case of ties, these will be broken by selecting

the department having a higher level of importance, as measured by the closeness rank. Subsequent departments are chosen on the basis of the total number of A, E, I, and O relationships between the department being selected and all those already selected, using the rank to break ties.

Departments are then placed on the open floor space according to their selection order to form a *layout*. Departments are arranged in such a way that the closeness relationships between adjacent departments are as high as possible. The *evaluation* of the layout is performed by determining a numerical value for each pair of adjacent departments and finding the sum of all pairs. Example 4.3 illustrates the entire procedure.

4.8.2 Illustration of Procedure

Example 4.3 is specifically designed to provide a detailed illustration of the four steps followed in the previously described layout procedure: determination of closeness ranks, selection order of departments, layout generation, and layout evaluation.

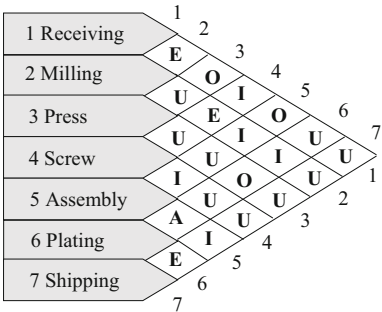
Example 4.3

The departmental area requirements and closeness relationship chart for seven departments are provided by Khator and Moodie [7]. It is desired to determine (a) the closeness ranks, (b) selection order, (c) departmental layout, and (d) evaluation score.

Departmental Area Requirements

Departments	Area (sq ft)
1. Receiving	12,000
2. Milling	8,000
3. Press	6,000
4. Screw Machine	12,000
5. Assembly	8,000
6. Plating	12,000
7. Shipping	12,000

Closeness Relationship Chart



Solution

Closeness Rank The closeness rank is calculated for each department on the basis of the number of A, E, I, O, and X relationships.

Departments	Number of each Type of Relationship					
	A	E	I	O	U	X
1. Receiving	0	1	1	2	2	0
2. Milling	0	2	2	0	2	0
3. Press	0	0	0	2	4	0
4. Screw machine	0	1	2	0	3	0
5. Assembly	1	0	3	1	1	0
6. Plating	1	1	1	1	2	0
7. Shipping	0	1	1	0	4	0

The departments having the largest number of A relationships (one each) are 5 and 6. In this case, there is a tie between departments 5 and 6. Now we look at the number of E relationships for departments 5 and 6:

Department 6 $\Rightarrow$ 1 A, 1 E

Department 5 $\Rightarrow$ 1 A, 0 E

Department 6 has the largest number of E's. Department 6 will receive rank 1 and department 5 rank 2. Choose department 6 and then 5.

Now we consider departments 1, 2, 3, 4, and 7. None of these have A relationships. Now we look for E relationships:

Department 1 $\Rightarrow$ 0 A, 1 E

Department 2 $\Rightarrow$ 0 A, 2 E

Department 3 $\Rightarrow$ 0 A, 0 E

Department 4 $\Rightarrow$ 0 A, 1 E

Department 7 $\Rightarrow$ 0 A, 1 E

Therefore, department 2 will receive rank 3.

Departments 1, 4, and 7 have the same number of E relationships. We look now for the number of I relationships. After this, we have the following results:

Department 1 $\Rightarrow$ 1 E, 1 I

Department 4 $\Rightarrow$ 1 E, 2 I

Department 7 $\Rightarrow$ 1 E, 1 I

Department 4 will receive rank 4.

Departments 1 and 7 have the same number of I relationships. Then we look for O relationships:

Department 1 $\Rightarrow$ 1 I, 2 O

Department 7 $\Rightarrow$ 1 I, 0 O

Department 1 will receive rank 5 and then department 7 will receive rank 6. Finally, department 3 will receive the last rank, rank 7. In conclusion, the following ranks have been obtained:

Rank	1	2	3	4	5	6	7
Department	6	5	2	4	1	7	3

Selection Order The selection order is determined by first identifying the most important department (rank 1). Thus, department 6 is selected first. The next department is one having an A relationship with the department selected earlier. If none has an A relationship, the search is made for a department with an E relationship, and so on. In case of ties the most important department, as indicated by its rank, is selected. Looking at the activity relationship diagram, we see that department 5 has an A relationship with department 6. Department 5 is selected second. For the remaining departments—1, 2, 3, 4, and 7—we find the one having the best set of relationships with departments 6 and 5:

Relationship with departments already selected	Department				
	1	2	3	4	7
Number of A's	0	0	0	0	0
Number of E's	0	0	0	0	1
Number of I's	0	2	0	1	1
Number of O's	1	0	1	0	0

Department 7 has one E and one I relationships with those chosen. Note that this is better than department 2's two I relationships. Therefore, department 7 is selected third. As an exercise, the students can verify that the following selection order of departments is obtained:

Selection	1	2	3	4	5	6	7
Department	6	5	7	2	4	1	3

Generation of Layout Departments are physically arranged in the order previously specified. Departments having higher closeness relationships should be adjacent if possible, keeping in mind constraints on departmental area and total layout area. The layout shown in Fig. 4.15 corresponds to the relationship chart given

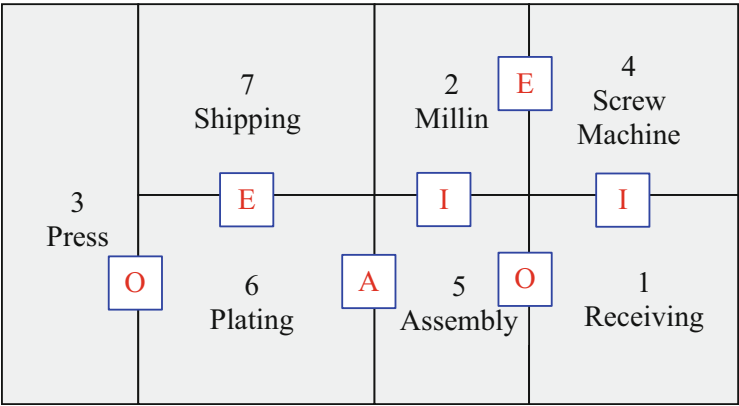
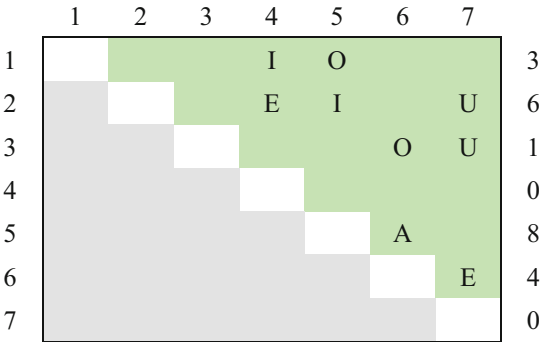


Fig. 4.15 Layout for Example 4.3

Fig. 4.16 Evaluation of layout for Example 4.3



below. It is assumed that the total departmental area is equal or less than the available space.

Evaluation of Layout To score the layout, the closeness relationships are given numerical values (for example, A = 8, E = 6, I = 4, O = 2, U = 0, X = -8) and for every adjacency shown on the layout, the corresponding numerical value is added to the score. Figure 4.16 shows the closeness relationships corresponding to adjacent departments. The calculations for the score are also shown. The score of the layout is equal to $3 + 6 + 1 + 0 + 8 + 4 + 0 = 22$.

4.9 Computerized Layout Procedures for Factory Layout Project

The final layout includes both the factory layout (Section III of the layout project) and the office layout (Section V of the layout project). The following computerized procedures are available for the students to develop their factory layout project. Each procedure follows a methodology based on the fundamental principles of systematic layout planning, with its own advantages and limitations. It is recommended that at least one of the procedures should be used for the factory layout and another one for the office layout.

- Facilities Layout Program (FLAP). This procedure is presented in Sect. 4.10.
- Computerized Relative Allocation of Facilities Technique (CRAFT). This procedure is presented in Sect. 4.11.
- Multi-Attribute Facility Layout and Design (MAFLAD). This procedure is presented in Sect. 4.12.

It is noted that the factory design project is intended to be a deterministic layout undertaking. When a stochastic layout is needed, a computerized procedure based on an algorithm referred to as STEP (*Sample Test Pairwise Exchange Procedure*) can be used. This procedure is described in Sect. 6.7.

4.10 Facilities Layout Program (FLAP) [9]

The Facilities Layout Program (FLAP) executes seven steps, as indicated in Fig. 4.17. The data input for the program is the closeness relationship chart. If, instead of this, there is a from-to chart available, this will be converted into a relationship chart. As indicated in the figure, two procedures are proposed for layout generation.

LAYOUT 1 PROCEDURE: In this procedure, the departmental placement pattern is based primarily on the length of the plant, whether it is even or odd.

Even Plant Length. The departmental placement pattern is illustrated in Fig. 4.18a. The number of cells in the grid shown is equal to the product of the length and the width of the plant. The procedure begins by separating the first three rows from the remaining rows by the thick line shown in the figure. Departments are considered according to the predetermined selection order. The allocation of the layout cells to departments starts at the top left cell, labeled “Start,” and proceeds vertically along the columns of the grid, without going beyond the thick line, and following a continuous S-shaped pattern until it reaches the third cell from the end. At this time, as marked by the label “Change” in the figure, the placement continues

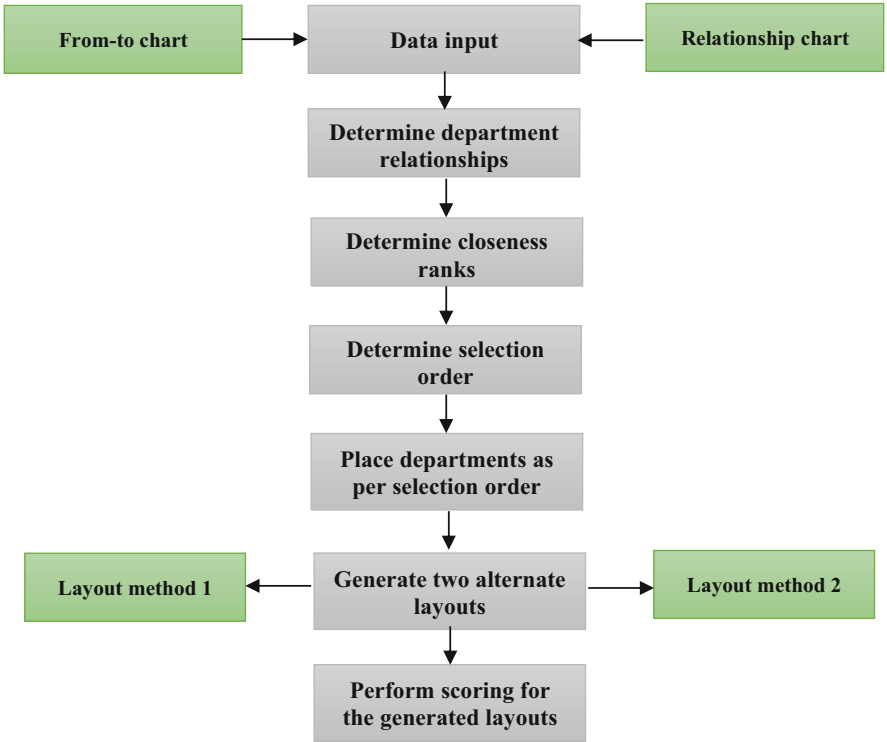


Fig. 4.17 Steps of the FLAP program procedure

Fig. 4.19 Pattern for Layout 2

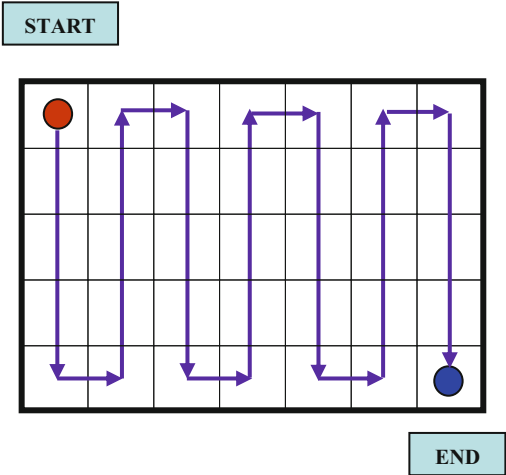


Table 4.6 Percentages for closeness codes

Percentage range	Relationship
90–100	A
75–89.9	E
55–74.9	I
30–54.9	O
0–29.9	U

Generating Relationship Charts from From–To Charts: The FLAP program accepts as input either a from–to chart or a relationship chart. However, as described earlier in this section, the closeness ranks and order of selection are determined on the basis of a relationship chart. For this reason, when a from–to chart is provided, the program converts it into relationship chart.

To accomplish the generation of a relationship chart, first the total flow between all departments is calculated by the program and it is assigned a weight of 100%. Then, for each entry of the from–to chart, the corresponding percent is obtained by comparing the flow of the entry to the total flow. The closeness codes are now assigned to each entry following the guidelines shown in Table 4.6.

4.10.1 Overview and Illustration of Program FLAP

FLAP was developed and coded in Visual Basic 6.0 by Pradip K. Krishnadevarajan in 2003 [9]. As a construction layout procedure, FLAP performs these four phases of layout planning [7]:

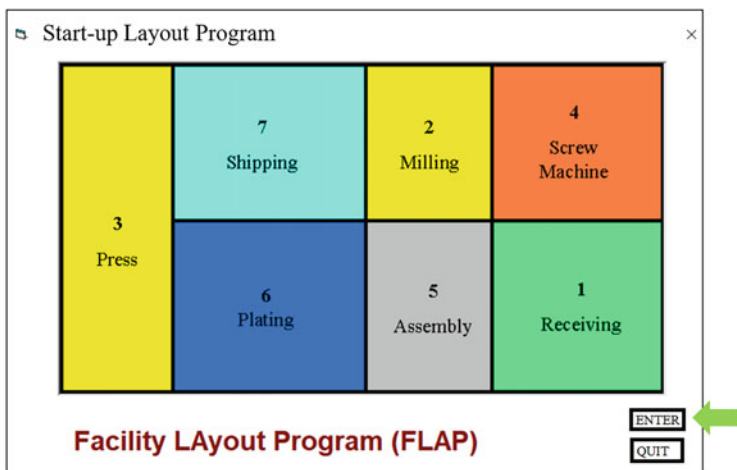


Fig. 4.20 Opening screen

1. Transplantation phase: development of a relationship or from-to chart.
2. Selection phase: determination of selection order on the basis of relationship between departments.
3. Placement phase: development of a systematic procedure to create layout.
4. Evaluation phase: computation of a score based on closeness relationships.

FLAP aids the user in generating a facility layout by acting as a decision support system tool and creating a highly user-friendly environment. Figure 4.20 shows the opening screen. This screen allows the user to either start the process or quit the program.

Figure 4.21 shows nine computer screens to illustrate the steps included in an application of FLAP using the data of Example 4.3. The total area required for the seven departments is equal to 70,000 square feet. Using area units equal to 1000 square feet, the required area is equal to 70. This corresponds to a rectangular area of dimensions 10×7 .

Screen ❶ shows three options for the user to provide input data: building the relationship chart (Option A), opening an available relationship (Option B), and opening an available from-to chart (Option C).

Option A. Build Relationship Chart: This option allows the user to key in the closeness relations (A, E, I, O, U, X) between the departments manually after selecting the number of departments (ranging from 3 to 40). In the application illustrated in Fig. 4.21, Option A is selected, and the number of departments is set equal to 7.

Option B. Open an Available Relationship Chart: When the number of departments is rather high, a more convenient option is to import the chart. The input file is a one-column text file named *anyname.txt*. The first line of the file contains the word RELATION. The second line has the number of departments. Starting

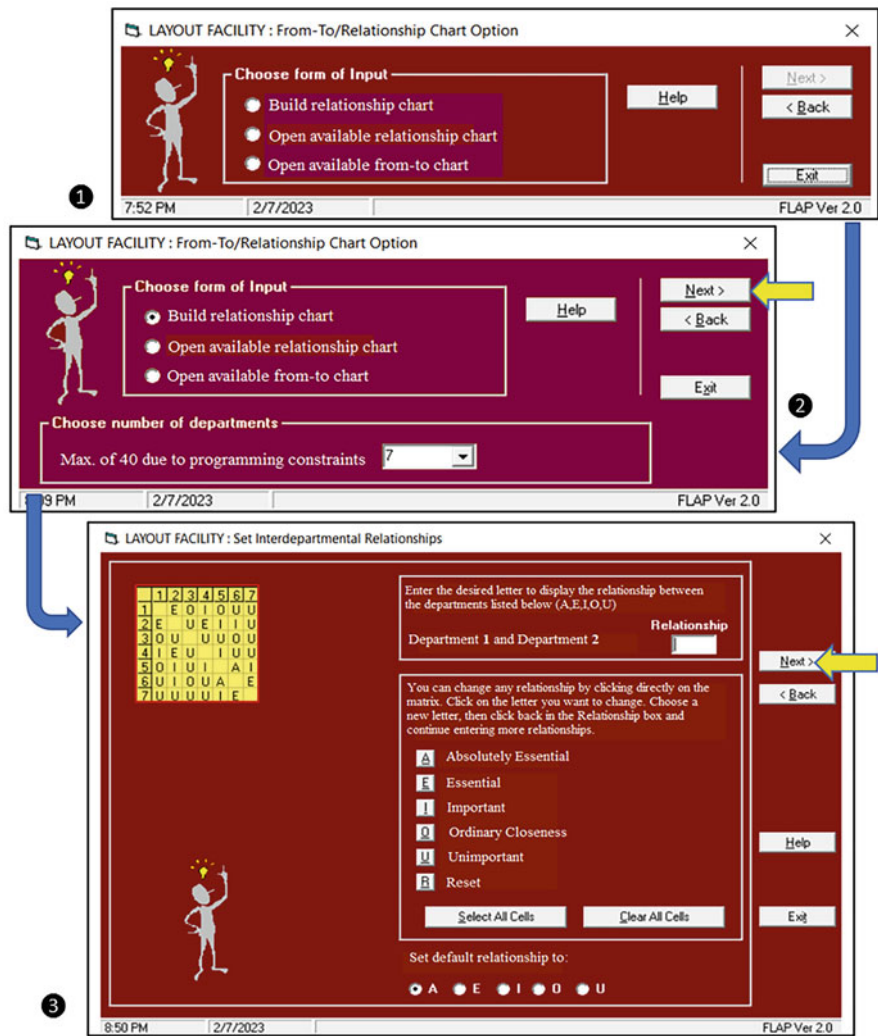


Fig. 4.21 FLAP computer screens for Example 4.3

with the third line, the relationships for the first department are provided, one relationship on each line; each entry is one of the letters A, E, I, O, U, or X. These letters are consecutively typed in either uppercase or lowercase. Once all relationships are specified for the first department, those for the second department are provided, and this procedure is repeated until all relationships are specified.

Option C. Open an Available From-To Chart: This option allows the user to import a one-column text file named *anyname.txt* containing the trip data between

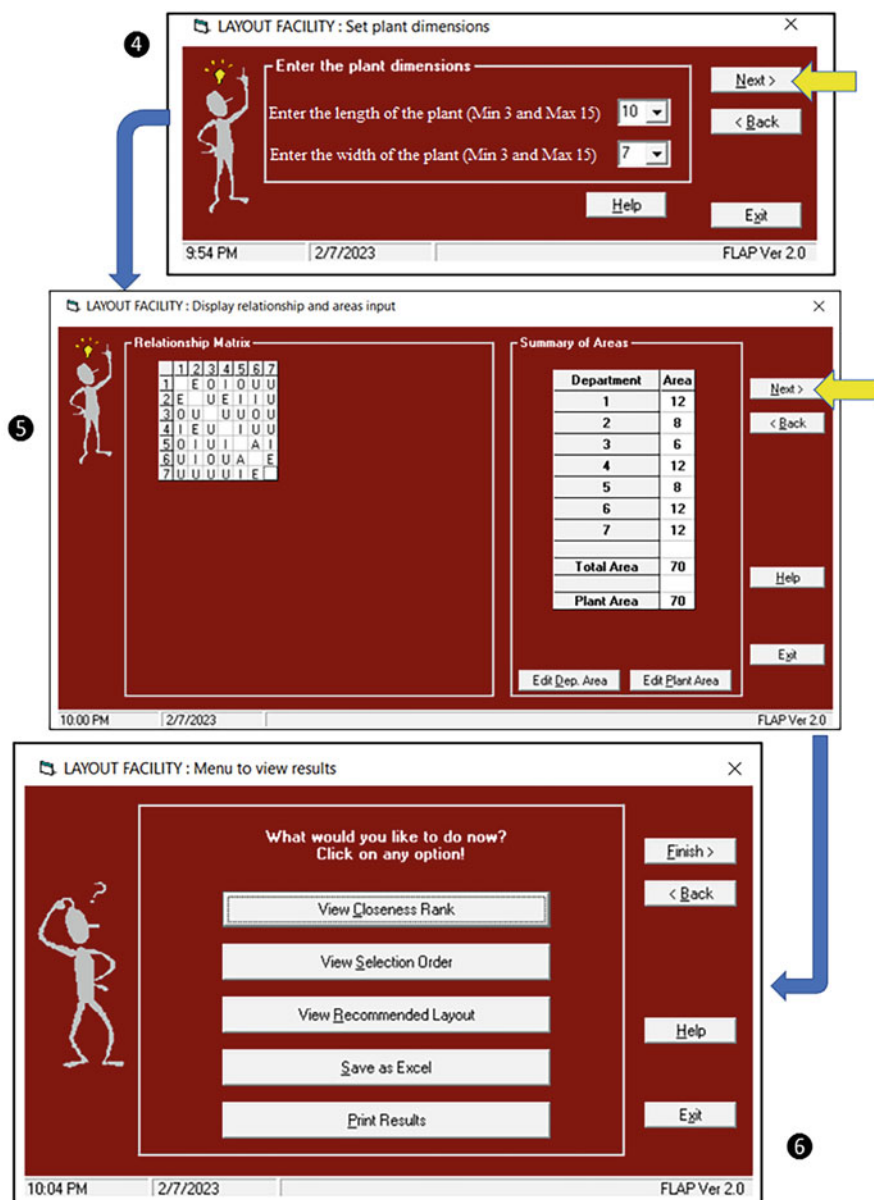


Fig. 4.21 (continued)

departments. The first line contains the word FROM. The second line shows the number of departments. The third line is set equal to zero and shows the beginning of trip data for department 1. The number of trips from department 1 to each other department is given on the lines that follow, starting with the

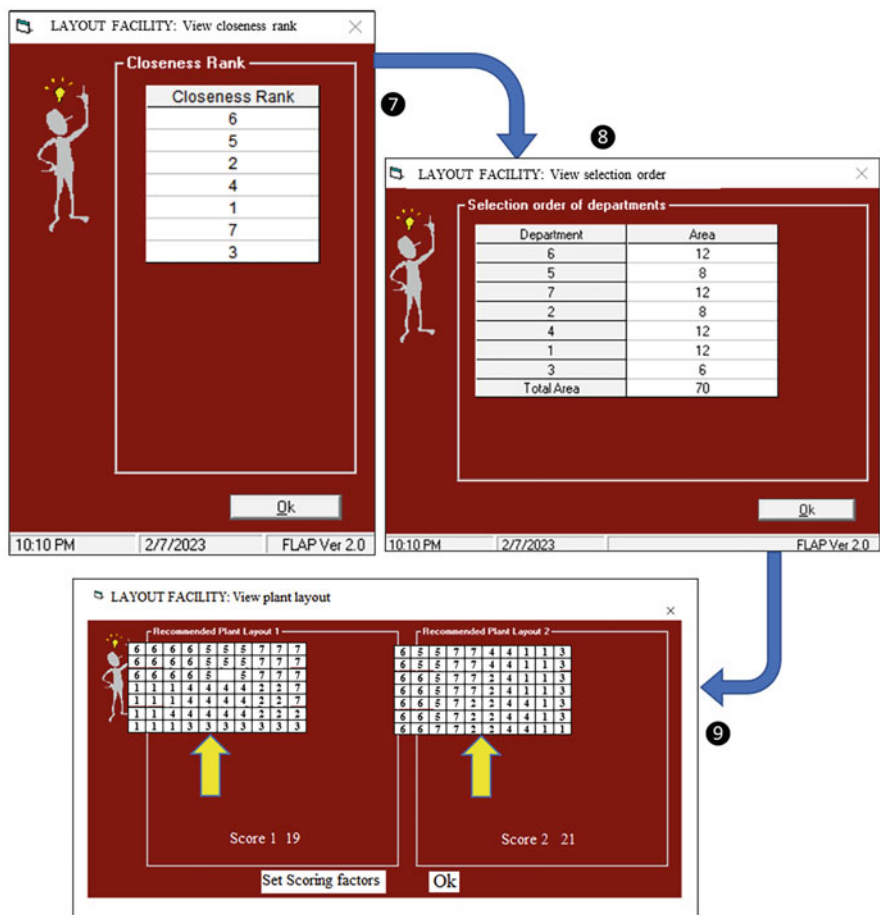


Fig. 4.21 (continued)

fourth. Once the trip data are completed for any department, the next line is set equal to zero to indicate the beginning of trip data for the next department, and so on.

Screen ② chooses Option A and enters the number of departments. Screen ③ shows the relationship matrix with the closeness codes for the departments. Screen ④ sets the plant dimensions. Screen ⑤ displays relationship chart and departmental areas. Screen ⑥ has a menu to view results:

- Closeness ranks (Screen ⑦)
- Selection order of departments (Screen ⑧)
- Recommended layout (Screen ⑨)

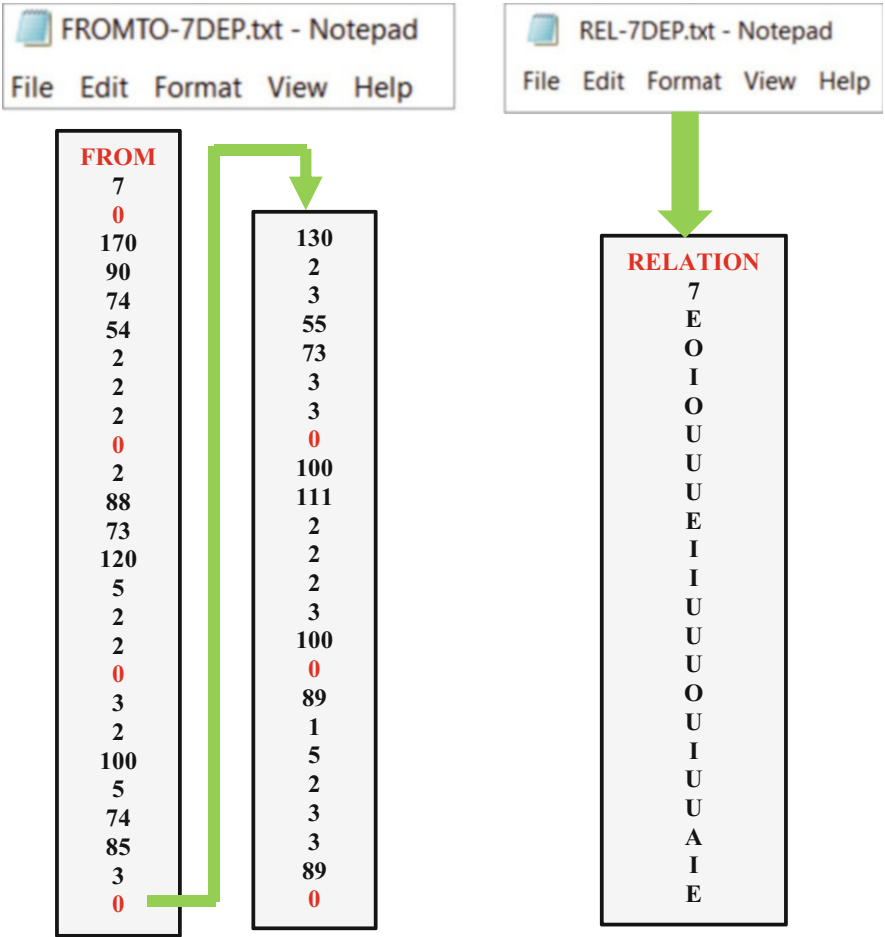


Fig. 4.22 Screens for Options B and C

- Saving results
- Printing results

If Option B is selected in the second screen of Fig. 4.21, text file *REL7-DEP.txt* is used. If Option C is selected, the text file *FROMTO7-DEP.txt* is used. The flows (trips) specified in the file are converted into relationship codes after calculating the percentages of trips between each pair of departments and using the guidelines of Table 4.6. The files for Options B and C are shown in Fig. 4.22.

4.11 Computerized Relative Allocation of Facilities Technique (CRAFT)

To run **CRAFT** first save program **layout.xla**. Then create a blank book file with excel. Now open **layout.xla** and **enable macros**. After this click on **ADD-INS** on the top of the screen. This causes the **OM_IE** menu to appear in the top left corner of the screen. Choose **New Layout** and follow the instructions provided in the spreadsheet. You must provide a name for the problem, the number of departments, the number of fixed points (in our case it can be set to zero), and distance measure (meters, feet, etc.). After clicking **OK** the program will create several tables with **white cells to be changed to desired data**. Yellow cells cannot be modified.

The tables with white cells to be modified are **FACILITY INFORMATION** (scale = 1, length, and width of layout area), **DEPARTMENT INFORMATION** (CRAFT starts with departments in a given sequence: an *F* means the position in the sequence is fixed; a *V* means that the position in the sequence is variable), **FLOW MATRIX** (from-to chart), and the **COST MATRIX**, which may be left unchanged to minimize total distance (instead of costs). The **FLOW MATRIX** can be copied from the **FROM-TO Chart Program (MENU Sheet)**.

Clicking on the **DEFINE FACILITY** red dot will allow the selection of several options. We want to select (a) Traditional Craft; (b) Sequential initial solution (initially the sequence is assumed to be 1, 2, 3, etc.) but any sequence can be specified as the initial solution; (c) Rectilinear distance; and (d) Set the width of departments (in cells), default value is 5. Now we click **OK**.

To consider a desired initial sequence different from the default sequence (1, 2, 3, etc.), proceed as follows:

1. For the initial solution option choose, **LEAVE BLANK**.
2. Click **OK**.
3. Define the initial layout by filling the plant with colors or indices of the departments. To do so choose the first department in the initial sequence and copy its colored cell (red for 1, green for 2, blue for 3, etc.) shown on the **FACILITY** sheet. Paste this colored cell as many times as needed on the plant area to complete the area (in cells) of the chosen department using the specified width for the departments (default value is 5). Proceed with the second department in the initial sequence, and so on until all departments are included. Click **OK**.
4. Click on the **EVALUATE** red button.
5. After clicking on **OK** the program opens a new sheet (**FACILITY** sheet) showing several red dot options. **EVALUATE** will calculate the score of the initial sequence. **SWITCH** will allow switching the order in any two departments being adjacent in the layout. **SOLVE** will provide a table with two options. Choose the **DO NOT STOP** option and click on **OK** to see the optimal layout.

4.11.1 Overview and Illustration of Program CRAFT

The CRAFT excel program discussed and illustrated in this section was developed by Professor Paul A. Jensen of the Department of Mechanical Engineering of the University of Texas at Austin (<https://utw11041.utweb.utexas.edu/ORMM/excel/layout.html>) [6].

CRAFT performs a path-oriented improvement routine based on pairwise exchanges between departments in a production plant. It uses a *heuristic method* for solving a mathematical model known as the quadratic assignment problem (QAP). It generates a possibly suboptimal arrangement considering the total *material handling cost* as the measure of effectiveness. The final solution strongly depends on the proposed initial solution. The program has a variety of features, such as the number of bays (idles) along which the departments are placed on the factory floor; changing the order of departments in the initial sequence; deciding if one or more departments have a fixed order in any solution; and determining the dimensions of the required area of the layout. These features allow the students to exercise their creativity in designing an optimal layout for their factory design project.

The input data needed to run the program consist of the following:

1. Number of departments and department areas.
2. An *initial arrangement* (number of bays, sequence of departments).
3. Number of trips between departments, and cost per trip (\$/trip/unit distance).
4. Plant area, length, and width.
5. Selection of *Rectilinear* or *Euclidean* distances to compute the cost. This cost is defined as $\text{number of trips} \times \text{distance} \times \text{cost per unit distance}$.

Figure 4.23 shows the computer screens for an illustrative example. In this example, a factory has four production departments (D1, D2, D3, D4) with areas equal to 25, 25, 20, and 20, respectively. The available space is rectangular with dimensions 10 by 10. This space is subdivided into three rectangular bays or aisles that span the entire length of the factory floor. The departments are arranged on these bays. It is desired to minimize the total distance traveled between departments using the following from-to chart:

4.12 Multi-Attribute Facility Layout and Design Program (MAFLAD)

MAFLAD has a long history, and the current version reflects many of the changes and improvements we have made to it over the years. The program interacts with the user, allowing the user to request a graphics display of the solution and to select one of three heuristics to be used in the branch-and-bound process. The program reads the data for the problem from an input data file and outputs the solution to an output data file that can be printed or saved for future use. Depending on the user's choices,

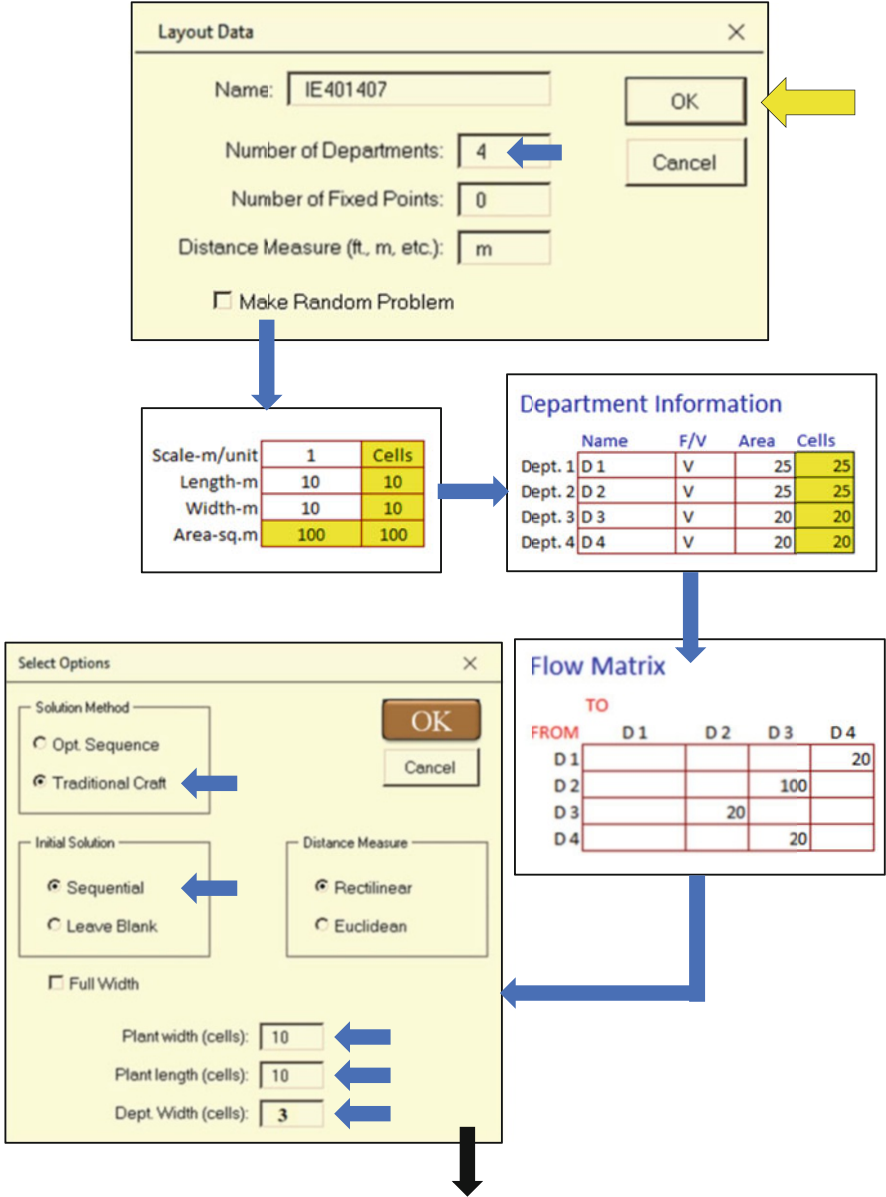


Fig. 4.23 Computer screens for CRAFT illustrative example

the program will display the solution graphically or numerically at the user's terminal. A complete user's manual including a description of the software is available on the website. The user's manual and programming for the Graphic version of MAFLAD (GMAFLAD) were created by Patrick Simon [14] as part of his MSc degree requirements at the University of Massachusetts.

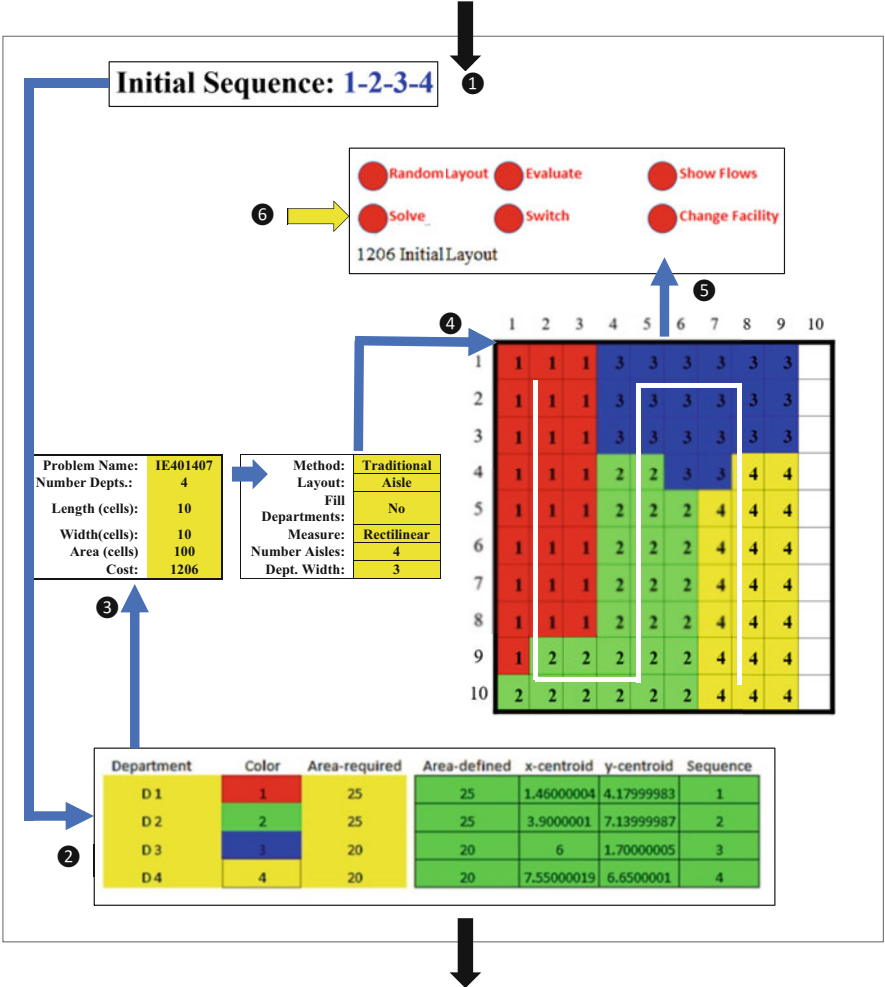


Fig. 4.23 (continued)

4.12.1 Overview of Program MAFLAD

The quadratic assignment problem (QAP) can be extended to become the quadratic set packing (QSP). This extension yields greater control over the placement and shape of the departments in the layout. One key to the current implementation is the data structure, which allows for a very efficient use of storage. While the running time of the basic algorithm is exponential, the effective design of the data structure has allowed for the solution of some relatively large problems while using considerably less storage.

The objective function in the QSP model is comprised of two terms. In the first term, site-placement utility values occur; in the second, quadratic utility flow terms occur. The QSP mathematic model is formulated as follows.

$$\begin{aligned} \text{Maximize } Z &= \sum_k \sum_t u_{kt} x_{kt} + \sum_k \sum_j u_{kj} \sum_{m, n \in A} \frac{1}{d_{mn}} x_{km} x_{jn} \\ \text{s.t.} \quad &\sum_k \sum_t \alpha_{ikt} x_{kt} \leq 1, \quad i = 1, \dots, I \text{ (subareas)} \\ &\sum_t x_{kt} = 1, \quad k = 1, \dots, K \text{ (activities)} \\ &x_{kt} = 0, 1, \quad k = 1, \dots, K, \quad t = 1, \dots, T \end{aligned}$$

where

- x_{kt} denotes the t th combination of subareas to which the k th activity (department) can be assigned: $x_{kt} = 1$ if the k th activity is assigned to the combination of subareas designated by t , and $x_{kt} = 0$ otherwise.
- α_{ikt} is 1 if the i th subarea is occupied by the k th activity alternative in the t th combination, and $\alpha_{ikt} = 0$ otherwise.
- A set of planar arcs indicating critical relationships between activity pairs x_k and x_j for each alternative (x_{km}, x_{jn}) .
- d_{mn} Euclidean/rectilinear distance between activity alternatives x_{km} and x_{jn} .
- u_{kt} deterministic/expected utility-of-place coefficient for the j th combination of cell activity x_k .
- u_{kj} deterministic/expected utility-of-flows coefficient between activities x_k and x_j .

Predetermined Activity Alternatives: In particular, the QSP formulation is based on the assumption that the study region is tessellated by a Cartesian grid and that clusters of grid activities representing alternate locations for each activity are predetermined.

Multi-Attribute Objective Function: The objective function is comprised of two terms. In the first term, site-placement utility values occur; in the second, quadratic utility flow values occur.

Constraints: The zero-one decision variables x_{ikt} and the coefficients of utility u_{kt} in the linear term of the objective function are based on known clusters of activities indexed by t for each activity k . Individual activities belonging to a cluster are designated by the zero-one α_{ikt} coefficients in the first set of constraints; that is, $\alpha_{ikt} = 1$ if activity i is a member of the t th cluster for activities k , and $\alpha_{ikt} = 0$ otherwise. This type of set packing model formulation captures the one-activity, one-site constraints of the QAP model.

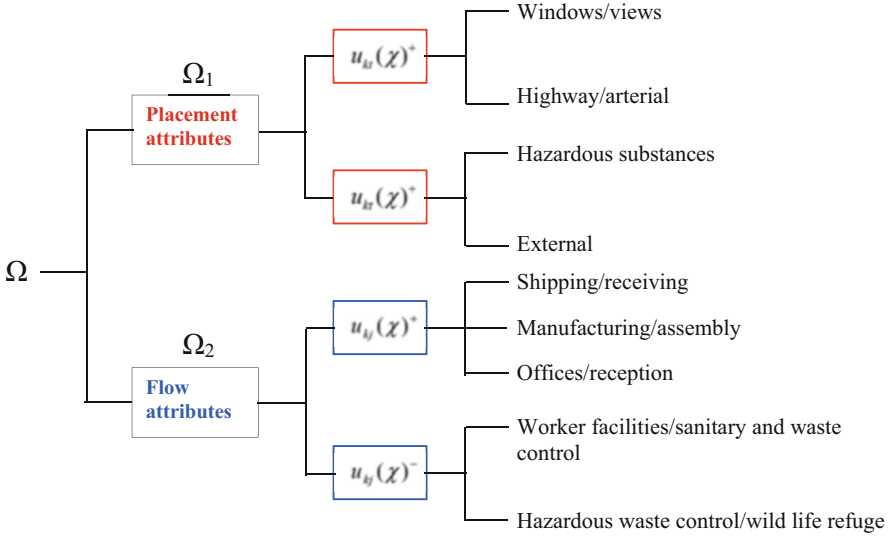


Fig. 4.24 Attribute decomposition

The multiplicity of criteria underlying large-scale problems necessitated the multi-attribute utility function in the QSP model. Figure 4.24 represents the two-stage decomposition process by which the multiple attributes are represented in the objective function. The $u_{kl}(\chi)^+$, $u_{kj}(\chi)^+$ terms represent monotonically decreasing utility functions over an attribute, while $u_{kl}(\chi)^-$, $u_{kj}(\chi)^-$ represent monotonically increasing utility functions over an attribute.

One advantage of the QSP formulation is in the predetermined clustering of activities, since it naturally leads to a hierarchical planning process so fundamental to large-scale problems. Figure 4.25 illustrates the hierarchical planning levels affordable in a QSP model; this is often the natural way to carry out the layout planning of large-scale facilities. The optimal configuration is solved for at the aggregate level or the Geographic Information System (GIS) level, further detailing is done at the intermediate Urban Information System (UIS) level, and then, finally, at the Architectural Information System (AIS) level, detailed decision-making occurs concerning the ultimate layout geometry of the activity specification.

MAFLAD offers the user three heuristics for searching and pruning the enumeration tree: *the greedy heuristic*, *best future value*, and *limited lookahead*.

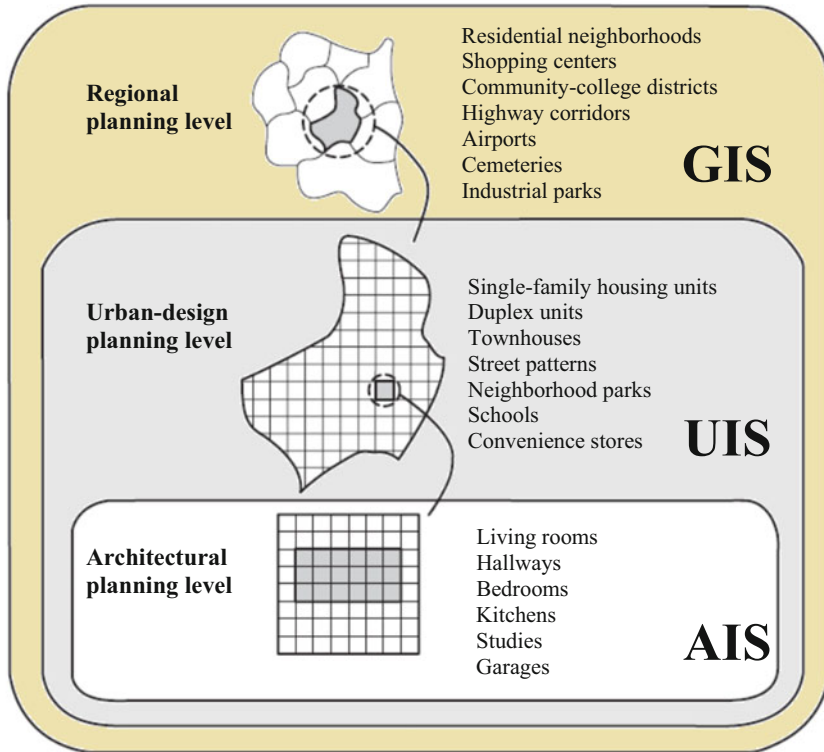


Fig. 4.25 Hierarchical planning levels

4.12.2 Branch-and-Bound Algorithm

The branch-and-bound algorithm is embedded in MAFLAD. It has seven steps:

- Step 1.** Preprocessing
- Step 2.** Activity node set generation
- Step 3.** Critical communication pairs generation
- Step 4.** Branching process
- Step 5.** Bounding process
- Step 6.** Backtracking
- Step 7.** Solution output

Step 1. Preprocessing

The input data consist of a list of activities and alternates for each x_k . For each x_{kt} there is a list of square cells used by the activity alternative and the value of place u_{kt} . Also specified is a list of critical or communicating pairs of activities from the set A and a per-unit value for flow between the activity pair, u_{kj} . This information is

transformed into a working set W_0^0 , which is assigned to the root node of the branch-and-bound tree.

Step 2. Activity Node Set Generation

Let us define x_{kt} as the t th alternate of the k th activity. Then x_{kt}, x_{jr} represents the activity pair formed by the t th alternate of the k th activity and the r th alternate of the j th activity. For each activity k , we form a set S_k . There is an element of this set for each alternate of activity k —the element of list of cell subareas used by the alternate, the place value, and its centroid. The structure of this data has a linked-list format.

Step 3. Critical Communicating Pairs Generation

At this step, using the critical pairs information, we form new sets that consist of pairwise combinations of the S_{kt} defined in the previous step. For each critical pair, we form all possible combinations of their alternates. If a pair of alternates overlap, they are not included in the set. Assume there are n critical pairs of activities, then we form n new sets, which consist of the alternatives for these critical pairs. Each element in these sets consists of the activities used by the pair of alternates, and the value $u_{kj}^* = u_{kt} + u_{jr} + \frac{1}{d_{tr}} u_{kj}$. We now build the working set of the root node, $W_0^0 = \{S^1, S^2, \dots, S^n\}$, where S^k is the set of all activity alternate pairs for the k th critical pair of activities. Any activity that is not a member of a critical pair is arbitrarily paired with another activity, with flow value $u_{kj} = 0$.

Step 4. Branching Process

The procedure begins by calling a selection routine for expanding the root node. This selection routine implements one of three user-chosen search heuristics to determine which is the best alternate pair to pick. Having selected an alternate pair from the current (first) set, that alternate pair is marked as being used. Let $|S^1| = r$. We form r working sets by selecting each element from S^1 , then reducing the remaining sets $\{S^2, \dots, S^n\}$ by pruning from them any element that conflicts with the element selected from S^1 . The pruning routine will examine all activity alternate pair sets from which assignments are yet to be made. Any alternate pair that conflicts with the assignment being made is marked as not usable in any future assignments. Any alternate pairs that are still unmarked after this last step are still feasible, given the current incumbent partial assignment. The procedure then steps to the next activity alternate pair set and finds the best assignment from that set. Again, the pruning routine is called to eliminate any alternate pairs that conflict with the current incumbent. This procedure continues until the bottom of the tree is reached, infeasibility is discovered, or lower bounding indicates that this branch of the tree is nonoptimal. Infeasibility is found when one of the activity alternate pair sets from which an assignment is yet to be made has no unmarked elements after the pruning operation. Depending on the heuristic used, infeasibility may also be discovered by the routine that finds the best alternate pair to use in an activity alternate pair set. In this case the set of alternate pairs is nonempty, but also nonoptimal.

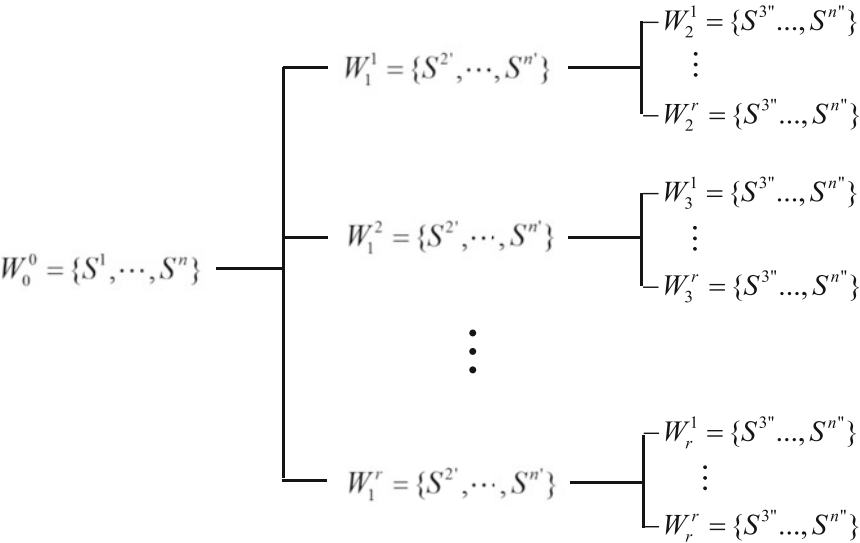


Fig. 4.26 Branch-and-bound enumeration tree

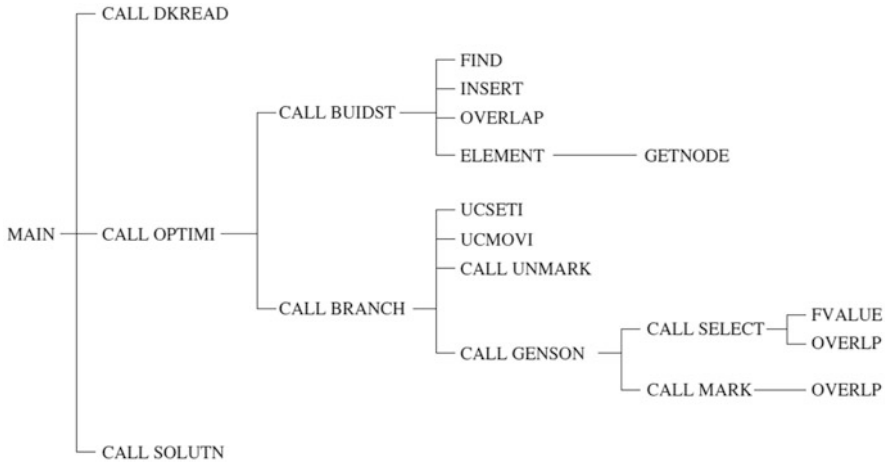


Fig. 4.27 Flowchart of major subroutines

Figure 4.26 illustrates the branch-and-bound process, indicating graphically the way in which the parallel algorithm functions, since each processor searches along one of the branches and then communicates with a bound to the other processors until the optimal solution is achieved.

Figure 4.27 illustrates the flowchart of major subroutines employed in MAFLAD. Three heuristics for finding the best assignment from an activity alternate pair set have been implemented. In all three cases, the search routine is passed a pointer to a

set of activity alternate pair nodes. Some of the nodes are marked; these are not considered for selection. The following heuristics are applied to the remaining nodes:

- Greedy Heuristic
- Best Future Value
- Limited Lookahead

Greedy Heuristic: The selection routine simply picks the alternate pair with the highest u_{kt} value. It does not use lower bounding in the selection process. Lower u_{kj} bounds are determined later by the pruning operations, but they are determined after the selection process.

Best Future Value: For each node under consideration the selection routine performs a pseudo pruning operation. It determines which future alternate pairs will remain if the node is selected as the one to assign. For each set of activity alternate pairs, it finds the most valuable remaining alternate pair and sums up these values. This gives a lower bound on the best you can do in future assignments. The selection routine picks the node that has the best future potential. If this value is less than the current lower bound, the selection is rejected.

Limited Lookahead: This procedure is almost the same as the best future value. The difference is that whereas the best future value computes a lower bound on the best we can do in the future by examining activity alternate pair sets all the way to the bottom of the tree, the limited lookahead will examine sets only to a user-specified depth. No lower bounding is used with this heuristic. As in the case of the greedy heuristic, the lower bound comes later in the pruning operation.

The best-future-value heuristic rule has provided the best computational results for the serial algorithm, and it is used in the vectorization and parallelization version of MAFLAD. Each critical pair term selected in the branching step that does not overlap in the best-future-value heuristic represents an assignment of the pair of activities in the solution. There are $n - 1$ arcs in any feasible assignment solution. The value of each assignment corresponds to an arc $a \in A' \subseteq A$. Once a feasible path is followed through its completion, a set $a \in A' \subseteq A$ of $n - 1$ arcs will represent a basic feasible solution to the constraints of the QSP model. The value of the lower bound is
$$\sum_{(k,j) \in A'} \left(u_{km} + u_{jn} + \frac{u_{kj}}{d_{mn}} \right).$$

Step 5. Bounding Process

For each node in the tree, lower bound is computed on the value of the branch on which this node lies. From each of the activity pair sets from which assignments are yet to be made, we select the most valuable of the alternates. We sum together these values and add the value of the current partial solution (the values of the nodes on the current branch from the root to the current node).

Step 6. Backtracking

Suppose we are making an assignment from an activity alternate set. We select an element of the set and mark it as having been selected. We then prune the remaining activity alternate sets, marking all those elements that conflict with the assignment just made. If we discover that a set of activity alternate pairs is empty after the pruning operation, we need to unmark all those elements that were marked as conflicting with the current assignment. We leave the current assignment marked; since it resulted in infeasibility, we do not wish to reuse it. We then call the selection routine to pick another alternate pair from the current set. The original activity alternate pair that resulted in infeasibility will not be chosen, since it is marked. If the selection routine can find another alternate pair to use, we start the pruning process as before. If the selection routine cannot find another alternate pair, we need to invoke another backup procedure. We need to back up to the previous activity alternate pair set and try another assignment from that set. We unmark all elements in the current set that are marked as being used (as opposed to conflicting with previous assignments). We then unmark all elements that are marked, as conflicting with the assignment from the previous activity alternate pair set. We back up to the previous set. Any element marked as being used is left marked, as we do not wish to reuse any assignment that created the infeasibility. We now call a selection routine that determines the best assignment to make from our new current set. Depending on the outcome, we call pruning or backup procedures as before.

Step 7. Solution Output

The program outputs the optimal solution as well as the three suboptimal solutions nearest in value that have been found.

4.12.3 An Illustration of Program MAFLAD

We illustrate the use of MAFLAD for the solution of manufacturing layout with 12 activities (departments). The available rectangular area is a 10×6 grid shown in Fig. 4.28 with the corresponding label for each cell.

The size, shape, centroid of shape, and alternatives are shown below for each of the 12 activities. In the description of the alternatives, we use the labels of the cells in Fig. 4.28. For example, activity 1 requires a square area consisting of 9 cells. For this activity there are 6 alternatives. These alternatives are displayed below as six rows of nine cells each. The first row indicates that the first alternative is to locate activity 1 in cells 1, 2, 3, 11, 12, 13, 21, 22, and 23 of the grid shown in Fig. 4.28.

It is noted that the program, if desirable, can rotate the shapes of the activities to add more flexibility to the layout generation procedure. The flow matrix (from-to chart) for the 12 activities of the example (taken from [2]) is shown in Fig. 4.29.

The optimal solution obtained by MAFLAD is displayed in Fig. 4.30. An example output of the solution process is seen in Table 4.7. One real advantage to MAFLAD is that one can iteratively play with the solutions and improve them as we go. In the next-best solution shown in Fig. 4.31, we see that we could rotate activity A_7 and place it between A_6 and A_3 . So, adding this alternative to the set of possible alternatives for A_7 and resolving with MAFLAD, we achieve the solution shown in Fig. 4.32, which has a better value than the previous next-best solution.

6	51	52	53	54	55	56	57	58	59	60
5	41	42	43	44	45	46	47	48	49	50
4	31	32	33	34	35	36	37	38	39	40
3	21	22	23	24	25	26	27	28	29	30
2	11	12	13	14	15	16	17	18	19	20
1	1	2	3	4	5	6	7	8	9	10
	1	2	3	4	5	6	7	8	9	10

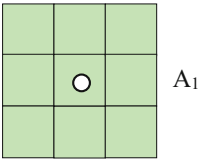
Fig. 4.28 Layout planning grid

	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆	A ₇	A ₈	A ₉	A ₁₀	A ₁₁	A ₁₂
A ₁		288	180	54	72	180	27	72	36	0	0	9
A ₂			240	54	72	24	48	160	16	64	8	16
A ₃				120	80	0	60	120	60	0	0	30
A ₄					72	18	18	48	24	48	12	0
A ₅						12	12	64	16	16	4	8
A ₆							18	24	6	12	3	3
A ₇								0	6	6	3	6
A ₈									16	16	16	4
A ₉										4	4	2
A ₁₀											2	2
A ₁₁												2
A ₁₂												

Fig. 4.29 Example flow matrix

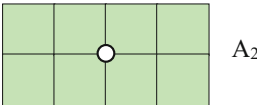
Activity 1 6 alternatives (each with 9 cells)

1	2	3	11	12	13	21	22	23
24	25	26	34	35	36	4	45	46
28	29	30	38	39	40	48	49	50
31	32	33	41	42	43	51	52	53
4	5	6	14	15	16	24	25	26
27	28	29	37	38	39	47	48	49



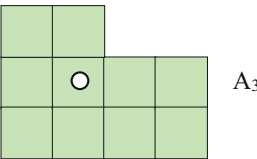
Activity 2 6 alternatives (each with 8 cells)

31	32	33	34	41	42	43	44
45	46	47	48	55	56	57	58
19	20	29	30	39	40	49	50
11	12	13	14	21	22	23	24
43	44	45	46	53	54	55	56
27	37	47	57	28	38	48	58



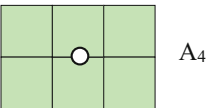
Activity 3 4 alternatives (each with 10 cells)

7	8	9	10	17	18	19	20	29	30
37	38	39	40	47	48	49	50	57	58
5	6	15	16	17	18	25	26	27	28
8	9	10	18	19	20	29	30	39	40



Activity 4 5 alternatives (each with 6 cells)

4	14	24	5	15	25
1	2	3	11	12	13
31	32	41	42	51	52
14	15	16	24	25	26
27	28	37	38	47	48



Activity 5 7 alternatives (each with 4 cells)

45	46	55	56
39	40	49	50
24	25	34	35
12	13	22	23
7	8	17	18
4	5	14	15
12	13	22	23

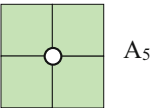
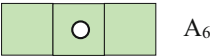


Fig. 4.29 (continued)

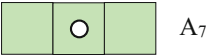
Activity 6 7 alternatives (each with 3 cells)

37	47	57
1	2	3
30	40	50
45	46	47
18	19	20
8	9	10
13	23	33



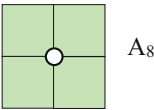
Activity 7 6 alternatives (each with 3 cells)

48	49	50
31	32	33
29	39	49
10	20	30
14	15	16
16	17	18



Activity 8 6 alternatives (each with 4 cells)

16	17	26	27
39	40	49	50
6	7	16	17
19	20	29	30
33	34	43	44
41	42	51	52



Activity 9 17 alternatives (6 in 1st row, 6 in 2nd row, 5 in 3rd row)

57	58	37	38	38	48	29	30	11	12	51	52
9	10	25	26	46	47	41	42	42	43	43	53
1	11	13	14	31	41	8	9	35	36		



Activity 10 9 alternatives (3 alternatives in each row)

52	53	51	52	54	55
7	17	49	50	1	2
38	39	39	40	42	43



Fig. 4.29 (continued)

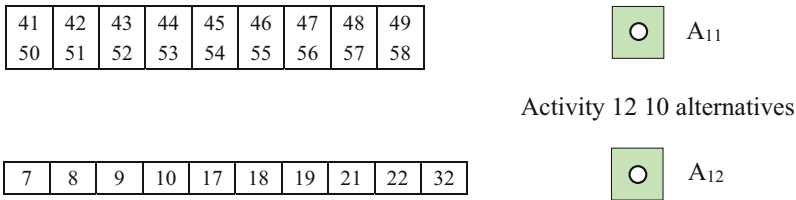


Fig. 4.29 (continued)

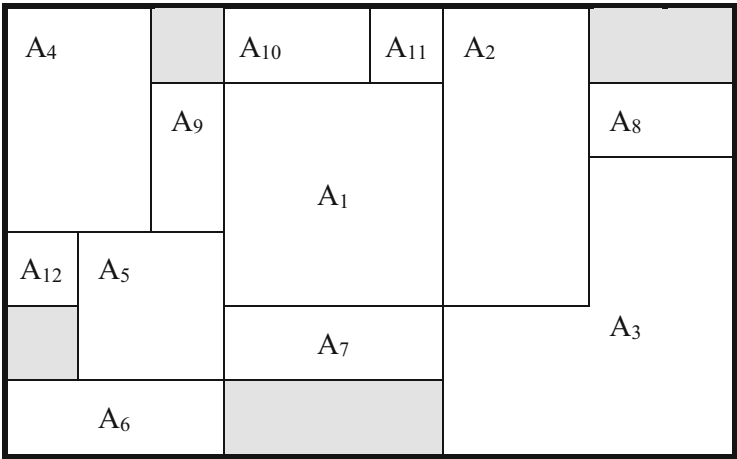


Fig. 4.30 Optimal solution, $Z = 757.29$

Table 4.7 MAFLAD output file of Example

THE NAME OF THE DATA FILE IS bazzl. dat CPU TIME USED IN Optimization is 0.0000 SEC THE STORAGE USED IN Optimization is 23,993 The value of the solution is 757.29		THE NAME OF THE DATA FILE IS bazzi.dat CPU TIME USED IN Optimization is 0.0000 SEC THE STORAGE USED IN Optimization is 23,993 The value of the solution is 727.25	
Activity	Alternate	Activity	Alternate
1	2	1	1
2	6	2	1
3	1	3	4
4	3	4	1
5	7	5	1
6	2	6	1
7	5	7	1
8	2	8	1
9	12	9	17
10	3	10	1
11	16	11	14
12	8H	12	1

Fig. 4.31 Next-best solution, $Z = 727.25$

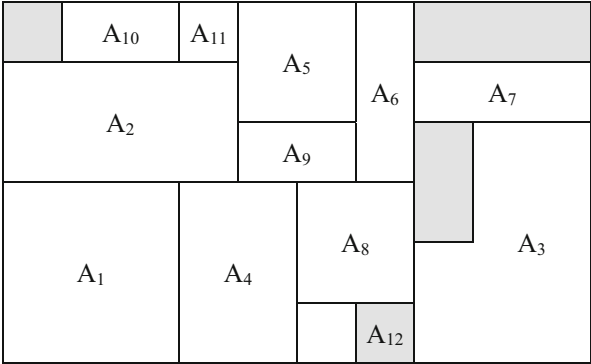
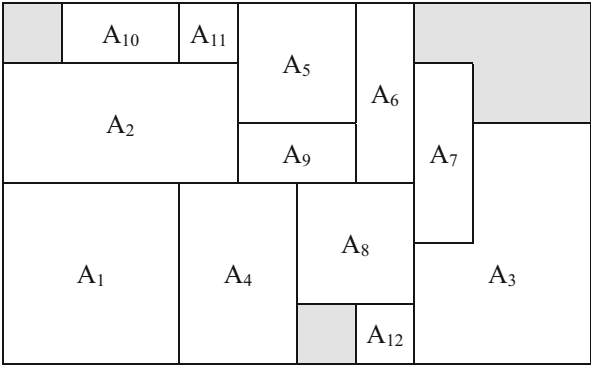


Fig. 4.32 Next-best improved solution, $Z = 743.11$



The Visual Basic program implementation entitled GMAFLAD is available on the website of the textbook, along with a detailed user manual. Figure 4.33 illustrates a screen shot of the program run for the example under consideration.

4.12.4 Factory Project GMAFLAD Example

This example considers a plant consisting of seven departmental activities. The names of these departments and their required areas in square feet are shown below:

1. Manufacturing	15,753.50
2. Warehouse (Shipping and receiving)	13,378.00
3. Assembly (Main and subassembly)	7722.00
4. Offices	5447.50
5. Net square footage	43,512.50
6. Non-assignable (30%)	13,053.75
7. Grand Total	56,566.25

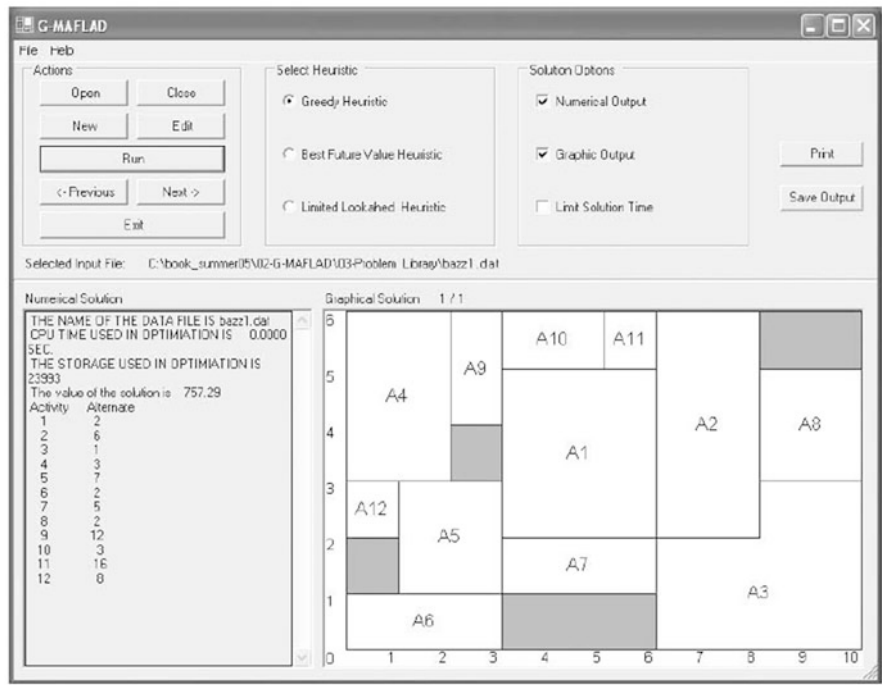


Fig. 4.33 Screen shot with optimal solution

It is important to add the non-assignable spaces (circulation, HVAC [heating, ventilation, and air conditioning] systems, bathrooms, and so on) to round out the facility footprint. While one wants to minimize the non-assignable spaces, these are critical to the overall practical functioning of the facility. The total area requirement is about 60,000 ft² and can be accommodated in a 300' by 200' rectangular facility, including both assignable and non-assignable activities. Program GMAFLAD will be used to show how it can be applied in the factory design project. A 6 by 4 grid (using 50-ft units) will be considered to represent the factory floor.

Receiving (RE) and Shipping (SH) were detailed as separate activities. Main Assembly (AS) and Subassembly (SA) were made distinct. Manufacturing (MA) was a single entity, and Packing (PK), Shipping (SH), and Offices (OF) were kept distinct, for a total of seven activities. The relationship matrix and corresponding graph decomposition are given in Fig. 4.34. In the flow matrix, we have used cardinal utility values of A(7–9), E(5–7), I(3–5), O(1–3), U(0) to translate the REL entries into flows in GMAFLAD.

Figure 4.35 shows the optimal solution obtained from the GMAFLAD program. There is a nice U-shaped flow from the Receiving area on through Manufacturing to Subassembly, Assembly, Packing, and Shipping. The Offices (A7) are assigned a corner location. Finally, Fig. 4.36 depicts the factory layout [11] generated based on the GMAFLAD solution.

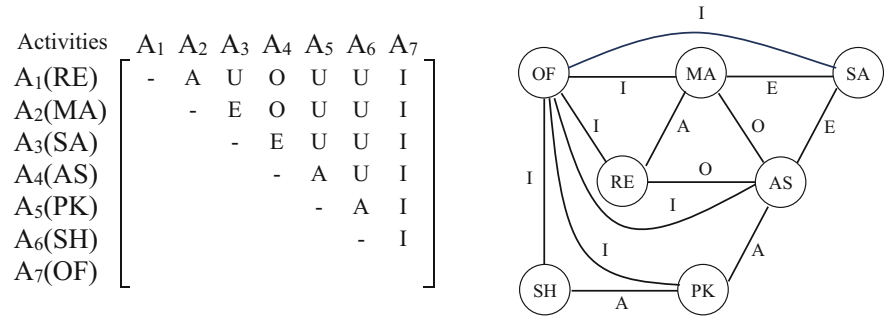


Fig. 4.34 Relationship chart and graph decomposition

Fig. 4.35 GMAFLAD optimal alternative

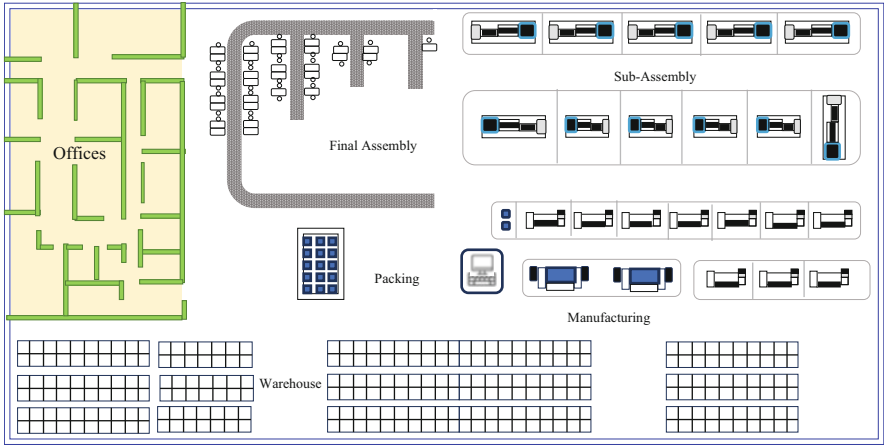
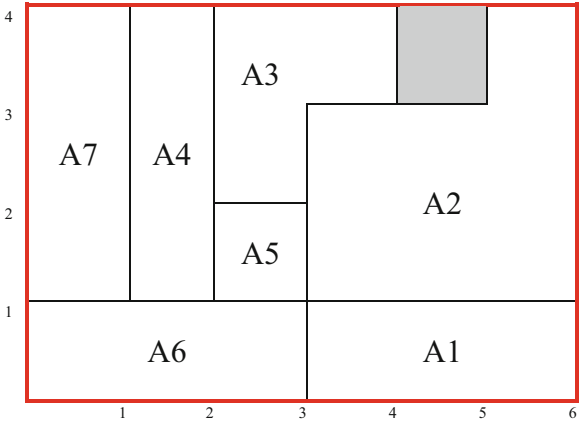


Fig. 4.36 Actual plant layout alternative

4.13 Summary and Recommendations

In essence, layout planning encompasses the analysis, conceptualization, design, and implementation of a production system for the manufacturing of goods or the design and supply of services. Modern facilities planning methodologies have a common foundation known as systematic layout planning, pioneered by Richard Muther and Knut Haganas, which provides layout planning with a systematic and structured process for decision-making.

The modern manufacturing facility experiences significant changes in product designs, process plans, demand volumes, product mix, product life cycles, and production routings. The concept of layout modules (each module representing a portion of the entire facility) extends current thinking on input data requirements and methods for facility layout, and supports the need for a new generation of facility layouts. Simultaneously, changes in the design of processing and material handling equipment are also inevitable.

An effective flow can be achieved by maximizing direct flow paths, combining flows and operations whenever possible by planning for the movement of materials, information, or people to be combined with a processing step. Material flow in a typical manufacturing facility is a critical activity in accomplishing timely product deliveries.

Space planning determines and lays out the use of space in and around a facility, ranging from site planning to workstation design. Space allocation in a facility bears a close relation to the equipment, material, personnel, and activities carried on in a department.

The Functional, Flow Line, Cellular, and Project layouts are traditional facility layouts that have been proposed in the literature. Using the SLP as a basis and with the help of computer algorithms and other layout techniques, a number of facility layout designs such as Agile, Flexible, Fractal, Holonic, Hybrid Cellular, Modular, Multichannel Manufacturing, and Responsibility Networks layouts can be formulated.

Relying completely on static analysis can be misleading in establishing a good layout. Production schedules, variation in product mixes, availability of material handling equipment, and random breakdowns create varying loads on the system. To take into account such variability, a final analysis of the material flow could be conducted by means of analytical queuing network and simulation models (as will be illustrated in Chap. 8). An analytical queuing network or simulation model can be built to study the effectiveness of different forms of material handling equipment by considering their detailed parameters such as speed, acceleration, movement paths, and traffic and control logic. In addition, analytical queuing network or simulation models can also help to make dynamic analysis of aisle congestion, buffer-space utilization, and traffic congestion at critical intersections.

To plan effective layouts that will be consistent with the technological level present in modern manufacturing, changes that are happening or expected to happen

in modern manufacturing plants should be anticipated. A typical list of these changes includes:

- Faster net flow through plant
- Reduced setup times
- Short conveyor runs
- Fewer forklift trucks
- Reduced lead times
- Reduced inventories
- Cooperation with suppliers
- Streamlined receiving
- Smaller-sized plants
- Precision placing

The McKinsey & Company is a management consulting firm that advises on strategic management to corporations, governments, and other organizations. In the article “Delivering the US manufacturing renaissance” [13] published in August 2022, a group of McKinsey authors (Tyler Carr, Eric Chewning, Mike Doheny, Anu Madgavkar, Asutosh Padhi, and Andrew Tingley) focus on the functions assumed by and the future of US manufacturing.

According to the article, manufacturing accounts for \$2.3 trillion in GDP, employs 12 million people, and supports hundreds of local economies. This corresponds to only 11% of US GDP and 8% of direct employment, but it results in significant contributions including 20% of the nation’s capital investment, 35% of productivity growth, 60% of exports, and 70% of business R&D spending [13].

The authors indicate that during the decade before the Coronavirus Disease-2019 (COVID-19) crisis, the sector gained 1.3 million manufacturing jobs between 2010 and 2019, following the loss of 5.8 million jobs over the previous 10 years. Additionally, the USA’s share of global manufacturing GDP, output, and exports became stable [13].

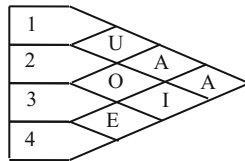
Finally, leading manufacturers, according to the article, are very engaged in the utilization of digital technology in a wide range of operations. The Global Lighthouse Network (GLN), a World Economic Forum initiative in collaboration with McKinsey, reports that major strategies for the realization of a manufacturing renaissance are improvements in sustainability, such as greenhouse-gas emissions; productivity, such as factory output; agility, such as shorter order-to-delivery lead times; speed to market; and customization [13].

4.14 Exercises

- 4.1 Explain the difference between a from-to chart and a relationship chart, indicating when each chart is more suitable.
- 4.2 Assume three products are made in four departments A, B, C, and D. Product 1 has a production volume of 20 pallets/week in the sequence ABCDB.

Product 2 has 10 pallets per week in sequence ACD. Product 3 has 4 pallets/week in sequence BD. (a) Construct a from-to chart. (b) Propose a relationship chart for this exercise. Explain your procedure.

- 4.3 A six-stage process goes through the sequence of machines 1-2-3-4-5-6. Each machine discards 7% scrap. The current demand is 2000 good units per day. (a) Determine the number of units per day started in the *third stage* (machine 3). (b) The standard time per part processed at the *third stage* is 2.5 minutes. The corresponding machine requires a 15-minute setup every day. Assuming one daily 8-hour shift, and a machine availability factor equal to 0.85, determine the fractional number of machines required in the *third-stage* operation.
- 4.4 Given the following relationship chart, determine the closeness rank, selection order, and a layout with maximum score ($A = 8$, $E = 4$, $I = 2$, $O = 1$, $U = 0$). Departmental areas are as follows: Department 1 = 100, Department 2 = 300, Department 3 = 100, Department 4 = 300. Each department has a *rectangular shape*. The total area available is a 20×40 rectangle.

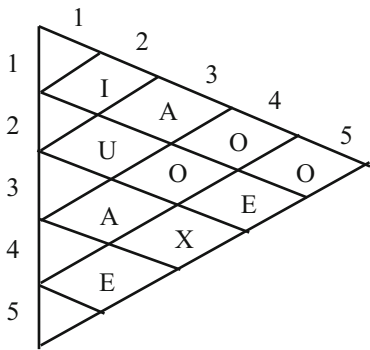


- 4.5 A factory has four planning departments (1,2,3,4). Product A is manufactured according to the sequence 1-2-3-4 and product B according to the sequence 3-4-2-1-2. The daily production volumes of products A and B are 10 and 20 parts, respectively. (a) Construct the from-to chart indicating the number of trips *from* one department *to* another. (b) Develop a relationship chart following these rules: “A” for any two departments with a total number of trips (*including both directions*) equal to 40 or more, “E” for 30 or more but less than 40; “I” for 20 or more but less than 30; “O” for 10 or more but less than 20; “U” for less than 10. Show all your calculations.
- 4.6 Describe each space determination method, indicating when each one is more appropriate.
- 4.7 List the five most important factors affecting aisle width.
- 4.8 Components 1 and 2 have similar handling requirements. Moving 2 units of either component 1 or 2 is equivalent to moving 1 unit of component 3. The production volumes for components 1, 2, 3 are 30, 12, 7, respectively. Moreover, the routing sequences are A-C-B-D-E for 1, A-B-D-E for 2, and A-C-D-B-E for 3. Find a from-to chart.
- 4.9 Read the article “A Microcomputer Program to Assist in Plant Layout” [7]. (a) Summarize the content of the article. (b) Clearly state the procedures for determining the closeness rank and selection order. (c) Make up a numerical example to illustrate the use of these procedures.

4.10 A manufacturing facility consists of five departments 1, 2, 3, 4, and 5. It produces four components having the manufacturing product routings and production volumes indicated below:

Component	Production Routing	Units per Week
1	1-2-3-4-5	20
2	2-3-5-1	25
3	4-5-3	10
4	5-4-3-2-1	30

- (a) Generate a from-to chart. (b) Find a relationship chart using the following rules: “A” for 85–66 trips between departments, “E” for 65-46, “I” for 45-26, “O” for 25-6, and “U” for 5-0. (c) Find closeness ranks and selection order. (d) Generate the layout with maximal score using A = 8, E = 4, I = 2, O = 1, and U = 0 points.
- 4.11 Find: (a) closeness rank; (b) selection order; (c) a proposed layout for a rectangular factory floor (show department locations considering arbitrary departmental areas) and the score of the layout using A = 8, E = 4, I = 2, O = 1, U = 0, X = −8. Consider the following relationship chart for a layout consisting of five departments:

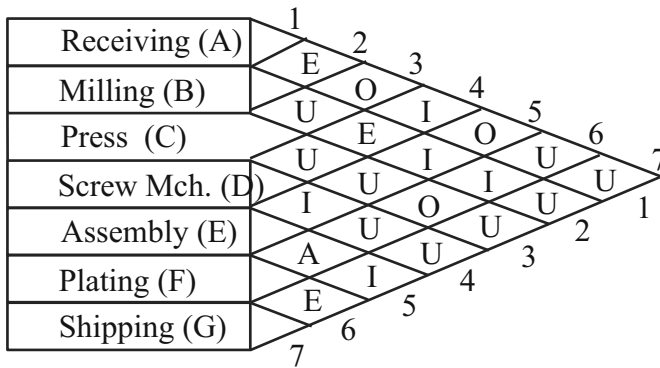


4.12 Run FLAP to generate a layout for a factory with seven departments having areas and closeness relationships as shown below.

Departmental Area Requirements

Departments	Area (sq. ft.)
1. Receiving	12,000
2. Milling	8000
3. Press	6000
4. Screw machine	12,000
5. Assembly	8000
6. Plating	12,000
7. Shipping	12,000

Activity Relationships.



4.13 Six components are produced according to the following production routings and units produced per week.

Component	Production Routing	Units per Week
1	A-B-G-H	20
2	A-C-D-H	25
3	A-D-E-F-H	10
4	5-4-3-2-1	30
5	A-B-C-D-H	15
6	A-E-F-G-H	20

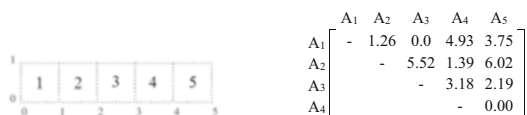
Assume the following space requirements given in blocks of 20 by 20 feet. Department A: 50, Department B: 30, Department C: 60, Department D: 40, Department E: 5, Department F: 5, Department G: 10, and Department H: 20. Recommend a design that can be arranged on a rectangular floor of at most 600 feet long by at most 200 feet wide.

4.14 A manufacturing facility consists of eight departments A, B, C, D, E, F, G, and H. It produces six components 1, 2, 3, 4, 5, and 6. The manufacturing product routings and production volumes are as indicated below:

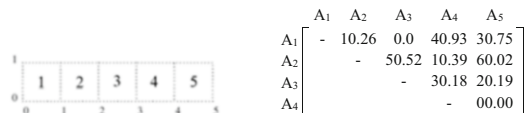
Component	Production Routing	Units per Week
1	A-B-G-H	20
2	A-C-D-H	25
3	A-D-E-F-H	10
4	A-B-C-E-H	30
5	A-B-C-D-H	15
6	A-E-F-G-H	10

Assume the following space requirements given in blocks of 20' by 20': Department A: 50, Department B: 30, Department C: 60, Department D: 40, Department E: 5, Department F: 5, Department G: 10, and Department H:

20. Run **CRAFT** to recommend a design that can be arranged on a rectangular floor of at most 600 feet in length by at most 200 feet in width. In the process of selecting the best design, several alternatives can be developed to choose the one considered to be most attractive. Different alternatives can be generated by changing the number of bays, the initial sequence, and/or fixing departments in the initial sequence. Assume that rectilinear (rectangular) distances instead of Euclidean (straight line) distances between departments are used. Moreover, assume that material handling costs per unit of distance are equal to one.
- 4.15 We have a five-cell layout on a serial line with the grid cells and matrix of flow values shown below. All activities can be allocated to any of the cells, and the placement value of any activity to the cells is a constant value of 1.00. The size of each activity is one cell.



- (a) Use the SLP approach (Chap. 4) to generate a solution.
- (b) Run GMAFLAD and print out the four best solution values.
- (c) Compare the two solutions generated in (a) and (b). Did you get the optimal solution using the SLP procedure?
- 4.16 In Exercise 4.15, add +10 to each flow value. Check the trade-off of flow vs. placement values on the solution generation process. What, if any, are the differences in the four GMAFLAD solutions?



References

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Chapter 5

Facility Location Models



5.1 Introduction

This section provides an overview of a class of basic facility location models and an introduction to the siting planning problem. The basic location models provide a foundation for more advanced formulations to solve a wide range of facility location problems. The site planning introduction focuses on the activities in the corresponding planning process and the software to facilitate their execution.

5.1.1 Facility Location Models

Consider a case where movable facilities are taken to be repaired in a maintenance center at a frequency that can be anticipated using relevant historical data. It is desirable to locate the maintenance center in such a way that, during a specified period, the total length traveled from all departments served will be minimal. In another case, a tool facility needs to be located in such a way that it will be equally accessible to the departments served by the facility. In another case, a medical emergency facility is going to be located so that the longest foreseeable trip will not exceed a specified maximum distance. In each of these cases several facilities could be considered instead of only one. These are just a few example situations where technical expertise on facility location is very useful.

This chapter will introduce basic location models: single-facility, location-allocation, and quadratic assignment models. In the first class of models, it is desired to find the location of a new facility given its interaction (number of trips) with a group of existing facilities. In the second class of models, it is desired to determine the number and location of new facilities, as well as the allocation of the existing facilities among the new ones, given the number of trips between each existing facility and one of the new facilities. It is assumed that each existing facility is

allocated (assigned) to exactly one new facility. In the third class of models, several facilities are located given the interaction among the facilities (number of trips) and the distance between the potential sites, subject to two types of constraints. These constraints establish that each facility must be located exactly once, and each site must accommodate exactly one facility. Details on the development and application of each model are given next.

5.1.2 *Siting Problem*

The site plan is a unifying instrument that integrates all necessary activities to provide a common operating picture and project roadmap for the development team. The identification and consolidation of all major earthwork, site engineering, and construction elements on a single plan helps keep the work by engineers, architects, general contractors, and developers aligned. An example, developed by a group of students in 2020, particularly illustrates the process for utilizing the software available in the factory project for carrying out the site planning design process.

5.2 Site Planning Design: Concepts and Example

In a student project, the Alpha team of Peter Elkhoury, Abigail Kennedy, Vincent Palumbo, and Maximillian Schuerbuescher in the year of 2020 carried out an intensive and comprehensive study of a factory project for designing and producing bicycles [1]. Their analysis of site planning is exemplary and we shall summarize some of the main points of their study. Their site analysis demonstrates how the layout planning software tools of GMAFLAD and CRAFT can work together to perform the site selection analysis.

5.2.1 *Site Description*

The overall site plan is seen in Fig. 5.1 which is a rather large hilly area, but has the potential for easily accommodating the factory. Because of the large size of the site, it affords at least two alternative site locations on rather level ground, and we want to objectively determine which site is most appropriate. Because of the extent of the site, there are many hills and valleys and very few flat areas. Clearly, the team considered only two alternative locations for their factory. We shall briefly review the process for selecting their factory site location using the software tools at our disposal. The process of using the software tools as described in this case study is highly recommended.

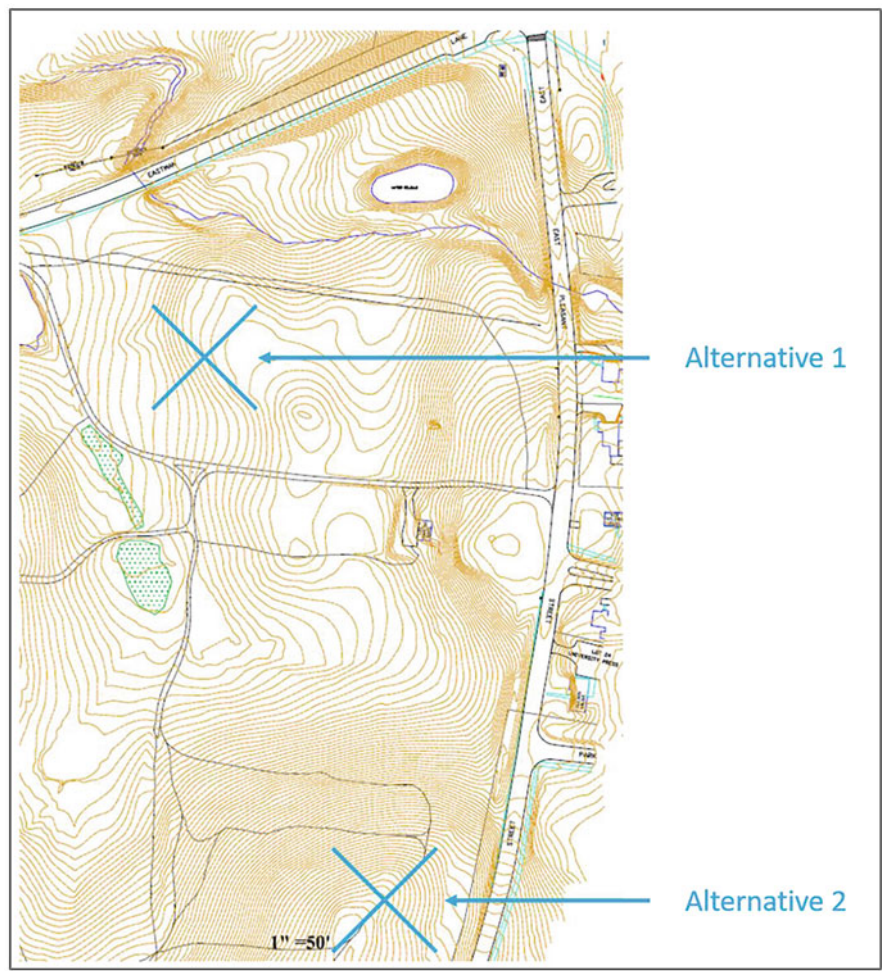


Fig. 5.1 Site plan with two alternative facilities locations

After briefly developing the parking, pedestrian and vehicular accessibility, and detailed site development, the team began to evaluate each site alternative. They used a combination of software tools GMAFLAD for generating the site design concepts and CRAFT to further refine the site plans to delineate and reinforce their site decisions. Chapter 6 describes in more detail the combination and integration of the software tools of GMAFLAD and CRAFT to determine the final factory layouts.

Figure 5.2 illustrates the first and second site plans with the site activities needed to realize their locations. Figure 5.3 illustrates a more detailed plan of the factory with the critical site activities needed for its realization. These site activities are shown independent of the factory and office activities which remain in the interior of

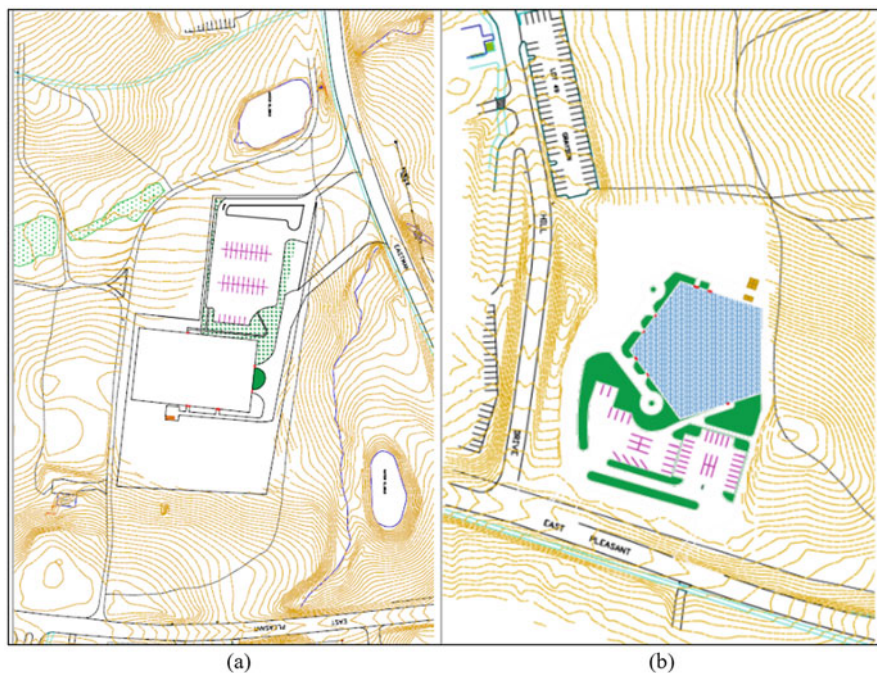


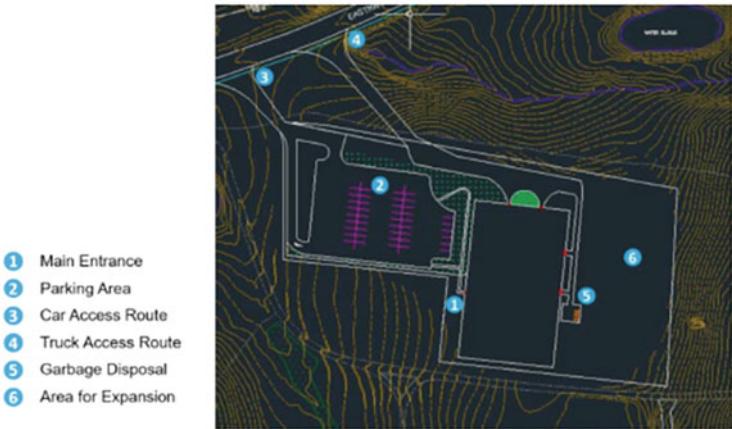
Fig. 5.2 (a) Site plan; (b) Alternative 2

the facility. We need to define these exterior activities in order to gauge the scale and extent of the environment of the factory.

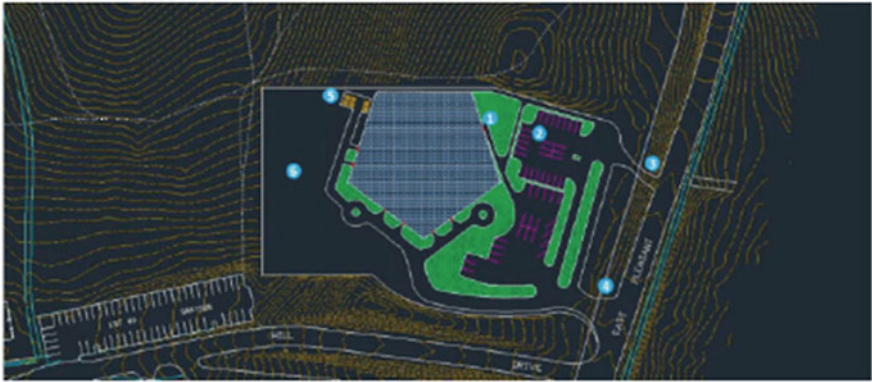
After an extensive analysis, the Alpha team selected the second alternative as their site choice and the final detailed site plan is shown in Fig. 5.3. Let us examine the rationale for their decision.

For the Alpha team, the first factor considered when choosing the initial placement of the site is the contours that are in the natural landscape. Hills and uneven surfaces limit the potential for different places where the site can go and be successful. The site of the Bicycle Manufacturing Facility (BMF) must also accommodate space for expansion, parking, flow of in and out personnel, as well as many other factors. Both site layouts are designed to handle Tractor-trailer Truck access, considered the safe turning degree for trucks, capacity of 45 cars for personnel parking, and lot lines set back 25 ft from the building. Both layout sites are also chosen with the consideration for a location where the contours are not too excessively steep for trucks to ascend.

Another evaluation criterion which has to be considered is the *flexibility* of the site. For example, *flexibility* in the event of a fire and operations must continue. Both the rectangular and pentagon layouts have potential with their surrounding land even with the hills and slopes providing natural obstacles, though in this area the rectangular layout has a slight advantage. Following down the evaluation criteria, both layouts are assessed in their functional flow of materials, vehicles, and pedestrians.



(a) Plan Site 1.



(b) Plan Site 2.

Fig. 5.3 (a) Detailed plan site 1; (b) Detailed plan site 2

The rectangular layout is very open which allows for optimal flow of materials and enough space for pedestrians. Both layouts have two entrances and exits which are optimal for the flow of vehicles and materials in and out of the facility. Having two separate accesses for vehicles and trucks, so material flows, the rectangular might have a slight advantage. The pentagon might have a problem if traffic of trucks and vehicles gets stuck at the bottom entrance and exit. Clear rules need to be set.

Next is the consideration of *safety*. The rectangular site is more spacious and distinct than the pentagon layout. It also might be safer because the trucks and vehicle entrances are clearly separated. When pedestrians for the pentagon layout choose the entrance where also trucks enter, it might be dangerous. In case of a fire, it might also be easier to evacuate one floor than evacuating two floors as for the pentagon office. Both layouts lack a separated path for pedestrians which has to be

considered for future layouts. In terms of *environmental impacts* in the form of disposal and waste concerns the pentagon might be the better site. The rationale behind this assertion is that the pentagon layout is further away from water than the rectangular layout which equates to less of an environmental impact from the waste and fuels burned at the facility. Figure 5.3a illustrates the detailed site plan for the first alternative and Fig. 5.3b does it for the second alternative.

After reviewing the criteria, it is believed that the second alternative layout in the shape of a pentagon is to be selected to initiate the site planning process. It is slightly more environmentally friendly and has less impact on ecology, vegetation, and wildlife. Because of the smaller area, there are slightly less site development costs and smaller maintenance as well as snow removal costs. On the other hand, this alternative needs additional work on the separation of the two entrances and the safety for pedestrians. The expansion costs are an additional disadvantage.

5.3 Single-Facility Location Model

Several types of *distance* measures of effectiveness are used in a diversity of facility location models. Typically, the objective function of the mathematical models is to minimize a total value of this measure of effectiveness subject to a set of constraints that differentiate among several cases to be considered in this chapter. The three best-known types of distance measures are:

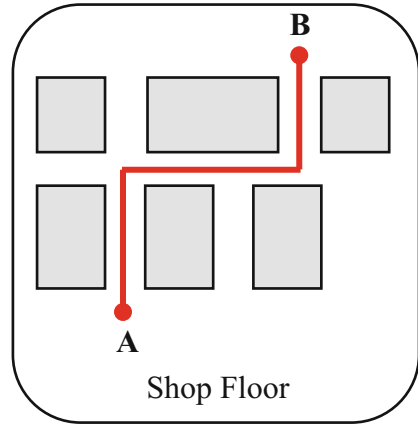
- (a) Rectilinear or rectangular.
- (b) Euclidean (straight line).
- (c) Actual distance (usually approximated by rectilinear or Euclidean or a combination of both types).

Although Euclidean distances may be used, in most applications the straight-line paths are not feasible because of limitations generated by the physical arrangement of facilities. These limitations may include obstacles presented by machines, material handling equipment, storage locations, and a diversity of building features (floor type, foundation strength, columns, building shape, and so on). In most applications a rectilinear distance, illustrated in Fig. 5.4, is used. Figure 5.4 shows the rectilinear path between points A and B. The shaded areas represent machines and equipment on the shop floor. Owing to their presence, it is not possible to travel along a straight line drawn between points A and B. Hence the distance has to be traversed along a rectilinear path along the aisles between the machines (space between the shaded areas).

Two typical distance-minimization problems will be considered for the location of a single new facility in this chapter:

- (a) Minimization of sum of weighted distances traveled from the new facility to each existing facility.

Fig. 5.4 Illustration of rectilinear distances



- (b) Minimization of the maximum distance between the new facility and any existing facility.

The following notation will be used to formulate the two objective functions associated with these measures of effectiveness:

$\mathbf{X} = (x, y)$: location of new facility

$\mathbf{P}_i = (a_i, b_i)$: location of existing facility i

$d(\mathbf{X}, \mathbf{P}_i)$: distance between new facility and existing facility i

The objective functions corresponding to the typical measures of effectiveness in single-facility location models can be expressed as follows:

- Minisum model (w_i is the number of trips associated with existing facility i):

$$\text{Minimize } f(\mathbf{X}) = \sum_{i=1}^m w_i d(\mathbf{X}, \mathbf{P}_i)$$

- Minimax model

$$\text{Minimize } f(X) = \max\{d(\mathbf{X}, \mathbf{P}_1), d(\mathbf{X}, \mathbf{P}_2), \dots, d(\mathbf{X}, \mathbf{P}_m)\}$$

5.3.1 Minisum Location Model with Rectilinear Distances

If rectilinear distances are used, the distance between two points is equal to the sum of the absolute values of the difference between their coordinates: $d(\mathbf{X}, \mathbf{P}_i) = |x - a_i| + |y - b_i|$. Thus the minisum problem can be formulated as:

$$\text{Minimize } f(X) = \sum_{i=1}^m w_i |x - a_i| + \sum_{i=1}^m w_i |y - b_i| \quad (5.1)$$

This objective function is *separable* in the sense that both x and y can be determined separately. The solution procedure for each coordinate is identical. The minimization problem for x can be formulated as minimizing $\sum_{i=1}^m w_i |x - a_i|$. This is equivalent to the linear program

$$\text{Minimize } \sum_{i=1}^m w_i (r_i + s_i) \quad (5.2)$$

subject to

$$x - r_i + s_i = a_i, \quad i = 1, 2, \dots, m \quad (5.3)$$

$$r_i, s_i \geq 0, \quad i = 1, 2, \dots, m \quad (5.4)$$

In order to see why this is an equivalent model, let us reason as follows. The quantity of the absolute value $|x - a_i|$ can be either negative or positive. Therefore, it can be expressed as the difference between two non-negative variables (unknown at this time). That is, $x - a_i = r_i - s_i$. Now suppose that r_i and s_i are such that if one is positive then the other one is zero (we will prove this later). As a result, we have

$$x - a_i = r_i \quad \text{if } r_i > 0 \text{ and } s_i = 0 \quad (5.5)$$

$$x - a_i = -s_i \quad \text{if } r_i = 0 \text{ and } s_i > 0 \quad (5.6)$$

Moreover,

$$\sum_{i=1}^m w_i |x - a_i| = \sum_{i=1}^m w_i |r_i| = \sum_{i=1}^m w_i r_i \quad \text{if } r_i > 0 \text{ and } s_i = 0 \quad (5.7)$$

$$\sum_{i=1}^m w_i |x - a_i| = \sum_{i=1}^m w_i |-s_i| = \sum_{i=1}^m w_i s_i \quad \text{if } r_i = 0 \text{ and } s_i > 0 \quad (5.8)$$

As a result of our analysis, we conclude that minimizing $\sum_{i=1}^m w_i |x - a_i|$ is equivalent to minimizing $\sum_{i=1}^m w_i (r_i + s_i)$ under the constraints $x - r_i + s_i = a_i, i = 1, 2, \dots, m; r_i, s_i \geq 0, i = 1, 2, \dots, m$. In order to see why the two variables r_i and s_i cannot be simultaneously positive in any basic solution, let us use the well-known tableau

Table 5.1 Simplex tableau

x	r_1	s_1	r_2	s_2	$\dots$	r_i	s_i	$\dots$	r_m	s_m	RHS
1	-1	+1	0	0	$\dots$	0	0	$\dots$	0	0	a_1
1	0	0	-1	+1	$\dots$	0	0	$\dots$	0	0	a_2
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
1	0	0	0	0	$\dots$	-1	+1	$\dots$	0	0	a_i
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$	$\vdots$		$\vdots$	$\vdots$	$\vdots$
1	0	0	0	0	$\dots$	0	0	$\dots$	-1	+1	a_m

format of the simplex method for the constraints of the linear program, shown in Table 5.1.

In Table 5.1, the column associated with r_i is the negative of the column associated with s_i . As a result, both variables cannot be positive in the same basic solution, since in such a case the basis matrix would have its determinant equal to zero.

Consider again the primal program given in Eqs. (5.2)–(5.4). Let z_i be the dual variable associated with the i th constraint. Therefore, the dual model corresponding to the above primal model is

$$\text{Maximize } a_1 z_1 + a_2 z_2 + \dots + a_m z_m \quad (5.9)$$

subject to

$$z_1 + z_2 + \dots + z_i + \dots + z_m = 0 \quad (5.10)$$

$$-z_i \leq w_i \quad i = 1, 2, \dots, m \quad (5.11)$$

$$z_i \leq w_i \quad i = 1, 2, \dots, m \quad (5.12)$$

Note that Constraints (5.11) and (5.12) imply that $|z_i| \leq w_i$. In summary, the dual model can be written as follows:

$$\text{Maximize } \sum_{i=1}^m a_i z_i \quad (5.13)$$

subject to

$$\sum_{i=1}^m z_i = 0 \quad (5.14)$$

$$|z_i| \leq w_i, \quad i = 1, 2, \dots, m \quad (5.15)$$

Now we note that

$$\begin{aligned}\sum_{i=1}^m a_i z_i &= \sum_{i=1}^m a_i z_i - x(0) = \sum_{i=1}^m a_i z_i - x \sum_{i=1}^m z_i \\ &= \sum_{i=1}^m z_i (a_i - x) \leq \sum_{i=1}^m |z_i| (x - a_i).\end{aligned}$$

Since $|z_i| \leq w_i$, we conclude that $\sum_{i=1}^m a_i z_i \leq \sum_{i=1}^m w_i |x - a_i|$. Thus, the value of the objective function for any feasible dual solution should be bounded by any feasible value of the objective function of the original model. At optimality,

$$\sum_{i=1}^m a_i z_i^* = \sum_{i=1}^m w_i |x_i^* - a_i|.$$

Proceeding with this analysis, let us arrange the a_i values in increasing order of magnitude: $a_{(1)} < a_{(2)} < \dots < a_{(m)}$. Now let us define t such that:

$$\sum_{i=1}^{t-1} w_{(i)} < \sum_{i=1}^m w_{(i)}; \quad \sum_{i=1}^t w_{(i)} \geq \sum_{i=t+1}^m w_{(i)} \quad (5.16)$$

$$z_{(i)}^* = -w_{(i)} \quad i = 1, 2, \dots, t-1 \quad (5.17)$$

$$z_{(i)}^* = w_{(i)} \quad i = t+1, t+2, \dots, m \quad (5.18)$$

$$z_{(t)}^* = -\sum_{i \neq t}^m z_{(i)}^* \quad (5.19)$$

$$x^* = a_{(t)} \quad (5.20)$$

The above solution is indeed an optimal solution as verified below:

$$\begin{aligned}\sum_{i=1}^m a_{(i)} z_{(i)}^* &= \sum_{i=1}^m a_{(i)} z_{(i)}^* - x^*(0) = \sum_{i=1}^m a_{(i)} (a_{(i)} - a_{(t)}) \\ &= \sum_{i=1}^{t-1} z_{(i)}^* (a_{(i)} - a_{(t)}) + \sum_{i=t+1}^m z_{(i)}^* (a_{(i)} - a_{(t)}) \\ &= -\sum_{i=1}^{t-1} w_{(i)} (a_{(i)} - a_{(t)}) + \sum_{i=t+1}^m w_{(i)} (a_{(i)} - a_{(t)}) \\ &= \sum_{i=1}^m w_{(i)} |x^* - a_i|\end{aligned}$$

The two conditions given in Eq. (5.16) actually result in a value t such that $\sum_{i=1}^t w_{(i)}$ exactly reaches or immediately exceeds the value of $\frac{1}{2} \sum_{i=1}^m w_i$. Therefore, the optimal value of the x -coordinate can be found as the value x^* that corresponds to a cumulative weight equal to $\frac{1}{2} \sum_{i=1}^m w_i$. A similar analysis can be conducted to find $y = y^*$. Based on the previous analysis the following rules will result in the optimal location (x, y) .

Rules to Find the Optimal Solution

- Scan the a_i values in increasing order and for each value compute $\sum_{j=1}^i w_j$.
- The value x^* is the first a_i at which the cumulative weight reaches or immediately exceeds $\frac{1}{2} \sum_{i=1}^m w_i$.
- Scan the b_i values in increasing order and for each value compute $\sum_{j=1}^i w_j$.
- The value y^* is the first b_i at which the cumulative weight reaches or immediately exceeds $\frac{1}{2} \sum_{i=1}^m w_i$.

Example 5.1

Machines 1, 2, 3, and 4 are located at the points (8, 5), (4, 2), (11, 8), and (13, 2), respectively. There are 9, 6, 4, and 12 trips per week respectively, between the machines and a new facility. Find the location of the new facility.

Solution

(a) Finding x^* :

- $a_{(1)} = a_2 = 4$; $a_{(2)} = a_1 = 8$; $a_{(3)} = a_3 = 11$; $a_{(4)} = a_4 = 13$
- $w_{(1)} = w_2 = 6$; $w_{(2)} = w_1 = 9$; $w_{(3)} = w_3 = 4$; $w_{(4)} = w_4 = 12$
- $\frac{1}{2} \sum_{i=1}^m w_i = \frac{31}{2} = 15.5$
- $w_{(1)} = 6 < \frac{1}{2} \sum_{i=1}^m w_i = 15.5$
- $w_{(1)} + w_{(2)} = 6 + 9 = 15 < \frac{1}{2} \sum_{i=1}^m w_i = 15.5$
- $w_{(1)} + w_{(2)} + w_{(3)} = 6 + 9 + 4 = 19 > \frac{1}{2} \sum_{i=1}^m w_i = 15.5$
- Therefore, $x^* = a_{(3)} = a_3 = 11$.

(b) Finding y^* :

- $b_{(1)} = b_2 = 2$; $b_{(2)} = b_4 = 2$; $b_{(3)} = b_1 = 5$; $b_{(4)} = b_3 = 8$
- $w_{(1)} = w_2 = 6$; $w_{(2)} = w_4 = 12$; $w_{(3)} = w_1 = 9$; $w_{(4)} = w_3 = 4$
- $\frac{1}{2} \sum_{i=1}^m w_i = \frac{31}{2} = 15.5$

- $w_{(1)} = 6 < \frac{1}{2} \sum_{i=1}^m w_i = 15.5$
- $w_{(1)} + w_{(2)} = 6 + 12 = 18 > \frac{1}{2} \sum_{i=1}^m w_i = 15.5$
- Therefore, $y^* = b_{(2)} = b_4 = 2$.

Tables 5.2 and 5.3 summarize the results shown above for both x and y . In each table the machines are arranged in increasing order of the coordinate value. It is noted that for the x -coordinate the value $\frac{1}{2} \sum_{i=1}^m w_i = 15.5$ is immediately exceeded by the value of 19 which corresponds to machine 3 and $a_3 = 11$. Therefore, $x^* = 11$. Similarly, for the y -coordinate, it is noted that the value $\frac{1}{2} \sum_{i=1}^m w_i = 15.5$ is immediately exceeded by the value of 18 which corresponds to machine 4 and $b_4 = 2$. Therefore, $y^* = 2$. Thus the new facility will be located at the point (11, 2).

5.3.1.1 Cumulative Weight Diagram

A graphical approach to the minisum location model is helpful to gain more understanding about the location problem. The graph to be constructed is known as a *cumulative weight diagram*. Here the number of trips for an existing facility is considered as its *weight*. This weight acts as a *force* pulling the new facility in the direction of the existing facility. The horizontal axis records the coordinate of the

Table 5.2 Calculation of optimal x coordinate

Machine i	Coordinate a_i	Weight w_i	$\sum_i w_i$
2	4	6	6
1	8	9	15
3	11	4	19
4	13	12	31

Table 5.3 Calculation of optimal y coordinate

Machine i	Coordinate b_i	Weight w_i	$\sum_i w_i$
2	2	6	6
4	2	12	18
1	5	9	27
3	8	4	31

location of existing facility i (either a_i or b_i). The vertical axis records the cumulative weight to the right of each coordinate.

The following steps can be followed to draw the cumulative weight diagram for the a_i coordinates and to obtain the optimal value of $x = x^*$ for the location of the new facility:

- On the horizontal axis mark the values of x equal to 0 and all $a(i)$ values for $i = 1, 2, \dots, m$.
- On the vertical axis mark the sum of the weight of each marked value of x plus those to its right.
- Starting at the left with $\sum_{i=1}^m w_i$, join horizontal and vertical linear segments with the length of each vertical displacement equal to the weight at each point.
- Find value $x = x^*$ in the diagram that corresponds to a cumulative weight of $\frac{1}{2} \sum_{i=1}^m w_i$.

A similar analysis is carried out to find $y = y^*$.

- On the horizontal axis mark the values of y equal to 0 and all $b(i)$ values for $i = 1, 2, \dots, m$.
- On the vertical axis mark the sum of the weight of each marked value of y plus those to its right.
- Starting at the left with $\sum_{i=1}^m w_i$, join horizontal and vertical linear segments with the length of each vertical displacement equal to the weight at each point.
- Find value $y = y^*$ in the diagram that corresponds to a cumulative weight of $\frac{1}{2} \sum_{i=1}^m w_i$.

Example 5.2

In Example 5.1, use the cumulative weight diagram approach to find the optimal location of the new machine. (a) Draw the cumulative weight diagram for x . (b) Draw the cumulative weight diagram for y . (c) Find the optimal location.

Solution

- Draw the cumulative weight diagram for x . In Fig. 5.5, W represents the cumulative weight.
- Draw the cumulative weight diagram for y . In Fig. 5.6, W represents the cumulative weight.
- Find the optimal values of x and y . Thus the optimal x coordinate is 11 and the optimal y coordinate is 2. Hence the optimal location is (11, 2).

Fig. 5.5 Cumulative weight diagram for x

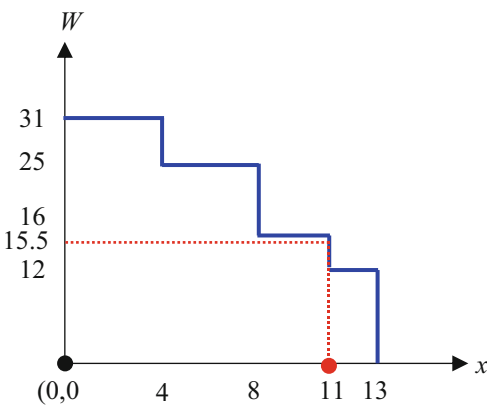
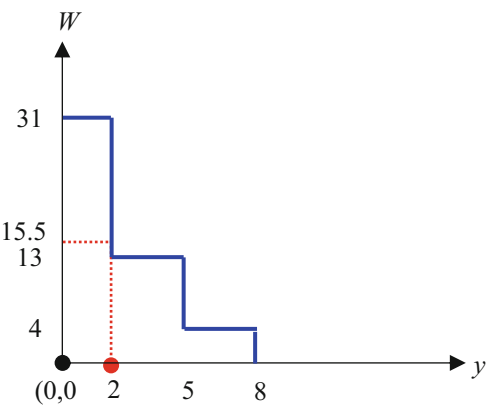


Fig. 5.6 Cumulative weight diagram for y



5.3.1.2 Contours for Minisum Model

Contours are important because they provide meaningful information on the shape of the surface of the objective function and allow the selection of attractive feasible locations when an optimal location is not possible. A typical shape of the response surface for the minisum model with rectangular distances is shown in Fig. 5.7. Three contours are shown in this figure. Note, particularly, that the shape may not be the same for all contours. As can be seen in this figure, the top contour has seven sides, while the middle and bottom contours have four sides each.

For this procedure we need the *resultant force* diagram for both x and y . The resultant force is defined as the sum of weights to the *left of a point* (a value of a_i) minus the sum of weights *at the point or to its right*. The procedural steps are outlined below:

- Horizontal axis: mark a_i values on the x -axis.
- Vertical axis: mark b_i values on the y -axis.
- Generate a rectangular grid using marked points on each axis.

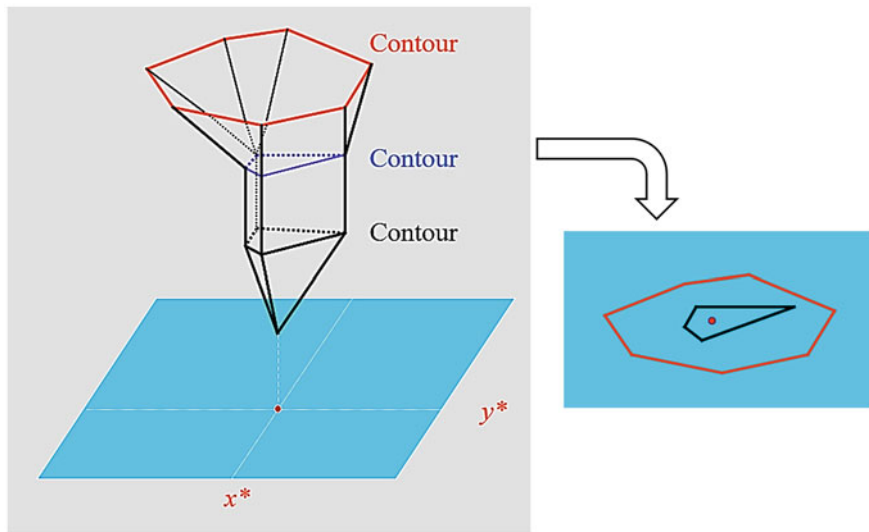


Fig. 5.7 Typical response surface with contours

- Find the resultant weight (force) for each interval in both axes.
- For each cell of the grid compute $S_{ij} = -M_i/N_j$, where M_i is the resultant weight (force) for the x -axis and N_j the resultant weight (force) for the y -axis.
- Choose any point in any cell, draw a linear segment having slope equal to S_{ij} , and join it to another segment in the next cell, continuing until a convex polygon is obtained. This is a contour with all points having the same value of the objective function.

We note that this diagram can be obtained from the *cumulative weight* diagram by changing the meaning of the vertical axis. Instead of being defined as the weight to the right of a point, it is redefined as the cumulative weight (in a force analogy). The optimal coordinates correspond to resultant forces equal to 0.

Example 5.3

In Example 5.1, draw the resultant force diagrams for x and y .

Solution

Figures 5.8 and 5.9 show the resultant force diagrams. The optimal location is (11,2).

Example 5.4

Draw a contour through the point (4,5) using the results obtained in Example 5.3.

Solution

Figure 5.10 shows the contour. The corresponding value of the objective function is equal to 250.

Two additional contours for the locations in Example 5.2 are shown in Fig. 5.11. One contour passes (4,2) and has objective function value equal to 231. The second

Fig. 5.8 Resultant force diagram for x

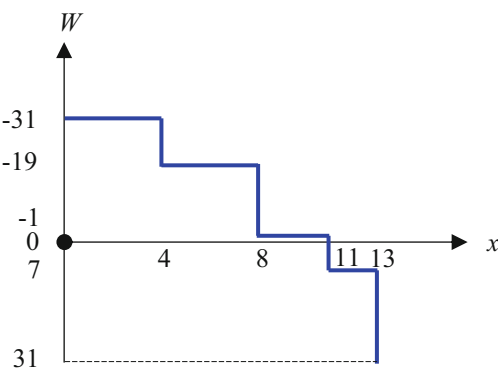
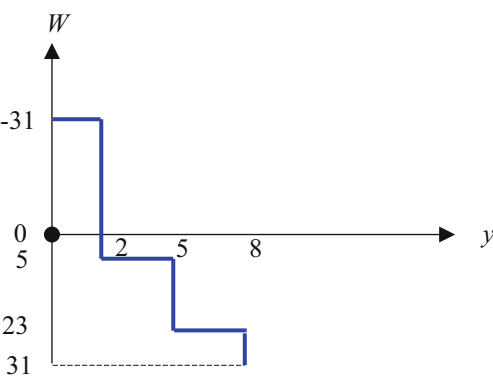


Fig. 5.9 Resultant force diagram for y



one passes through (13,2) and has objective function value equal to 142. As an exercise, the student is asked to verify these values of the objective function.

5.3.2 Extension to Rectangular Areas

Consider a situation where an area is associated with some facilities. These facilities may be referred to as *area facilities*. All others may be referred to as *point facilities*. Previously the weight (usually number of trips) assigned to the distance to any existing facility was associated with one point. Now it is associated with an area. A reasonable assumption in this case is to consider a *uniform* distribution of the weight over the area. It is also reasonable to assume that an area facility has a rectangular area or a combination of rectangular areas.

In the event that there are one or more point facilities inside the same area facility, the area of the facility is divided into smaller rectangular areas as determined by vertical lines drawn through the point facilities. Additionally, the total weight of the area facility is proportionally divided among the smaller rectangular areas. The

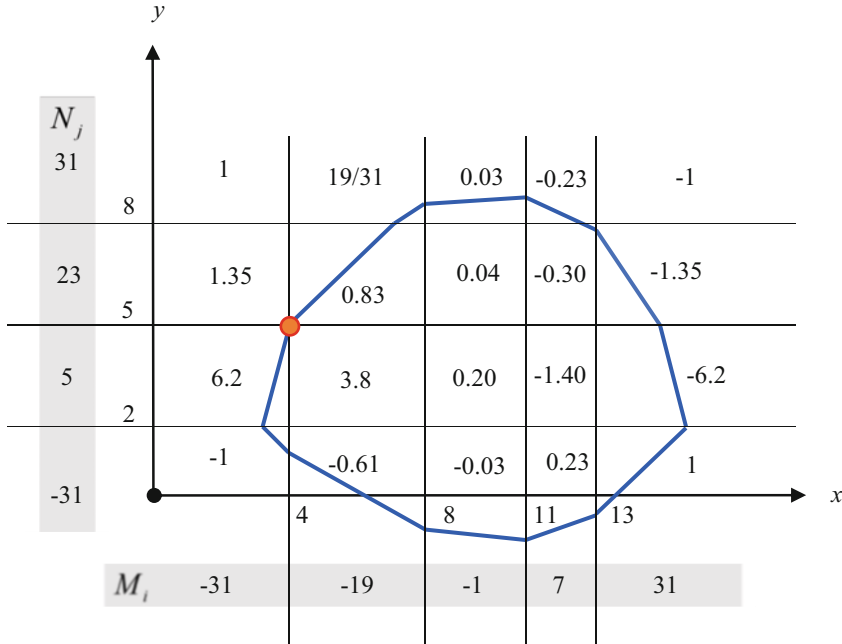


Fig. 5.10 Contour through point (4,5)

extension of the graphical procedure used to draw a cumulative weight curve for the minimum model with rectilinear distances can be achieved by means of the following rules:

1. On the horizontal axis mark the values of x corresponding to all point facilities, as well to the vertical sides of each rectangle (representing either an area facility or a rectangular portion of an area facility that contains point facilities). Now scan these marks from left to right.
2. On the vertical axis assign the value $\sum_{i=1}^m w_i + \sum_{i=1}^p v_i$ to the first mark on the horizontal axis. It is assumed that there are m point facilities and p area facilities. Moreover, the weight of point facility i is equal to w_i and that of area facility i is equal to v_i . Proceed through all marks on the horizontal axis adjusting the cumulative weight in the following fashion:
 - (a) For an interval between two *adjacent* point facilities the cumulative weight curve has a horizontal segment.
 - (b) At the location of a point facility the weight curve has a vertical drop equal to the weight of the point facility.
 - (c) For an interval including a rectangle, the curve decreases linearly.
 - (d) The magnitude of the drop is equal to the weight of the rectangle.

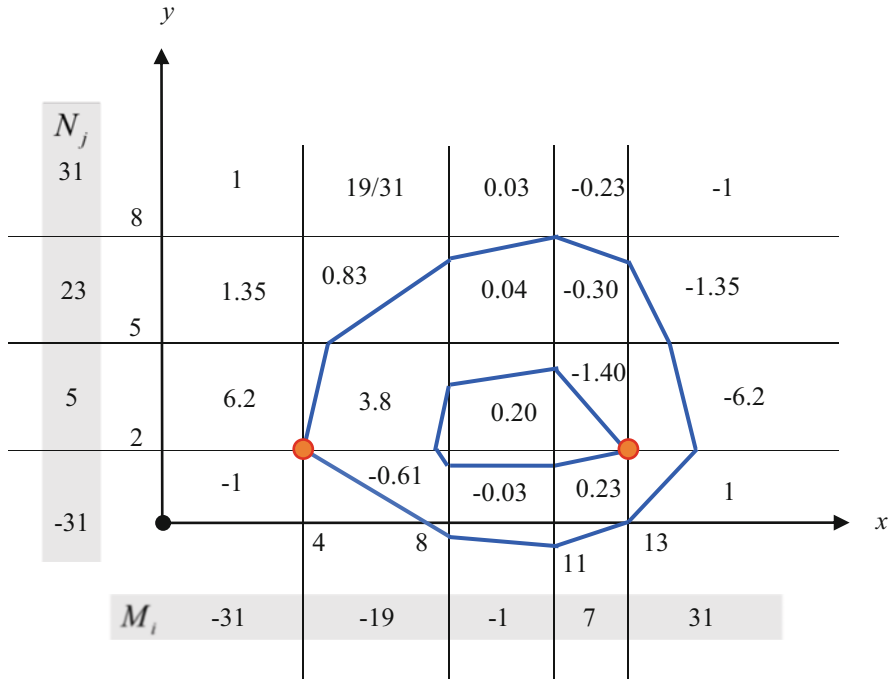
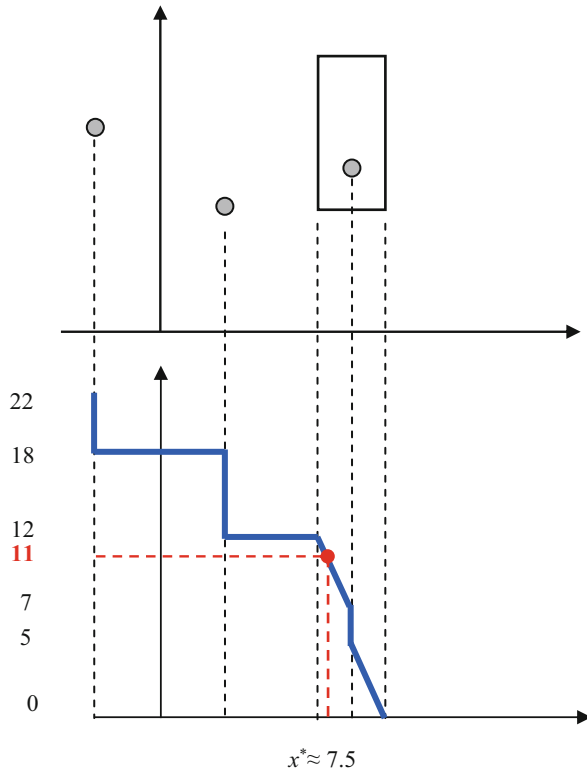


Fig. 5.11 Additional contours

3. Find value $x = x^*$ in the diagram that corresponds to a cumulative $\frac{1}{2} \left(\sum_{i=1}^m w_i + \sum_{i=1}^p v_i \right)$.
4. A similar analysis is carried out to find y^* . On the horizontal axis mark the values of y corresponding to all point facilities, as well to the vertical sides of each rectangle (representing either an area facility or a rectangular portion of an area facility that contains point facilities). Now scan these marks from left to right.
5. On the vertical axis assign the value $\sum_{i=1}^m w_i + \sum_{i=1}^p v_i$ to the first mark on the horizontal axis. Proceed through all marks on the horizontal axis adjusting the cumulative weight in the following fashion:
 - (a) For an interval between two *adjacent* point facilities the cumulative weight curve has a horizontal segment.
 - (b) At the location of a point facility the weight curve has a vertical drop equal to the weight of the point facility.
 - (c) For an interval including a rectangle, the curve decreases linearly.
 - (d) The magnitude of the drop is equal to the weight of the rectangle.

Fig. 5.12 Cumulative weight diagram for x -coordinate



6. Find value $y = y^*$ in the diagram that corresponds to a cumulative weight equal to

$$\frac{1}{2} \left(\sum_{i=1}^m w_i + \sum_{i=1}^p v_i \right).$$

Example 5.5

Consider the three point facilities and one area facility shown in the graph with their locations and number of trips to a new facility. Draw the corresponding cumulative weight diagram for the x -coordinate.

Solution

The cumulative weight diagram for the x -coordinate is shown in Fig. 5.12. The optimal value of x is approximately equal to 7.5. This is found by drawing a horizontal line through the cumulative weight value equal to half of the sum of weights, and reading the corresponding x -value. As an exercise, the student is asked to repeat this analysis to find the value of the y -coordinate.

5.3.3 Minimax Location Model for Single-Facility

The minimax problem for the location of a single facility involves locating a new facility with respect to m existing facilities with the objective of minimizing the maximum distance from the new facility to the existing facilities. The minimax model is primarily concerned with worst-case scenarios and not the average case. A few examples of the minimax problems are locating emergency service facilities, such as fire extinguishers, ambulance or helicopter service to respond to accidents, fire stations, and bomb disposal squads to be located in sensitive localities.

The minimax single-facility location problem can be further classified according to the type of distance between the facilities as follows:

1. Euclidean distance minimax single-facility location model.
2. Rectilinear distance minimax single-facility location model.

5.3.4 Minimax Location Model for Rectilinear Distances

The *unweighted* minimax single-facility location problem with rectilinear distances is to locate a new facility in such a way that its distance to the farthest existing facility is minimized. The corresponding model is formulated as

$$\text{Minimize } f(x, y) = \max |x - a_1| + |y - b_1|, |x - a_2| + |y - b_2|, \dots, |x - a_m| + |y - b_m| \quad (5.21)$$

Let us introduce the following notation:

$$\begin{aligned} c_1 &= \min_{i=1\dots m} (a_i + b_i) \\ c_2 &= \max_{i=1\dots m} (a_i + b_i) \\ c_3 &= \min_{i=1\dots m} (-a_i + b_i) \\ c_4 &= \max_{i=1\dots m} (-a_i + b_i) \\ c_5 &= \max(c_2 - c_1, c_4 - c_3) \end{aligned}$$

When the solution is not unique, all multiple optimal solutions can be shown to be the points of the linear segment connecting the points: $(x, y) = \frac{1}{2}(c_1 - c_3, c_1 + c_3 + c_5)$ and $(x, y) = \frac{1}{2}(c_2 - c_4, c_2 + c_4 - c_5)$. At any optimal point, the maximum distance is equal to $\frac{c_5}{2}$.

Proof The optimization problem is equivalent to the following LP model:

$$\begin{aligned} & \text{Minimize } z \\ & \text{subject to} \\ & |x - a_i| + |y - b_i| \leq z \quad i = 1, 2, \dots, m \end{aligned}$$

Now, rewrite each constraint as $-z + |y - b_i| \leq x - a_i \leq z - |y - b_i|$. Next, it is straightforward to verify that each constraint is equivalent to the following four inequalities:

1. $x + y - z \leq a_i + b_i$
2. $x + y + z \geq a_i + b_i$
3. $-x + y - z \leq -a_i + b_i$
4. $-x + y + z \geq -a_i + b_i$

Using the notation previously introduced, the equivalent model can be formulated as indicated below:

$$\begin{aligned} & \text{Minimize } z \\ & \text{subject to} \\ & x + y - z \leq c_1 \quad (5.22) \\ & x + y + z \geq c_2 \quad (5.23) \\ & -x + y - z \leq c_3 \quad (5.24) \\ & -x + y + z \geq c_4 \quad (5.25) \end{aligned}$$

From (5.22) and (5.23) we can conclude that $z \geq \frac{1}{2}(c_2 - c_1)$. From (5.24) and (5.25) we conclude that $z \geq \frac{1}{2}(c_4 - c_3)$. Thus, $z \geq \frac{1}{2}c_5$. Now it is straightforward to verify that the points $(x, y) = \frac{1}{2}(c_1 - c_3, c_1 + c_3 + c_5)$ and $(x, y) = \frac{1}{2} \times (c_2 - c_4, c_2 + c_4 - c_5)$ satisfy the constraints and have $z = \frac{1}{2}c_5$. Therefore, these are optimal (basic) solutions. Furthermore, all points on the linear segment joining these points are also optimal (non-basic) solutions.

Example 5.6

An emergency service unit is needed to serve the following subdivisions in a city, with locations shown in Table 5.4. (a) Propose a model (criterion) to solve this problem. (b) Determine the optimal location.

Solution

- (a) The single-facility **minimax model** is the most appropriate for this application, since it is desirable to locate the emergency facility in such a way that the longest possible distance traveled in an emergency will be minimized.

Table 5.4 Coordinates of locations

Subdivision	x-Coordinate	y-Coordinate
A	4	3
B	5	11
C	13	13
D	10	6
E	4	6
F	10	10
G	14	2

(b) The optimal location can be determined as follows:

$$c_1 = \min\{4 + 3, 5 + 11, 13 + 13, 10 + 6, 4 + 6, 10 + 10, 14 + 2\} = 7$$

$$c_2 = \max\{4 + 3, 5 + 11, 13 + 13, 10 + 6, 4 + 6, 10 + 10, 14 + 2\} = 26$$

$$c_3 = \min\{-4 + 3, -5 + 11, -13 + 13, -10 + 6, -4 + 6, -10 + 10, -14 + 2\} = -12$$

$$c_4 = \max\{-4 + 3, -5 + 11, -13 + 13, -10 + 6, -4 + 6, -10 + 10, -14 + 2\} = 6$$

$$c_5 = \max\{26 - 76 - 12\} = 19$$

Therefore, the solution lies on the linear segment joining the points: $(x^*, y^*) = (7 + 12, 7 - 12 + 19)/2 = (9.5, 7)$ and $(x^*, y^*) = (10, 6.5)$.

5.3.4.1 Contours for Minimax Model

In order to find a contour for a specified value of the objective function z , we can proceed as follows. Inequalities (5.22)–(5.25) given above can be re-written as:

$$x + y \leq c_1 + z \quad (5.26)$$

$$x + y \geq c_2 - z \quad (5.27)$$

$$-x + y \leq c_3 + z \quad (5.28)$$

$$-x + y \geq c_4 - z \quad (5.29)$$

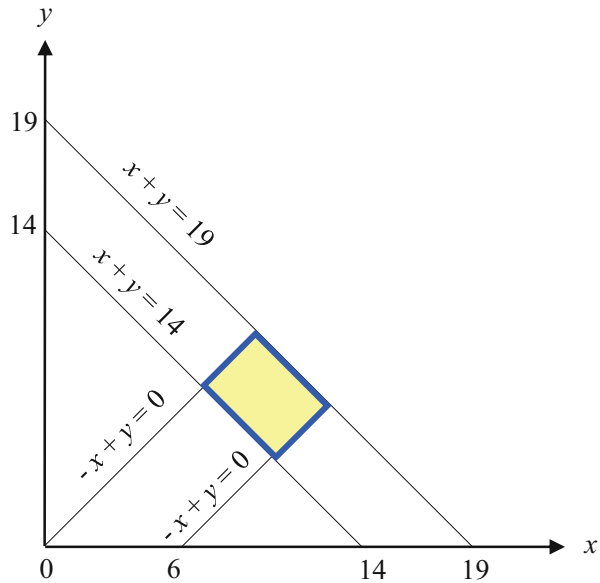
Example 5.7

In Example 5.6 find the equations for the borderlines of the contour for $z = 12$.

Solution

A contour for a specified value of z is the boundary of the region defined by inequalities (5.26)–(5.29). In the current numerical illustration, $z = 12$. In this case, inequalities (5.26)–(5.29) can be formulated as $x + y \leq 19$, $x + y \geq 14$, $-x + y \leq 0$, $-x + y \geq -6$. The following straight-line equations are the borderlines of the desired contour:

Fig. 5.13 Contour for Example 5.7



$$\begin{aligned} x + y &= 19 \\ x + y &= 14 \\ -x + y &= 0 \\ -x + y &= -6 \end{aligned}$$

Figure 5.13 shows the bounding contour along with the optimal solution.

5.4 Location-Allocation Problem

The primary objective in this problem is determining the number and location of new facilities, as well as the allocation of item movement between the new and existing facilities. A common example is the location of distribution centers that receive products from production facilities and distribute products to retail or wholesale outlets. To formulate a general mathematical model, the following notation will be used:

ψ = total cost per unit time

n = number of new facilities

$\mathbf{X}_j = (x_j, y_j)$, coordinate location of new facility j

$\mathbf{P}_i = (a_i, b_i)$, coordinate location of existing facility i

5.4.1 Mathematical Model

$$\text{Minimize } \psi = \sum_{j=1}^n \sum_{i=1}^m z_{ji} w_{ji} d(\mathbf{X}_j, \mathbf{P}_i) + g(n) \quad (5.30)$$

subject to

$$\sum_{i=1}^m z_{ji} = 1 \quad i = 1, 2, \dots, m$$

$$n = 1, 2, \dots, m$$

The decision variables are n , z_{ji} , and $\mathbf{X}_j$. Each existing facility interacts with only one new facility. Since no capacity conditions are specified, we are assuming that a new facility is able to handle all interchanges with existing facilities. Normally we can assume that $w_{1i} = w_{2i} = \dots = w_{ni}$, since identical new facilities are to be located.

5.4.2 Solution Procedure

1. Find number of possible combinations for a given value of n and m :

$$S(n, m) = \sum_{k=0}^{n-1} \frac{(-1)^k (n-k)^m}{k!(n-k)!} \quad (5.31)$$

2. For each combination indicate which existing facilities are assigned to each new facility.
3. Use the single-facility procedure to locate each new facility (using rectilinear distances).
4. For each group (one new facility and its associated existing facilities) compute the trip costs.
5. Find total cost for all groups (trip cost plus cost of owning and operating the new facilities).
6. Scan all combinations and eliminate infeasible ones (those with overlapping service areas).
7. Find the minimal-cost feasible combinations for the value of n being considered, ψ_n .
8. Repeat the above procedure for $n = 1, 2, \dots, m$, and select the global optimal solution as the one corresponding to the minimum among $\psi_1, \psi_2, \dots, \psi_m$.

Table 5.5 Total cost for $n = 1$

Combination	Allocations to F_1	Location of F_1	Total cost \$
1	1, 2, 3	(1,1)	700

Table 5.6 Possible combinations for $n = 2$

Combination	Allocations to F_1	Allocations to F_2
1	1	2,3
2	2	1,3
3	3	1,2

Table 5.7 Location of F_2 in first combination

a_i	w_i	$\sum_i w_i$	b_i	w_i	$\sum_i w_i$
1	5	5	1	15	15
2	15	20	2	5	20

Example 5.9

Consider a location–allocation problem with three machines (existing facilities). Determine the number of repair centers (new facilities). The three machines are located at the points (0, 0), (1, 2), and (2, 1). It is anticipated that the number of times these machines are taken to the repair center in one planning period will be 10, 5, and 15, respectively. Determine the number of repair centers (new facilities) and allocations of machines to these centers. Assume rectilinear distances, a cost of \$5 per unit distance, and \$300 as the cost of owning and operating each new facility during the planning period.

Solution

For $n = 1$ and $m = 3$, Eq. (5.31) yields $S(1, 3) = 1$. Consistently with this result, only one new repair center is needed. Furthermore, the solution to the minisum problem indicates that this repair center is located at the point (1,1). The travel cost associated with this location is $[(1 + 1)(10) + (0 + 1)(5) + (1 + 0)(15)](2)(5) = \400 . The owning cost of one center is \$300. Hence the total cost is $\psi_1 = \$400 + \$300 = \$700$. Table 5.5 summarizes the optimal solution for this case.

For $n = 2$ and $m = 3$, the value of $S(2,3) = 3$. These three combinations are listed in Table 5.6. To find the optimal location of the repair facilities and the corresponding allocation of the machines to these facilities we evaluate the cost for all the combinations mentioned in this table.

The total cost for the first combination in Table 5.6 is found as follows. In this combination machine 1 is assigned to repair center F_1 and machines 2 and 3 to repair center F_2 . Thus repair center F_1 is located at (0,0) since the facility and the machine share the same location. To determine the location of F_2 , first we list the coordinate values for machines 2 and 3 in increasing order and compute the cumulative weight. The solution corresponds to the coordinate value where half of the weight total is exactly reached or immediately exceeded. The calculations are shown in Table 5.7. From the results shown in Table 5.7, it is determined that F_2 is located at (2,1).

Table 5.8 Location of F_2 in second combination

a_i	w_i	$\sum_i w_i$	b_i	w_i	$\sum_i w_i$
0	10	10	0	10	10
2	15	25	1	15	25

Table 5.9 Location of F_2 in third combination

a_i	w_i	$\sum_i w_i$	b_i	w_i	$\sum_i w_i$
0	10	10	0	10	10
1	5	15	2	5	15

Table 5.10 Total costs for $n = 2$

Combination	Allocations to F_1	Allocations to F_2	Location of F_1	Location of F_2	Total cost \$
1	1	2,3	(0,0)	(2,1)	700
2	2	1,3	(1,2)	(2,1)	900
3	3	1,2	(2,1)	(0,0)	750

The travel cost for F_1 is equal to 0, since the facility and the machine assigned to it share the same location. Additionally, the travel cost for F_2 is equal to $\$(5)(2 \times 2)(5) = \100 . Therefore, the total cost for the first combination is $\$(2)(300) + \$100 = \$700$.

Now let us consider the combination for the second row in Table 5.6. The repair facility F_1 (new facility) shares its location with machine 2 located at (1,2). We use the cumulative weight procedure for machines 1 and 3 summarized in Table 5.8 to determine that F_2 is located at (2,1).

The travel cost for F_1 is equal to 0, since the facility and machine 2 share the same location. The travel cost for F_2 is equal to the travel cost between F_2 and machine 1 plus the travel cost between F_2 and machine 3. The travel cost for F_2 is equal to $\$5(10 \times 2)[(2 - 0) + (1 - 0)] + \$5(15 \times 2)[(2 - 2) + (1 - 1)] = \300 . The total cost is equal to the owning cost of two repair facilities plus the travel cost, or $2(300) + 0 + 300 = \$900$.

Similarly, we calculate the total cost for the third combination shown in Table 5.6. The repair center F_1 is located at (2,1). Table 5.9 summarizes the results for the location of repair center F_2 at the point (0,0).

The travel cost for F_2 is equal to $\$5(2 \times 5)(1 + 2) + 0 = \150 . Thus the total cost for the third combination is $2(300) + 150 = \$750$. The machine allocations, corresponding locations of repair facilities and the costs for the three combinations are summarized in Table 5.10. The first combination yields the lowest cost, thus $\psi_2 = \$700$.

Finally, for $n = 3$, each new facility will share its location with one existing machine, as shown in Table 5.11. In this case the travel costs are zero and the total cost is $\psi_3 = \$900$.

The global minimum cost is the minimum among the values of ψ_1 , ψ_2 , and ψ_3 , which is \$700. There are two optimal solutions: (1) locate just *one* repair center at

Table 5.11 Total cost for $n = 3$

Combination	Machine allocated to			Location of F_1	Location of F_2	Location of F_3	Total cost \$
	F_1	F_2	F_3				
1	1	2	3	(0,0)	(1,2)	(2,1)	900

(1,1) and allocate all three existing facilities to it; (2) locate *two* repair centers, one at (0,0) to serve machine 1 and a second one at (2,1) to serve machines 2 and 3.

5.5 Quadratic Assignment Problem

The *quadratic assignment problem* (QAP) was introduced by Koopmans and Beckman in 1957 [2]. The objective of the problem is to assign a set of facilities to a set of locations in such a way as to minimize the total assignment cost. The problem is a generalization of the well-known *linear assignment problem*. In the linear model, each facility is assigned to exactly one location without considering any interaction between facilities. This interaction, in facilities location, is usually represented in terms of number of trips between facilities. The quadratic assignment problem allows the inclusion of this interaction, in addition to the consideration of distances between locations. The quadratic assignment model will be formulated using the following notation:

r_{ij} number of trips from facility i to facility j
 d_{rs} distance between locations r and s
 $x_{rs} = 1$ if facility i is assigned to location r ; $x_{rs} = 0$, otherwise

The objective function is to minimize the total distance traveled in trips between facilities. As indicated above, the binary variables are defined to determine the location of each facility, given several available sites. The total distance traveled between any two facilities will depend on the location chosen for each facility and the number of trips from one facility to the other. Thus the objective function is

$$\text{Minimize } Z = \sum_{i=1}^n \sum_{j=1}^n \sum_{r=1}^n \sum_{s=1}^n r_{ij} d_{rs} x_{ir} x_{js} \quad (5.32)$$

subject to

$$\sum_{r=1}^n x_{ir} = 1, \quad i = 1, \dots, n \quad (5.33)$$

$$\sum_{i=1}^n x_{ir} = 1, \quad r = 1, \dots, n \quad (5.34)$$

$$x_{ir} \in \{0, 1\}, \quad i = 1, \dots, n; \quad r = 1, \dots, n \quad (5.35)$$

The first constraint limits each new facility to be assigned to exactly one location. The second constraint limits each location to contain exactly one new facility. Note that the objective function is formulated as the sum of a homogenous second-degree polynomial (each term is associated with the product of two variables). Also note that the constraints are exactly the same as in the classical assignment problem.

Example 5.10

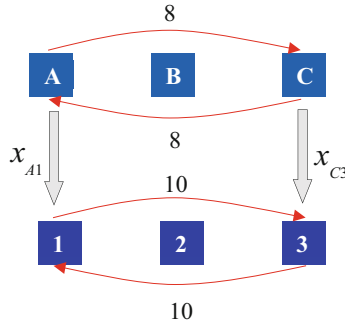
Three new facilities A, B, and C are to be located at three locations 1, 2, and 3. The number of trips between facilities and distances between locations are shown below. Formulate the quadratic assignment model.

Flow (trips)				Distance			
	A	B	C		1	2	3
A	0	2	8	1	0	8	10
B	2	0	4	2	8	0	4
C	8	4	0	3	10	4	0

- Write the binary variables for a quadratic assignment model.
- How many terms does the objective function have in the model?
- Formulate the quadratic assignment model.

Solution

- The binary variables for a quadratic assignment model are x_{Aj} , x_{Bj} , x_{Cj} for $j = 1, 2, 3$. Here, $x_{ij} = 1$ if facility i is assigned to location j , and 0 otherwise.
- There are six possible location combinations for any two facilities. Since there are three ways to pair these facilities (A and B, A and C, and B and C, the total number of terms in the objective function is 18).
- To illustrate the calculation of the terms of the objective function, we will consider the assignment of facility A to location 1, and facility C to location 3. The graph shown below represents the assignments with the corresponding number of trips and distances between locations. In this case the total distance covered between the two facilities is equal to $(8 \times 10) + (8 \times 10) = 160$. The corresponding term in the objective function is $160 x_{A1}x_{C3}$.



The QAP for this problem is formulated as follows:

$$\begin{aligned}
 \text{Minimize } Z = & 32x_{A1}x_{B2} + 40x_{A1}x_{B3} + 16x_{A2}x_{B3} \\
 & + 128x_{A1}x_{C2} + 160x_{A1}x_{C3} + 64x_{A2}x_{C3} \\
 & + 64x_{B1}x_{C2} + 80x_{B1}x_{C3} + 32x_{B2}x_{C3} \\
 & + 32x_{A2}x_{B1} + 40x_{A3}x_{B1} + 16x_{A3}x_{B2} \\
 & + 128x_{A2}x_{C1} + 160x_{A3}x_{C1} + 64x_{A3}x_{C2} \\
 & + 64x_{B2}x_{C1} + 80x_{B3}x_{C1} + 32x_{B3}x_{C2}
 \end{aligned}$$

Subject to:

$$\begin{aligned}
 x_{A1} + x_{A2} + x_{A3} &= 1 \\
 x_{B1} + x_{B2} + x_{B3} &= 1 \\
 x_{C1} + x_{C2} + x_{C3} &= 1 \\
 x_{A1} + x_{B1} + x_{C1} &= 1 \\
 x_{A2} + x_{B2} + x_{C2} &= 1 \\
 x_{A3} + x_{B3} + x_{C3} &= 1 \\
 x_{ir} &\in \{0, 1\}, \quad i = A, B, C; \quad r = 1, 2, 3
 \end{aligned}$$

5.6 Heuristic Methods for Solving the QAP

Two major classes of heuristic procedures for solving the quadratic assignment problem are *construction procedures* and *improvement procedures*. In order to simplify their description, we will use two concepts: (a) incremental cost after adding a new facility; (b) cost difference associated with the pair-wise interchange of facilities and locations. Additional details on the scope and design of computerized procedures are given in Chapter 6.

5.6.1 Incremental Cost After Adding a New Facility

The following notation is used to mathematically represent the total cost or distance associated with moving items between facility i and facility k , and between facility j and facility k :

r_{ij}	rate of item movement (trips) between facility i and facility j
$a(i)$	location to which facility i has been assigned
$d(a(i), a(j))$	distance (or cost) between the locations assigned to facilities i and j

The total distance or cost for facility k , for is given by

$$p_k(\mathbf{a}) = \sum_{1 \leq i < k} r_{ik} d(a(i), a(k)) + \sum_{k < j \leq n} r_{kj} d(a(k), a(j)) \quad (5.36)$$

The above relationship can be rewritten as

$$p_k(\mathbf{a}) = \sum_{j=1}^n r_{kj} d(a(k), a(j)) \quad (5.37)$$

Equation (5.37) represents the total cost associated with facility k . This relationship is used in the design of construction procedures, such as the one described later in this section.

5.6.2 Pairwise Interchange

It is assumed that an initial solution $\mathbf{a} = \{a(1), a(2), \dots, a(n)\}$ is given for which the total cost or distance traveled is represented by $TC(\mathbf{a})$. Furthermore, let $\mathbf{a}'$ denote the solution after interchanging the location of facilities u and v , and let $TC(\mathbf{a}')$ be the corresponding total cost or distance traveled. The effect of the switch in locations is measured by the *differential total cost*:

$$DTC_{uv}(\mathbf{a}) = TC(\mathbf{a}) - TC(\mathbf{a}') \quad (5.38)$$

Clearly, to calculate $TC(\mathbf{a}) - TC(\mathbf{a}')$ we need to subtract those terms involving facilities u or v in $TC(\mathbf{a}')$ from those involving u or v in $TC(\mathbf{a})$. It can be shown that the differential total cost is

$$DTC_{uv}(\mathbf{a}) = \sum_{i=1}^n (r_{iu} - r_{iv}) [d(a(i), a(u)) - d(a(i), a(v))] - 2r_{uv} d(a(u), a(v)) \quad (5.39)$$

The relationship given in Eq. (5.39) is used in the design of heuristic improvement procedures, such as the one described later in this section.

5.6.3 Heuristic Construction Procedure

The heuristic procedure follows a sequence of steps that allows the building up of the solution in an iterative fashion. Initially all facilities are considered as members of the set of *unassigned facilities* F_2 . In essence, the procedure builds a set of *assigned facilities* F_1 by selecting facilities from F_2 in an arbitrary order and assigning locations according to the general principle that pairs of facilities having greater interaction (more trips) should be assigned to closer locations. The notation $a(F_1)$ will be used to indicate the set of locations that are assigned to those facilities transferred from F_2 into F_1 . The *heuristic procedure construction* can be described as follows:

1. Initially select a facility f from $F_2 = \{1, 2, \dots, n\}$ and assign it to location 1. Update $F_1 = \emptyset$ to $F_1 = \{f\}$.
2. Repeat the following steps: (a) select $i \notin F_1$ arbitrarily; (b) identify all available locations $r \notin a(F_1)$ and calculate $\min_r \{p_i(F_1) | r \notin a(F_1)\}$; (c) assign $a(i)$ to location k corresponding to the minimum value found in (b); (d) update F_1 to $F_1 \cup \{i\}$; (e) stop if $F_2 = \emptyset$; otherwise, go to (a).

The heuristic procedure is straightforward and easy to implement. However, the quality of the solution strongly depends on the selection of the initial location. If the first facility selected has large weights, it should be assigned to the location that is easy to reach from other facilities. One might need to run the algorithm several times until the satisfied result has been obtained. This algorithm has another drawback: it is not clear that using the minimization of the incremental cost as a criterion for selecting the location is appropriate, since it might simply postpone the assignment of a critical unassigned facility until there are no more good locations for it.

5.6.4 Heuristic Improvement Procedure

The basic idea here is to modify a given solution so that the total cost or distance traveled is reduced. The existing solution is modified through application of an iterative pairwise interchange technique until there is no further reduction in travel cost or distance. Note that the switch in the locations of two facilities u and v should be made when $DTC_{uv} > 0$. The steps of the heuristic improvement procedure are listed below:

1. Arbitrarily assign each facility to a location to obtain an initial solution $\mathbf{a}_0$.
2. Select arbitrarily facilities u and v from the set of assigned facilities.
3. Evaluate DTC_{uv} . If the value is greater than zero, then the location interchange between facility u and v should be made. Otherwise, select a new pair of facilities and repeat this step.
4. Stop when the improved solution is obtained.

Although the cost difference may be positive, the pairwise interchange may in some cases result in a relatively small total cost difference. In these cases, an additional strategy can be to evaluate all possible combinations of location interchanges between facility u and v to determine the interchange that has the largest positive cost difference.

This strategy is known as the *steepest-descent pairwise interchange* (SDPI). The steps of a computer code for the algorithm are listed below:

```

DO for (NOT Done)
  Done = true
  Max = 0
  Do for i = 1 TO n - 1
    Do for j = (i+1) TO n
      Calculate  $DTC_{ij}(a)$ 
      IF  $DTC_{ij}(a) > \text{Max}$  THEN
        Max =  $DTC_{ij}(a)$ 
        u = i
        v = j
      Done = false
    ENDIF
  Loop Ends
Loop Ends
IF Max > 0 THEN
  Interchange locations
ENDIF
Loop Ends

```

Example 5.11

Illustrate the heuristic procedures considering the assignment of four machines (A, B, C, D) to four locations (1, 2, 3, 4) in a job shop. The number of trips per day between machines and the distances between locations are shown in the two *symmetric* matrices **W** and **D**, respectively.

$$\mathbf{W} = \begin{pmatrix} 0 & 2 & 8 & 3 \\ 2 & 0 & 4 & 9 \\ 8 & 4 & 0 & 5 \\ 3 & 9 & 5 & 0 \end{pmatrix} \quad \mathbf{D} = \begin{pmatrix} 0 & 8 & 10 & 2 \\ 8 & 0 & 4 & 7 \\ 10 & 4 & 0 & 9 \\ 2 & 7 & 9 & 0 \end{pmatrix}$$

Solution

A. Applying the Heuristic Construction Procedure

Iteration 1: Let $i = 3$, $a(3) = 1$; now, $F_1 = \{3\}$ and $a(F_1) = \{1\}$.

Iteration 2: Let $i = 4$; we now consider all possible locations r such that $r \notin a(F_1)$. In this case, $r = 2, 3$, and 4 . For these values, $r_{43}d_{21} = (5)(8) = 40$; $r_{43}d_{31} = (5)(10) = 50$; and $r_{43}d_{41} = (5)(2) = 10$. Hence, $\min\{40, 50, 10\} = 10$, and $a(4) = 4$. Now update $F_1 = \{3, 4\}$ and $a(F_1) = \{1, 4\}$.

Iteration 3: Let $i = 2$; again, consider all possible locations such that $r \notin a(F_1)$. Here, $r = 2, 3$. For these values, $r_{23}d_{21} + r_{24}d_{24} = (4)(8) + (9)(7) = 95$, and $r_{23}d_{31} + r_{24}d_{34} = (4)(10) + (9)(9) = 121$. Hence, $\min\{95, 121\} = 95$, and $a(2) = 2$. Now update $F_1 = \{3, 4, 2\}$ and $a(F_1) = \{1, 4, 2\}$.

Iteration 4: Let $i = 1$; the remaining location is $r = 3$. Thus $a(1) = 3$ and $F_2 = \emptyset$. The solution is $a = \{3, 2, 1, 4\}$. Therefore,

Machine A is assigned to location 3

Machine B is assigned to location 2

Machine C is assigned to location 1

Machine D is assigned to location 4

The total cost for this assignment is calculated as follows:

$$\begin{aligned} \text{TC}(a) &= \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n r_{ij} d(a(i), a(j)) \\ &= \frac{1}{2} [r_{11}d_{33} + r_{12}d_{32} + r_{13}d_{31} + r_{14}d_{34} + r_{11}d_{23} + r_{22}d_{22} + r_{23}d_{21} + r_{24}d_{24} \\ &\quad + r_{31}d_{13} + r_{32}d_{12} + r_{33}d_{11} + r_{34}d_{14} + r_{41}d_{43} + r_{42}d_{42} + r_{43}d_{41} + r_{44}d_{44}] \\ &= \frac{1}{2} [(0)(0) + (2)(4) + (8)(10) + (3)(9) + (2)(4) + (0)(0) + (4)(8) \\ &\quad + (9)(7) + (8)(10) + (4)(8) + (0)(0) + (5)(2) + (3)(9) + (9)(7) \\ &\quad + (5)(2) + (0)(0)] \\ &= 220 \end{aligned}$$

A lower bound on the value of the objective function of this problem can be computed as follows:

Ordering values of r_{ij} in descending order and d_{pq} in ascending order gives the vectors $\mathbf{r} = (9, 8, 5, 4, 3, 2)$ and $\mathbf{d} = (2, 4, 7, 8, 9, 10)$. The lower bound is $LB = \mathbf{r} \cdot \mathbf{d}' = (9)(2) + (8)(4) + (5)(7) + (4)(8) + (3)(9) + (2)(10) = 164$.

The cost obtained by applying the heuristic construction procedure is greater than the lower bound cost. Hence the solution obtained may be suboptimal. It is

Table 5.12 Differential total costs

(u, v)	$DTC_{uv}(\mathbf{a})$
(1,2)	-56
(1,3)	8
(1,4)	-53
(2,3)	-50
(2,4)	2
(3,4)	-55

Table 5.13 Differential total costs

(u, v)	$DTC_{uv}(\mathbf{a})$
(1,2)	-60
(1,3)	8
(1,4)	-61
(2,3)	-54
(2,4)	2
(3,4)	-55

recommended to run the procedure several times, choosing a different sequence of facilities for each run and then selecting the best solution (having minimum cost).

B. Applying the Heuristic Improvement Procedure

An initial solution $\mathbf{a}_0 = (2,4,3,1)$ will be considered. This means that facility 2 is assigned to location 1, facility 4 to location 2, and so on. The basic procedure is to explore all possible location interchanges associated with each pair of facilities i and j . After the corresponding DTC_{ij} values are calculated, the interchange to be implemented is that associated with a maximal value. The algorithm terminates when no further interchanges can be made.

First pass: Calculate the differential total costs for each combination of interchanges, as shown in Table 5.12. The largest differential total cost is 8 and corresponds to (1,3); therefore facilities 1 and 3 will be exchanged. Now, $\mathbf{a} = (3, 4, 2, 1)$.

Second pass: Calculate the differential total costs for each combination of interchanges, as shown in Table 5.13. According to these results, facilities 2 and 4 (maximum value is 2) should be exchanged. Now, $\mathbf{a} = (3, 1, 2, 4)$.

Third pass: Calculate the differential total costs for each combination of interchanges as shown in Table 5.14. Since all values of DTC are negative, the algorithm is terminated.

The final solution is as follows:

Machine A is assigned to location 3.
Machine B is assigned to location 1.
Machine C is assigned to location 2.
Machine D is assigned to location 4.

Table 5.14 Differential total costs

(u, v)	$DTC_{uv}(\mathbf{a})$
(1,2)	-58
(1,3)	-8
(1,4)	-65
(2,3)	-56
(2,4)	-2
(3,4)	-55

Table 5.15 Flow and distance matrices

Flow (trips)				Distance			
	A	B	C		1	2	3
A	0	2	8	1	0	8	10
B	2	0	4	2	8	0	4
C	8	4	0	3	10	4	0

The total cost for this assignment is calculated as follows, using $\mathbf{a} = (3, 1, 2, 4)$:

$$\begin{aligned}
 TC(\mathbf{a}) &= \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n r_{ij} d(a(i), a(j)) \\
 &= \frac{1}{2} [r_{11}d_{33} + r_{12}d_{31} + r_{13}d_{32} + r_{14}d_{34} + r_{21}d_{13} + r_{22}d_{11} + r_{23}d_{12} \\
 &\quad + r_{24}d_{14} + r_{31}d_{23} + r_{32}d_{21} + r_{33}d_{22} + r_{34}d_{24} + r_{41}d_{43} + r_{42}d_{41} \\
 &\quad + r_{43}d_{42} + r_{44}d_{44}] \\
 &= \frac{1}{2} [(0)(0) + (2)(10) + (8)(4) + (3)(9) + (2)(10) + (0)(0) \\
 &\quad + (4)(8) + (9)(2) + (8)(4) + (4)(8) + (0)(0) + (5)(7) \\
 &\quad + (3)(9) + (9)(2) + (5)(7) + (0)(0)] \\
 &= 164
 \end{aligned}$$

This cost is exactly equal to the lower bound value. Hence an optimal solution has been obtained.

Example 5.12

Table 5.15 shows flows (trips) between facilities A, B, C and distances between locations 1, 2, 3.

Use the steepest descent pair wise interchange heuristic (SDPI) and arrive at the final solution starting with $\mathbf{a}_0 = (1, 2, 3)$.

Table 5.16 Differential total costs

(u, v)	$DTC_{uv}(\mathbf{a})$
(1,2)	24
(1,3)	-8
(2,3)	12

Table 5.17 Differential total costs

(u, v)	$DTC_{uv}(\mathbf{a})$
(1,2)	-24
(1,3)	4
(2,3)	-24

Table 5.18 Differential total costs

(u, v)	$DTC_{uv}(\mathbf{a})$
(1,2)	-16
(1,3)	-4
(2,3)	-36

Solution

First pass: Calculate the differential total costs for each combination of interchanges. They are shown in Table 5.16. Facilities 1 and 2 are exchanged (maximum value of DTC is 24). Thus $\mathbf{a} = (2, 1, 3)$.

Second pass: The differential total costs for each combination of interchanges are shown in Table 5.17. Facilities 1 and 3 are exchanged (maximum DTC value is 4). Thus $\mathbf{a} = (3, 1, 2)$.

Third pass: Calculate the differential total costs for each combination of interchanges. They are shown in Table 5.18. As all values of DTC are negative, the algorithm is terminated.

Thus the final solution is as follows, for $\mathbf{a} = (3, 1, 2)$.

Facility A is assigned to location 3.

Facility B is assigned to location 1.

Facility C is assigned to location 2.

The total cost or the value of the objective function is

$$\begin{aligned}
 TC(\mathbf{a}) &= \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n r_{ij} d(a(i), a(j)) \\
 &= \frac{1}{2} [r_{11}d_{33} + r_{12}d_{31} + r_{13}d_{32} + r_{21}d_{13} + r_{22}d_{11} + r_{23}d_{12} + r_{31}d_{23} \\
 &\quad + r_{32}d_{21} + r_{33}d_{22}] \\
 &= \frac{1}{2} [r_{11}d_{33} + r_{12}d_{31} + r_{13}d_{32} + r_{21}d_{13} + r_{22}d_{11} + r_{23}d_{12} + r_{31}d_{23} \\
 &\quad + r_{32}d_{21} + r_{33}d_{22}] \\
 &= 84
 \end{aligned}$$

The lower bound of this problem can be computed as follows; ordering values of r_{ij} and d_{pq} gives the following vectors $\mathbf{r} = (8, 4, 2)$ and $\mathbf{d} = (4, 8, 10)$. The lower

bound $LB = rd' = (8)(4) + (4)(8) + (2)(10) = 84$. Thus the cost obtained using SDPI matches with the lower bound, and hence the solution is optimal.

5.7 Exercises

- 5.1 Without using formulations, briefly describe the purpose of the typical mathematical models used in facility planning.
- 5.2 Find the optimal solution for the minisum location model assuming squared Euclidean distances.
- 5.3 Four existing facilities are located at (4,2), (8,5), (11,8), and (13,2). The weights are equal to 1/6, 1/3, 1/3, and 1/6, respectively. (a) Draw the resultant weight diagram for x . (b) Draw the resultant weight diagram for y . (c) Determine the optimal solution from both diagrams. (d) Construct the grid for finding contours. (e) Draw the contour through the point (6,9) and the contour through the point (9,6).
- 5.4 Four machines are located in a plant at points (0,10), (20,0), (40,10), and (10,10). These machines require maintenance at expected frequencies of 10, 11, 12, and 5 times per month, respectively. Because of the nature of the maintenance, all machines must be maintained at the maintenance center. A machine can be serviced by exactly one maintenance center. Moreover, the cost of transporting the machines to and from the maintenance center is \$10 per unit of distance, including the cost of lost profits resulting from the machines being down. The monthly cost of owning and operating a maintenance center is \$6000. Rectilinear travel is assumed. (a) Calculate the number of possible allocations for two maintenance centers. (b) List all possible combinations indicating which machines are allocated to which maintenance center. (c) Find the total cost per month associated with the allocation of machine 1 to the first center, and machines 2, 3, and 4 to the second center.
- 5.5 Consider a single-facility rectilinear mini-max location problem with existing facilities located at (2,10), (7,9), (7,12), (3,15), and (1,14). (a) Find the optimal solution. (b) Find a contour line of value 8. Draw a graph showing the location of all facilities, the optimal solution, and the contour.
- 5.6 Consider a mini-max single-facility location problem with existing facilities at (1,1), (2,2), (3,3), and (4,4). Assuming rectilinear distances, find the optimal location of the new facility and the corresponding value of the objective function.
- 5.7 In Exercise 5.6 draw the contour corresponding to the value $z = 10$. Compute the coordinates of each corner point of the contour.
- 5.8 Consider the problem of designing a complex of six novelty and craft shops A, B, C, D, E, F in a resort area. The six shops are to be located in a rectangular building consisting of six locations arranged as two rows and three columns. The corresponding 6 cells or sites in a rectangular grid of the floor of the building are numbered from left to right and top to bottom as 1, 2,

3, for the first row; and 4, 5, 6 for the second row. Each of the six sites is a candidate for the location of each shop. The travel costs between locations, shown in the matrix on the left, are proportional to the rectilinear distances. Distances are measured in units of site widths, between the centers of sites. The matrix on the right shows the number of trips between facilities:

0	1	2	1	2	3
1	0	1	2	1	2
2	1	0	3	2	1
1	2	3	0	1	2
2	1	2	1	0	1
3	2	1	2	1	0

0	4	6	2	4	4
4	0	4	2	2	8
6	4	0	2	2	6
2	2	2	0	6	2
4	2	2	6	0	10
4	8	6	2	10	0

(a) What kind of model can be used for solving this problem? (b) Find a lower bound on the total cost. (c) If shops A, B, C, D, E and F are assigned to locations 2, 4, 5, 3, 1, and 6, respectively, find the total cost of this assignment. (d) How many terms does the objective function have? (e) Find the terms (coefficients and variables) associated with the assignments of facilities A and B.

- 5.9 There are three plants A, B, and C with potential sites 1, 2, and 3. The following costs per trip between locations (on the left) and number of trips between plants (on the right) are given:

-	3	2
3	-	6
2	6	-

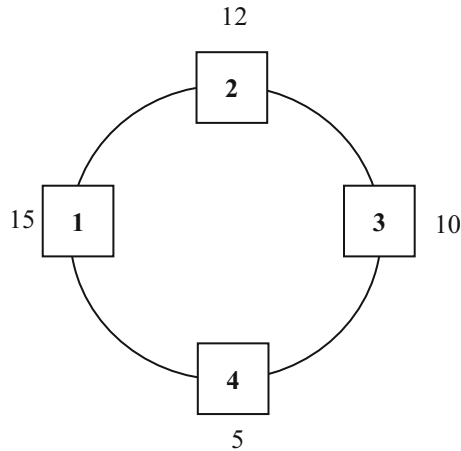
-	8	5
8	-	4
5	4	-

Write the mathematical formulation of the model, including the numerical value of each coefficient in both the objective function and each constraint. Find the optimal solution.

- 5.10 Machines 1, 2, 3, 4, and 5 are located at the points $(-1,0)$, $(4,1)$, $(-7,2)$, $(-2,3)$, $(5,4)$, respectively. There are 6, 9, 4, 1, and 2 trips per week, respectively, between the machines and a new facility. (a) Use the resulting force diagram to calculate the x -coordinate of the optimal location for a minisum model considering rectangular distances. (b) Find the optimal location using a minimax model.
- 5.11 We are interested in determining the location (x, y) of an ambulance. There are four points of emergency located at $(4,2)$, $(8,5)$, $(11,8)$, and $(13,2)$. The distance from these points to the nearest hospital are 1, 2, 3, and 4, respectively. Find the location of the ambulance using the minimax criterion. (a) Find the optimal location. (b) Draw the contour through the point $(9,6)$ and indicate the value of the objective function.
- 5.12 Four facilities A, B, C, and D are located at the corners of a square layout starting at the bottom left corner and proceeding clockwise. It is desired to

find the location of a repair center that will serve these facilities. The expected number of trips from A, B, C, and D to the repair center are 10, 15, 35, and 5, respectively. Assume rectilinear distances.

- 5.13 Machines 1, 2, 3, and 4 are evenly spaced along a circumference having a known radius. The number of trips to a new facility is shown in the diagram given below for each machine. Using rectangular distances and the minisum model, find the location of the new facility. Show all your results.



- 5.14 In a company, departments send jobs to be processed to locations each having a microcomputer available. Let t_{ij} be the time needed to take one job from Department i to Location j . Assume that $i = 1, 2, \dots, n$; $j = 1, 2, \dots, m$. Moreover, let d_i be the demand (number of jobs) from Department i . Let K be the number of microcomputers available for processing the jobs sent by the departments. Formulate a mathematical model to determine the location of each microcomputer (at most one microcomputer per location) in order to minimize the total time. Assume that all jobs from each department must be assigned to exactly one location.
- 5.15 Given the assignment (1, 3, 4, 2) and the matrices

$$D = \begin{pmatrix} 0 & 7 & 10 & 5 \\ 7 & 0 & 4 & 8 \\ 10 & 4 & 0 & 9 \\ 5 & 8 & 9 & 0 \end{pmatrix} \quad W = \begin{pmatrix} 0 & 3 & 8 & 2 \\ 3 & 0 & 4 & 9 \\ 8 & 4 & 0 & 4 \\ 2 & 9 & 4 & 0 \end{pmatrix}$$

- Apply the SDPI improvement heuristic procedure.
- Solve using the construction heuristic procedure.
- Calculate the lower bound on the total cost.

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Chapter 6

Computerized Layout Procedures



6.1 Introduction

The cycle of facilities design and management can be best described as follows. When a new plant is to be built, a site-selection analysis must be conducted to determine where to build it. Once a site is selected (Chap. 10), the preparation of data for the layout planning process is initiated, and this will eventually produce an overall layout. From this initial step, one can begin to proceed into developing detailed facility layout schematic alternatives. Figure 6.1 represents the evolution of the layout and network design process.

Working with the overall plan and the schematic layout alternatives, one can develop an evaluation process to compare and choose the best alternative. After performing this evaluation, one can use computer software for generating detailed layouts of the plant and operations. Finally, given this detailed layout plan development, one continues with the implementation of the best alternative, such as the one depicted in Fig. 6.2. One can observe in this layout solution for a supply-chain network (Chap. 1) that the raw materials and finished good warehouses are collocated with the manufacturing facility.

Once the installation is in place, the facilities management information system is initiated in order to provide timely information the next time design change(s) are to be made. Thus, through this iterative feedback loop process, an information-based manufacturing system is developed.

The first area in which the computer became a truly powerful tool was that of computerized layout development. In the early 1960s algorithms and heuristic procedures were developed to design block-plan layouts. Today one can find a great many (possibly 100 or more) computer programs developed as theses or dissertations. Also, an increasing number of commercial programs are available. All these computerized procedures require a substantial amount of programming, but the field continues to generate more and more powerful and effective procedures as a result of

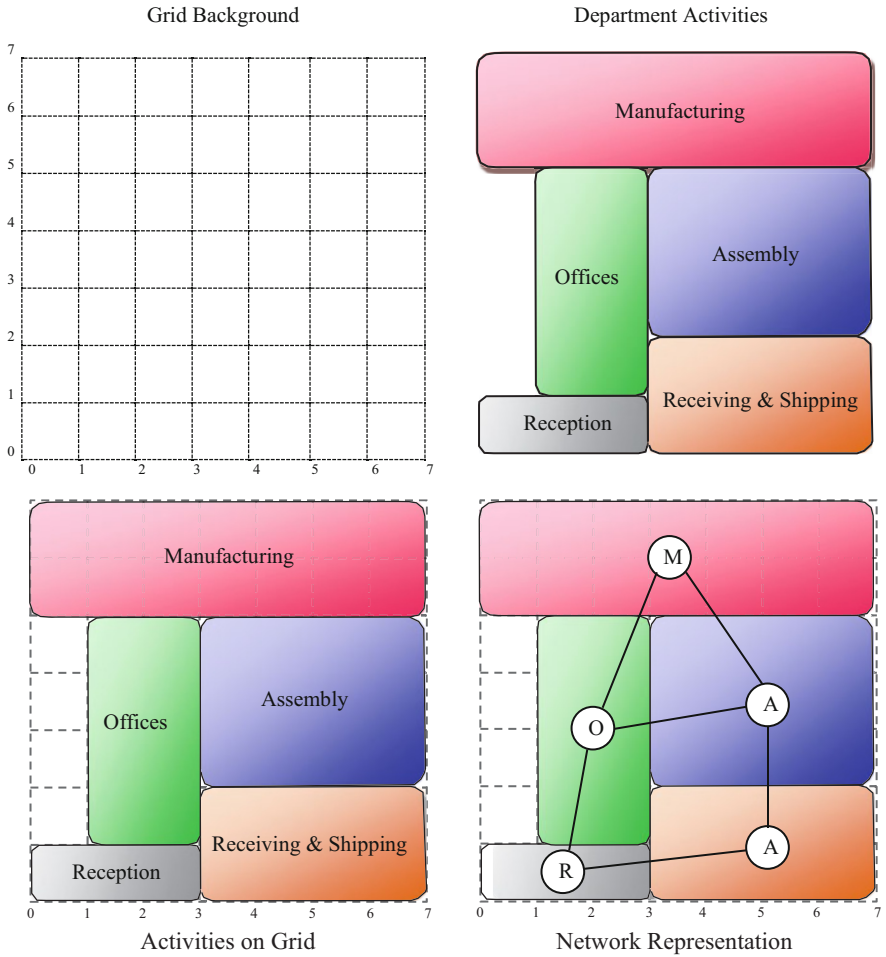


Fig. 6.1 Evaluation of floor plan and network $G(V, A)$

the extraordinary growth experienced by computer science, engineering, and technology.

For an extended literature review of layout planning methodologies, the reader is referred to the work by Pérez-Gosende, Mula, and Díaz-Madroñero [33].

This chapter presents an overview of basic planning issues, principles involved in computerized facility layout, and selected computerized layout design programs. In addition to this introductory section, Sect. 6.2 focuses on the scope of the chapter and provides basic definitions. Section 6.3 addresses some computerized software issues. Exact optimization procedures are presented in Sect. 6.4 and some well-known traditional heuristic procedures are described in Sect. 6.5. Section 6.6 illustrates how software can be integrated in layout generation based on FLAP, GMAFLAD,

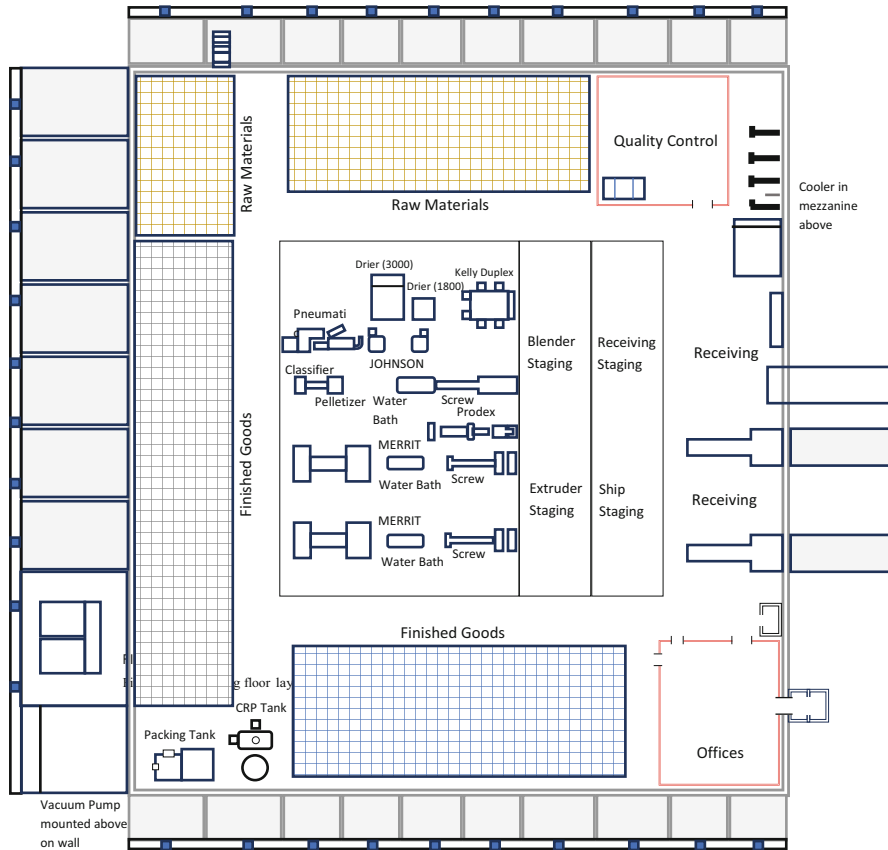


Fig. 6.2 Manufacturing floor layout

and CRAT programs. A procedure known as STEP is discussed in Sect. 6.7 and the chapter closes with a summary in Sect. 6.8.

6.2 Scope and Definitions

A facility design project may be viewed as a task in network design comprised of two fundamental problems: (1) the generation or selection of the topological configuration of the finite set of nodes (V) and finite set of arcs (A) which define the planar graph $G(V, A)$ (Chap. 1); (2) the optimal assignment of the activities to the nodes of $G(V, A)$ (Chap. 5), as shown in in Fig. 6.1.

The first problem often assumes an underlying topology upon which the facility design is based: a linear, star, rectangular grid, hexagonal grid, or ring configuration.

The second problem assumes the topology and seeks an optimal assignment of activities or other objects to the nodes of $G(V, A)$. While the general network design problem is extremely complex, its decomposition into these two subproblems is reasonable and worth examination.

This section examines the second problem and explores the impact of fundamental network design topologies on the optimal assignment of activities, where deterministic and random traffic flows between the nodes occur in $G(V, A)$.

Facility layout problems can be generally formulated as quadratic assignment problems (QAPs) (see Chap. 5), which consider the assignment of activities to locations in order to minimize the sum of fixed location costs and traffic flow costs, where traffic flows are deterministic [20, 38, 9].

In practice, however, traffic flows are fundamentally stochastic and dynamic. Consider a pedestrian circulation system or material handling system which interconnects all rooms in a building or workstations in a factory, where random arrivals and congestion could occur within this traffic system [4, 22]. The circulation system includes the hallways, corridors, conveyors, elevators, stairwells, landings, and other physical transport elements. Therefore, avoiding congestion in a circulation system becomes an important issue for facility layout and planning. In Sect. 6.7 concerning the program STEP, our objective is to assign activities to locations in order to minimize the congestion within a circulation system [40].

General planar configurations are often comprised of grid, ring, and star topologies and their combinations. In fact, urban areas [35] and architectural floor plans normally have grid configurations with occasional star and ring segments; most airports are constructed in rings; and most telecommunication nets are connected with ring and star topologies.

Different topologies yield different performance measures. As the network configuration plays an important role in facility layout, it is necessary to evaluate the different topologies and select an appropriate configuration. Figure 6.2 illustrates a floor plan of a manufacturing facility and its circulation system, which actually is a grid topology. Figure 6.2 also illustrates the detail that is necessary in a final facility layout, with all equipment specified and detailed dimensions included. While this does not represent a construction working drawing, it is the basis for such documents.

6.3 Facility Layout Software Issues

As a way of providing an overview of this chapter, the fundamental planning issues underlying the design of facility layout software will be presented. These issues act as guidelines for the design and use of the software in facilities planning. One important point to be made at the outset is that the layout planning problem is essentially a multi-objective planning problem, so that, even with exact optimization solutions (e.g., minimizing material flow), the layout must be tempered, massaged, and modified to include unforgotten variables and constraints and often qualitative

aspects not included with the optimal layout solution. For example, structural columns and existing heating, ventilating, and air-conditioning (HVAC) duct works are notorious layout obstacles and should be addressed.

Essentially nine basic issues underlie layout software development:

1. *Optimal vs. Suboptimal Solutions.* Because of the inherent computational complexity of facility planning, one must carefully determine whether or not optimal solutions are desired. One of the most difficult combinatorial optimization problems concerns the design of an optimal configuration of large-scale manufacturing and service facilities. The NP-completeness of the quadratic assignment problem (QAP) and its associated problem formulations are well known [13, 34]. This facet of the problem bodes well for the creation of heuristics for the QAP or the development of algorithms for special cases, which may lead to the optimal solution for larger problems. Even with parallel machine computations, optimal solutions for quadratic assignment problems (Chap. 5) where $N \geq 30$ can take up to one year of computing time. However, if one knows the optimal solution to a problem, one rests assured that there is nothing better.
2. *Equal vs. Unequal Areas.* QAPs are equal-area problems. If unequal-area problems are required, the complexity of achieving optimal solutions skyrockets. One then must either reformulate the QAP or else rely on some heuristics for the solution. One reformulation of the QAP which achieves optimal solutions, namely MAFLAD, was presented in Chap. 4.
3. *Existing vs. New Facilities.* Existing facilities often have fixed locations of activities, immovable walls and columns, and fixed-position equipment (heating, ventilating, and air-conditioning systems), which makes the activity layout much more difficult. Software can account for such conditions, but must be especially tailored for these constraints. Office activities and warehouse facilities need to be located on the perimeter of a building, and unless this is controlled, infeasible solutions will often result.
4. *Deterministic vs. Stochastic Flows.* Normally, the from-to chart and material handling flows are deterministic. When they are stochastic, different model assumptions must be accounted for. Section 6.7 presents the STEP program, which accounts for stochastic congestion in the layout.
5. *Quantitative Flow Data vs. Qualitative REL-Data.* One major decision to be made is whether quantitative ratio scale flow data, as embodied in QAP-type approaches, is available or whether ordinal scale REL qualitative data, as embodied in graph-theoretic models, will be followed. The solution techniques are different, as are the solutions generated. While some type of hybrid approach may be possible (such as with BLOCPLAN), many software approaches treat the two separately.
6. *Grid Decomposition vs. Continuous Space Decomposition.* Given the shape requirements of activities and the natural complexity of the layout problem, many programs assume a grid decomposition of the layout in order to place the activities within the perimeter of the building. This is sensible, but another approach is to assume that the activities can be in any location within the

perimeter of the building. This decision to allow for continuous space decomposition affects the required solution methodology. Continuous space decomposition will require nonlinear programming approaches rather than combinatorial optimization approaches.

7. *Explicit Shape vs. Rectangular Activity Shape.* Many layout programs either control the shape of an activity (i.e., must be rectangular) or else let it be arbitrary. If one is precise about the elemental units within a factory, then often the shape of the activities will not be rectangular, since the machines in the layout are often L-shaped, U-shaped, Z-shaped, or some other configuration. Even the way one works at an office desk often has L-shaped or U-shaped work flows and is not merely rectangular. Software that controls the shape of activities is markedly different than that which does not. Controlling the shape of an activity in the layout normally requires a discrete or combinatorial optimization approach.
8. *Layout and Material Handling Integration.* Combining the material handling system or circulation system in the layout is a very desirable feature in layout planning, but makes the problem even more difficult. Certain software tools have been designed to carry out this integration, but the difficulty remains. In one sense, it is easier to treat each problem separately—(1) the layout, (2) the material handling system, not necessarily in that order—since both are NP-Hard optimization problems. This will be discussed further in Chap. 8.
9. *Multistory Layouts.* Finally, one must decide whether or not a multistory facility is appropriate. For the factory project within the course, only single-story facilities need be considered. Of course, there are always exceptions to the rule, and an existing facility may be multistory, yet for the most part single-story solutions are the norm. While this topic is in general beyond the scope of this book, one can consider generalized quadratic assignment (GQAP) type problems, which address it. We shall not consider GQAP problems in any detail.

Figure 6.3 illustrates the range of computerized traditional approaches available for the facility layout problem. While CORELAP and ALDEP are often classified merely as “construction” procedures, their fundamental graph-theoretic nature is also worth pointing out.

We will discuss many of these QAP approaches, starting with exact approaches, and contrast these with the exact GTLN approaches and then with the various heuristic approaches in each category. There are many other software approaches that we will not cover, and some textbooks discuss them [18, 39]. We have addressed those that form a representative sample of the major software types.

6.4 Exact QAP and GTLN Optimization Procedures

Facility layout and location [8, 22], very large-scale integration (VLSI) design and communication network problems [26, 27], regional and land use planning [35], and other cellular layout and location design problems [3] that concern the optimal

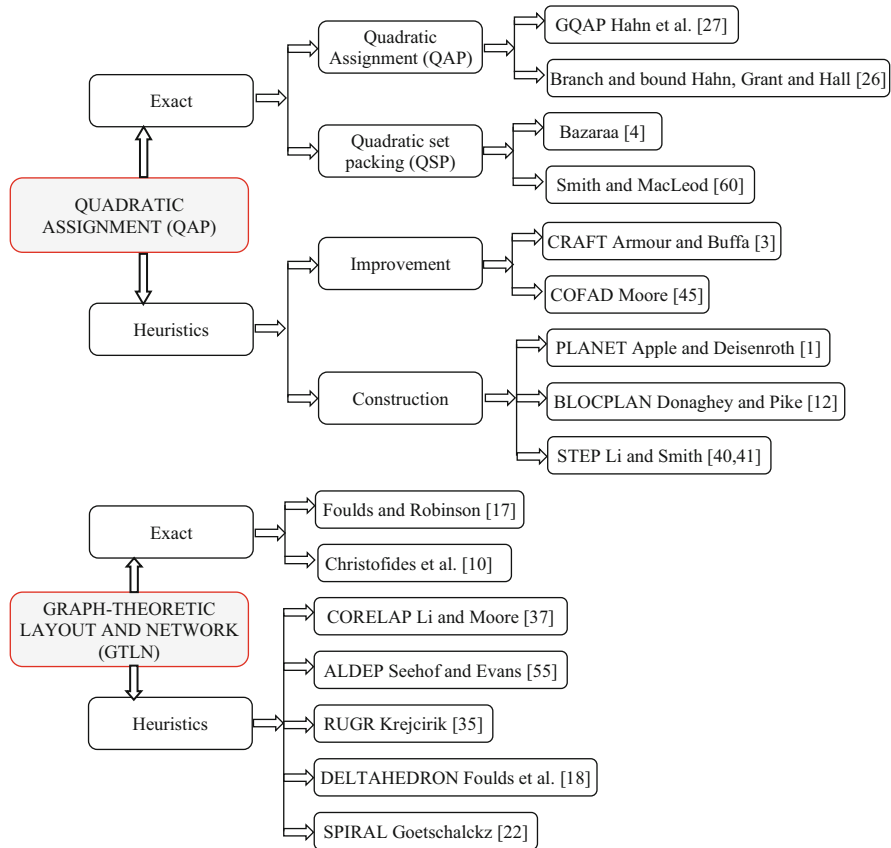


Fig. 6.3 Classification (morphologies) of layout programs

assignment of activities to locations are complex combinatorial optimization problems. The problem can be represented as a quadratic assignment problem (QAP) [20]; see also Chap. 5.

The general form of the QAP model given below differs from the formulation in Chap. 5. There are two terms in the objective function: (1) a linear placement cost term and (2) a flow placement term. The linear placement cost term is sometimes ignored in QAP programs, but it can be an important concept, especially when fixed activities occur in the layout.

$$\text{Minimize } \sum_{i=1}^n \sum_{k=1}^n c_{ik} x_{ik} + \sum_{i=1}^n \sum_{j=1}^n \sum_{k=1}^n \sum_{h=1}^n f_{ij} d_{kh} x_{ik} x_{jh} \quad (6.1)$$

subject to

$$\sum_{i=1}^n x_{ik} = 1 \quad k = 1, \dots, n \quad (6.2)$$

$$\sum_{k=1}^n x_{ik} = 1 \quad k = 1, \dots, n \quad (6.3)$$

$$x_{ik} = 0, 1 \quad i, k = 1, \dots, n \quad (6.4)$$

where

c_{ik} = linear placement cost term for locating activity i in location k

f_{ij} = the flow of material between activity i and activity j

d_{kh} = the distance between location k and location h

x_{ik} = 1 if activity i is assigned to location k and equal to 0 otherwise

The first set of constraints ensures that exactly one activity is assigned to each location; the second set results in each activity being assigned to exactly one location. The reader is also referred back to Chap. 5 for further details about QAP exact and heuristic approaches.

6.4.1 Exact Graph-Theoretic Procedures

Graph-theoretic layout and network-based procedures (GTLN) are a natural methodology for developing facility layout plans. We introduced graph-theoretic ideas in Chap. 1, where we discussed planar graphs. The mathematical model which follows is based on [12, 29].

We are given ordinal scale data such as a relationship (REL) matrix as described in Chap. 4:

w_{ij} = the closeness rating for siting activity i adjacent to activity j , $w_{ij} \geq 0$

n = the number of activities

V = the set of activities

E' = the set of all possible edge pairs available in the REL matrix

We wish to

$$\text{Maximize } \sum_{(i,j) \in E'} w_{ij} x_{ij} \quad (6.5)$$

subject to

$$G(V, E) = \text{a planar subgraph of } G' = (V, E') \quad (6.6)$$

$$E = \{(i, j) \in E' | x_{ij} = 1\} \quad (6.7)$$

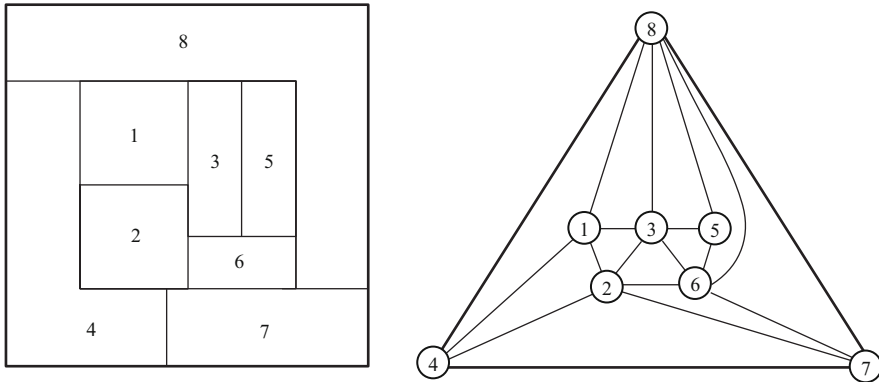


Fig. 6.4 Graph-theoretic layout model solution

This problem is well known to be NP-Complete, so, as in the QAP, exact solutions are difficult to generate.

Some key differences between the QAP and the graph-theoretic (GTLN) models are [12]:

- The GTLN model is more suitable for new than for existing layouts, whereas the QAP approaches can account for fixed area and the shape of activities and predetermined locations.
- The GTLN model ignores the linear placement term in the QAP model, so it is somewhat less general than QAP models.
- GTLN approaches include only directly adjacent activities in the objective function, whereas QAP approaches include nonadjacent pairs.

Figure 6.4 illustrates the planar graph solution below and the block plan layout derived from it above. As we shall show, both the QAP and GTLN models closely overlap, since the layout problem is essentially a network design problem, as argued earlier in the chapter.

6.5 Heuristic Procedures

We now consider heuristic procedures for solving the facility layout problem. The input information required by most heuristic computerized procedures generally consists of (a) from-to chart, flow matrices, relationship charts; (b) area requirements for departments; (c) in some cases, cost information on material handling. As already explained, the relationship chart indicates closeness codes between departments (A = absolutely important, E = especially important, I = important, O = ordinary closeness, U = unimportant, X = not desirable to be close).

These computer heuristic procedures can be grouped into three categories, depending on the logic used to develop the block plan: (1) improvement heuristics; (2) construction heuristics; and (3) graph-theoretic and network-based procedures.

We provide a select sampling of available procedures, as indicated by the tree diagram.

6.5.1 *Improvement Procedures*

These procedures require a feasible layout as input and continue to modify the layout by swapping areas and scoring the revised layouts until no further improvement can be found. The scores are based upon a from-to chart, which is part of the input. Two well-known improvement-type procedures are:

CRAFT Computerized Relative Allocation of Facilities Technique

COFAD Computerized Facilities Design

1. *Computerized Relative Allocation of Facilities Technique (CRAFT)*

This program, originally developed by Armour and Buffa [2], uses a path-oriented improvement routine based on pairwise and three-wise exchanges of departments to reduce the total distance or transportation cost associated with a given from-to chart. The final layout is dependent on the initial layout, so it is suggested to try different initial layouts.

The transportation cost for a particular move between two departments is defined as the product of the number of trips by the corresponding distance and then by a specified cost per unit distance. As a result, transportation costs are not directly associated with the material handling equipment used.

The CRAFT procedure assumes that the facility (1) has a rectangular or squared shape and (2) has no interior void spaces. These assumptions can actually be satisfied in most cases by creating dummy departments in the desired layout. A detailed description with computer run illustrations was given in Sect. 4.11.

Input

1. Number of departments (up to 40)
2. Plant area, length, and width
3. Number of bays
4. Department areas
5. Number of trips and cost per unit distance between departments
6. Initial layout as a sequence of departments (some can be fixed in the sequence)
7. Selection of rectilinear or Euclidean distances to compute the cost

Output

1. Graphical display of the arrangement.
2. Total cost.

Outline of Procedure

1. Compute centroids for departments in the initial layout.
2. Create a distance matrix between centroids.
3. Compute transportation costs of initial layout.
4. Consider interchanges of department with equal area or with common borders.
5. Select the interchange with the greatest cost reduction.
6. Compute cost and repeat the procedure until no further reductions in cost are obtained.

Pros

1. Widely used in practice, even though somewhat dated, and forms the basis of many other layout approaches.
2. Can deal with fixed activity locations and thus incorporate considerations of obstacles and impediments in the layout.
3. Flexible with different activity shapes and also can accommodate a variety of plant shapes [19].
4. Utilizes dummy activities to deal with unrealistic activity alignments [17].

Cons

1. Final solution is very dependent on the initial starting solution, so multiple starting solutions are recommended.
2. Results are not as effective when activities have different sizes, and, furthermore, activities can be split into nonadjacent cells [19].
3. Considers exchanging only those activities that are either adjacent (share a boundary wall) or equal in area [39].
4. A “steepest-descent” heuristic and thus can overlook optimal exchanges [39].

II. COFAD Computerized Facilities Design

This program, originally developed by Moore in 1974 [30], is basically a modification of CRAFT to incorporate material handling alternatives. Its goal is to jointly select a layout and a material handling system that will result in a minimal or significantly reduced transportation cost. The cost associated with a move between two departments is defined as follows, depending on the type of equipment used:

(a) For fixed-path equipment

$$\text{cost} = \text{variable cost} \times \text{length of move} + \text{nonvariable cost}$$

(b) For mobile equipment:

$$\text{cost} = \text{variable cost} \times \text{time of move} + \text{nonvariable cost} \times \text{equipment utilization}$$

Input

The input data for running the program are in essence the same data required for running CRAFT. Material handling equipment information also is required.

Output

The output of the program consists of a factory layout and the recommended material handling system for each move between departments.

Outline of Procedure

Again, the procedure of the COFAD program follows the same general guidelines as the CRAFT procedure. COFAD can be viewed as having two phases:

1. Alternate between improving a layout and improving its material handling system.
2. Stop when fluctuations in flow volumes do not result in reduced total costs.

Pros

1. Similar to CRAFT in its positive aspects.

Cons

1. Distance measurements are centroid-to-centroid, not along the aisles, which is not reflective of actual distance movements in the material handling system.

6.5.2 Construction Procedures

These procedures start with an open floor space and construct a single-floor layout logically, based upon input data, a relationship chart, and space allocations. A partial list of construction procedures includes:

PLANET	Plant layout analysis and evaluation technique
CORELAP	Computerized relationship layout planning
ALDEP	Automated layout design program
BLOCPLAN	Block plan

The general steps of construction procedures are:

1. **Transplantation:** input from problem is represented as input for program.
2. **Selection:** departments are selected according to their relationships and a closeness rank.
3. **Placement:** using the selection order and a logical procedure, the layout is generated.
4. **Evaluation:** the layout is given a score that indicates its overall value.

III. *Plant Layout Analysis and Evaluation Technique (PLANET)*

This program, developed by Apple and Deisenroth in 1972 [1], is used to generate and evaluate plant layouts. It does not restrict the final layout to a uniform shape, nor does it allow fixing departments to certain locations, resulting in unrealistic layouts. Its best use is for generating an initial layout, which can be used as input to an improvement procedure. The measure of effectiveness is defined as total handling costs. The program assumes that the flow between departments is the same in both directions.

Input

The input data again are similar to those required by CRAFT. However, PLANET allows three different ways of describing the material flow: (1) by means of a production sequence of all parts to be moved within the facility, plus the cost per move; (2) by means of a from-to chart; (3) by a penalty matrix or relationship chart.

Output

The output consists of the plant layout along with its evaluation.

Outline of Procedure

PLANET uses three different methods for selecting departments:

1. Start with the two departments with highest priority and highest flow-between cost. Keep on adding departments according to the highest priority and highest flow-between cost to any department in the group already selected.
2. Start with the two departments with highest priority and highest flow-between cost. Keep on adding departments according to the highest priority and highest sum of flow-between costs to all the departments already selected.
3. Start with the department of highest priority and highest sum of flow-between costs to all other departments. Keep on adding departments in the same manner. The first two selected departments are placed side by side, and the next selected department is located around the existing departments to minimize the increase in handling cost.

Pros

1. Three methods of selecting activities to be placed in the layout give some flexibility to the floor-plan scheme that evolves.

2. Allows the user to vary placement values and carry out several runs to generate difference solutions [17].
3. Transforms ordinal scale data into ratio scale data [17].

Cons

1. Locates the first activity in the center of the layout and then clusters the remaining activities around the perimeter of the evolving solution, which may not be the most optimal approach.
2. Is only a construction procedure.
3. Cannot handle unrealistic plant shapes [17] or unrealistic activity alignments.

IV. *Computerized Relationship Layout Planning (CORELAP)*

This program, developed in 1967 by Lee and Moore [23], is a layout construction program. It uses the total closeness rating (TCR), which is the sum of all numerical values assigned to the closeness relationships in a relationship chart ($A = 6, E = 5, I = 4, O = 3, U = 2, X = 1$) between a department and all other departments. Its goal is to generate a layout using as measure of effectiveness a layout score that depends on the TCR.

Input

The input data required for running the program consist of activity information and ordinal scale flow data such as an REL chart.

Output

The output from the program is a plant layout along with the score.

Outline of Procedure

1. The first step is to select the department with highest TCR and place it in the center of the layout. Whenever there is a tie, the department with the largest area is selected, or, in case of equal areas, the department having the lowest department number. The second department selected is one with an A relationship with the first one; if none exists, then an E relationship; if none exists, then an I relationship, and so on. In case of ties use the department with highest TCR, or the one with largest area, or the one with smallest department number, as before. The third department added is one with an A relationship with the first department or the second department. If none is found, try a next-best relationship code until a department is selected. In case of ties use the tie-breaking rules explained earlier. This procedure is repeated until the departments are assigned.
2. Once a department is selected, it is located in such a way as to minimize the sum of the numerical values assigned to the closeness relationships with all the neighboring departments.
3. A layout score is then computed for the final layout as the sum for all departments of the products of numerical closeness ratings and lengths of shortest paths.

Pros

1. Fairly simple in concept and can be carried out by hand as well. Much like Prim's algorithm for creating minimum spanning trees.
2. Because traffic flow data may be limited, use of the REL chart in CORELAP may be quite acceptable.
3. Can fix certain activities to outside walls and corners of the facility [18] but not in the interior of the layout.

Cons

1. Uses the qualitative REL chart as opposed to quantitative traffic flow data.
2. Final solution is very much dependent on the set of sorted scores from the REL chart.
3. Places the first selected activity in the middle of the plant, which can be misleading, and those subsequent are placed with the strongest value to those already placed.
4. No improvement process is allowed, only construction.
5. Each activity is restricted to be a unit square shape.

V. *Automated Layout Design Program (ALDEP)*

Originally developed by Seehof and Evans in 1967 [35]. This program has the same basic requirements and achieves the same objectives as CORELAP. It differs in the way the first department is selected and how ties are broken, which is at random. Another difference is that CORELAP tries to generate a good layout, while ALDEP generates up to 20 different layouts, rates them, and lets the user make the selection.

Input

1. Department information
2. Relationship (REL) chart
3. Sweep width
4. Minimal closeness rating
5. Minimal layout score

Output

The output from the program consists of up to twenty layouts with their associated ratings.

Outline of Procedure

1. The program starts by selecting a department randomly and adding departments in a manner similar to that followed by CORELAP. Ties are broken randomly. In addition, any selected department must comply with a minimum closeness rating (user specified); if no department satisfies this requirement, the program will select one at random.

2. The placement of departments is done by locating the first one on the upper-left corner of the floor space, and proceeding downward with the remaining departments. The user specifies the width of the downward extension (referred to as the sweep width). When the bottom of the layout is reached, placement continues by sweeping departments upward and downward until all departments are located.
3. Once the layout is completed, it is rated by assigning values to the closeness relationships between adjacent departments. The score for the layout increases by 64 if two adjacent departments have an A relationship, 16 for an E, 4 for an I, 1 for an O, and nothing for a U; the score is decreased by 1024 for an X.

Pros

1. Randomly picks a starting activity solution, as opposed to CORELAP's choice.
2. Can handle multistory layouts 1 . . . 32.
3. Can incorporate fixed activity locations.
4. Computationally efficient—achieves alternative layouts quickly.

Cons

1. May not result in any solution at all.
2. Uses ordinal scale data as opposed to ratio scale data.
3. Scoring is based on adjacency rather than material flow relationships.

VI. **Block Plan (BLOCPLAN)**

Developed by Donaghey and Pike in 1991 [6], this program generates and evaluates block type layouts. It features different layout generation methods and multistory layouts. It does both generation and improvement of layouts. The generation is done either by randomly locating the departments or by considering the relationships between departments. The improvement is accomplished by pairwise exchange of departments.

Input

1. Number of departments (up to 18)
2. Department names and areas
3. Relationship chart or from-to chart
4. Length/width ratio of the plant
5. Product information: number of products, unit loads, department sequence
6. Information of any department with fixed location

Output

The output consists of a graphical display of the plant layout along with the corresponding score. It is a very effective layout program.

Pros

1. May be used as a construction and improvement algorithm [39], since it uses an REL chart and a from-to chart as input data, which provides a great deal of flexibility to the user.
2. Can do single and multistory layouts.

Cons

1. Handles only up to 18 total activities [18].

6.5.3 *Graph-Theoretic Heuristics*

Levin in 1964 [24] first proposed using graph theory to model facility layout development with planar and dual graphs. Krejcirik in 1969 [21] developed one of the first computerized procedures of this kind, called RUGR. It required a relationship diagram as input. Since then, many other authors have developed procedures; see Foulds for a good discussion of alternative graph-theoretic approaches [12]. Another important survey paper of computerized heuristics is by Liggett [28]. The Deltahedron heuristic was developed by Foulds and Robinson in 1978 [11] and has had many subsequent variations. It begins with four vertices connected to form a complete graph, then adds additional vertices, one at a time, within the graph into triangular faces to maximize the sum of the edge lengths. Leung in 1992 [29] further developed a variation of the Deltahedron heuristic. Goetschalckx in 1992 [14] developed an interactive program called SPIRAL that creates regularly shaped layouts based upon a hexagonal grid structure. The SPIRAL GTLN heuristic is among the best known. We describe it in some detail.

VII. *Spiral*

SPIRAL builds a planar graph solution on a hexagonal topology grid. The following information about the program was derived from the SPIRAL user's manual [15].

Input

1. Input a flow matrix and convert it from an asymmetric to a symmetric matrix, if necessary. Find the sum of all flow relationships, which is used to evaluate the efficiency of layout alternatives.
2. Sort the pairwise relationships by nonincreasing values.
3. Place the first two activities with the highest flows into the layout on the hexagonal grid.
4. Place the remaining activities on the hexagonal grid according to the sorted list of activities.
5. Once the list of activities is exhausted, sum the flow relationships of the generated layout and compare its efficiency to the total relationship value at the first step. The breaking of ties in the layout generation process can be used to generate alternative layouts.

Output

The generated layout is converted into a block plan using a sweep pattern similar to ALDEP.

Pros

1. Fast and simple to use.

Cons

1. Based upon activity adjacencies and not total flows in the layout.
2. Similar disadvantages voiced for GTLN layout approaches as opposed to QAP- based layout approaches.

6.6 Software Integration

We consider a bicycle factory project to illustrate the integration of computer programs to successfully complete the design of the layout for the factory. There are two major steps in this process: (1) Generating an initial layout alternative, (2) Optimizing this layout alternative. We shall employ FLAP and GMAFLAD to generate layout alternatives in Step 1, and CRAFT to optimize one of these alternatives in Step 2. Many of the other software tools could be utilized in this two-step process. For example, one could employ SPIRAL to generate an alternative, then COFAD to optimize the layout.

6.6.1 Departmental Area Requirements

Table 6.1 shows the width, length, and area of each of the 20 planning departments to be placed in the factory layout.

6.6.2 From–To Chart

Based on the operational sequences shown in Fig. 6.5, the corresponding From–To chart is depicted in Fig. 6.6. This chart is integrated with GMAFLAD to place departments on the available area in such a way that the distance moved by the parts is minimized.

Table 6.1 Departmental area requirements

Department	Width	Length	Area
1 Receiving and storage	33.33	33.33	1111.11
2 Injection molding	54.78	31.35	1717.20
3 3D printing	45.33	37.84	1715.21
4 Extruding (aluminum)	40.81	34.97	1426.93
5 Sawing	20.00	10.67	213.33
6 Anodizing	22.00	24.00	528.00
7 Laser cutting	28.00	12.00	336.00
8 Compression molding (carbon fiber)	66.65	45.53	3034.24
9 Hardening	62.25	32.93	2050.10
10 Drilling	25.00	20.00	500.00
11 Polishing	28.00	24.00	672.00
12 Painting	36.35	31.75	1154.11
13 Sand casting	41.38	38.77	1604.29
14 Compression molding (rubber)	25.08	27.81	697.29
15 Bending	14.89	15.50	230.82
16 Welding	34.00	31.50	1071.00
17 Chain producing	12.59	10.63	133.79
18 Drawing	57.17	12.07	689.81
19 Extruding (rubber)	19.19	10.68	204.87
20 Assembly, inspection, packaging and shipping	41.67	41.67	1736.87

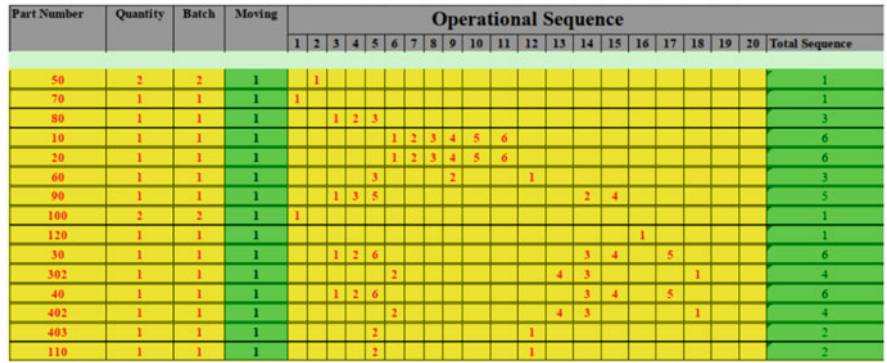


Fig. 6.5 Operational sequences

6.6.3 Initial Solutions

Based on the flows shown in Fig. 6.6, the from-to chart can be converted into the relationship chart given in Fig. 6.7. This chart in turn can be used as input to FLAP (construction procedure) to obtain the two solutions shown in Fig. 6.8. Two more initial solutions, depicted in Fig. 6.9, are obtained by GMAFLAD (improvement

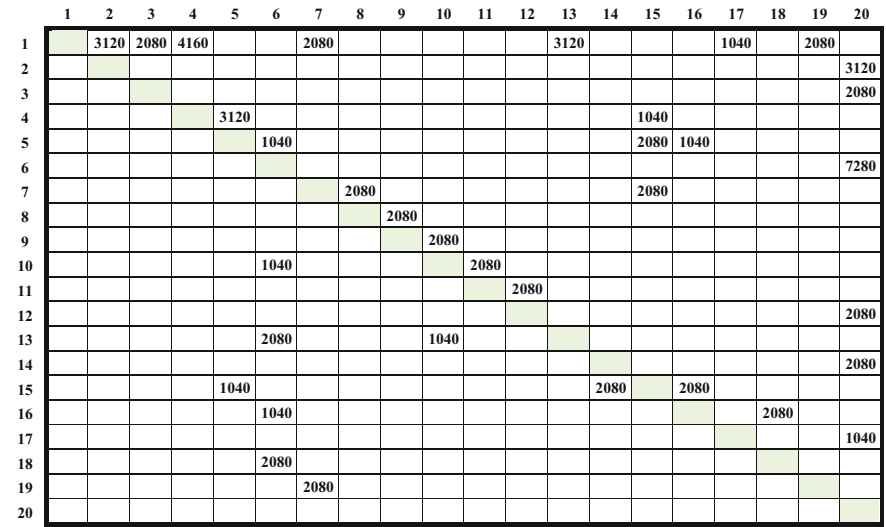


Fig. 6.6 From-to chart

procedure). After examining the four available initial solution, the second GMAFLAD alternative is chosen to be further improved by CRAFT.

CRAFT is now used to develop an improved solution based upon the second alternative generated by GMAFLAD. Table 6.2 shows CRAFT generated data. Finally, based on this, Fig. 6.10 shows the CRAFT final solution.

6.6.4 CRAFT Final Layout

6.7 STEP Algorithm

This section describes the *Sample Test Pairwise Exchange Procedure (STEP)* developed by Li and Smith [26, 27], which is a hybrid of a graph theoretic and improvement approach using an underlying Steiner circulation flow graph to estimate the congestion in the layout, and a sampling design scheme to perturb the arrangement of the activities.

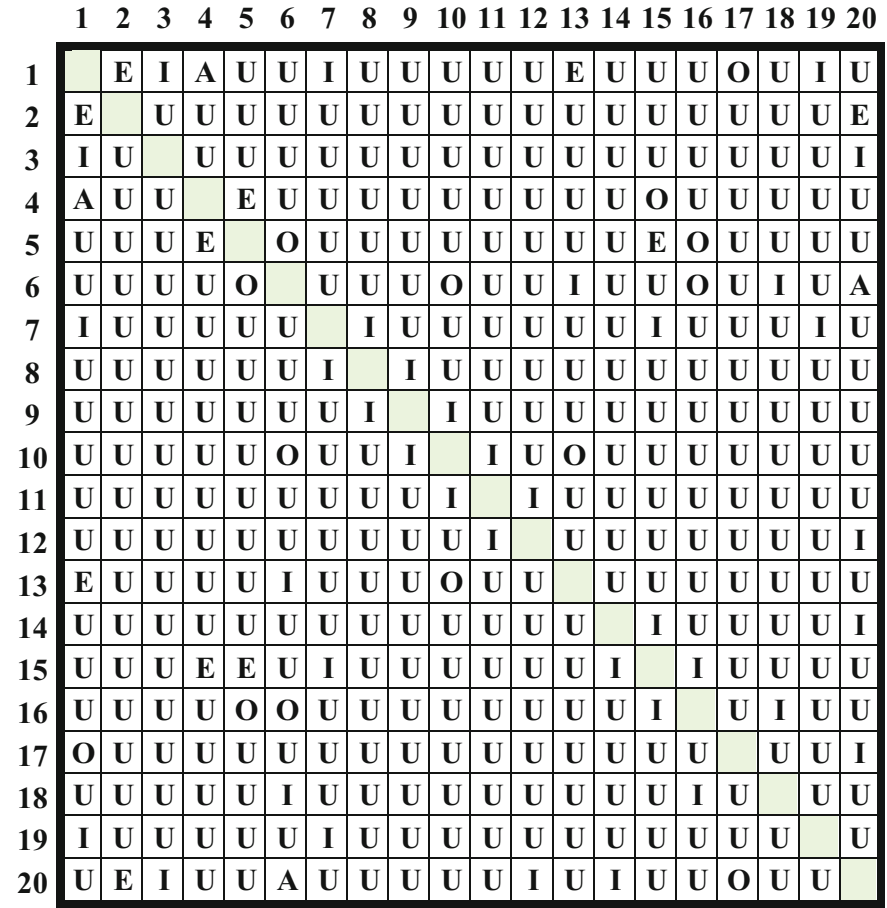


Fig. 6.7 Relationship chart generated by FLAP

6.7.1 Network Representation of the Facility

A floor plan of a facility can be represented as a planar graph or a network, $G(V;A)$. Figure 6.11 is a floor plan or a block plan representation of six room areas. It illustrates a planar graph representation of the floor plan, where each room is represented by a node and adjacent rooms sharing a wall are represented by connecting arcs.

Figure 6.11 represents the classical layout design approaches, which have primarily focused on laying out the block plan without considering the traffic flow in an aisle. Since customer traffic flow and the consequent congestion exist in the movement system, it is necessary to consider aisle travel explicitly in the major layout design. Figure 6.12 is a floor plan representation of six rooms and an aisle system. It

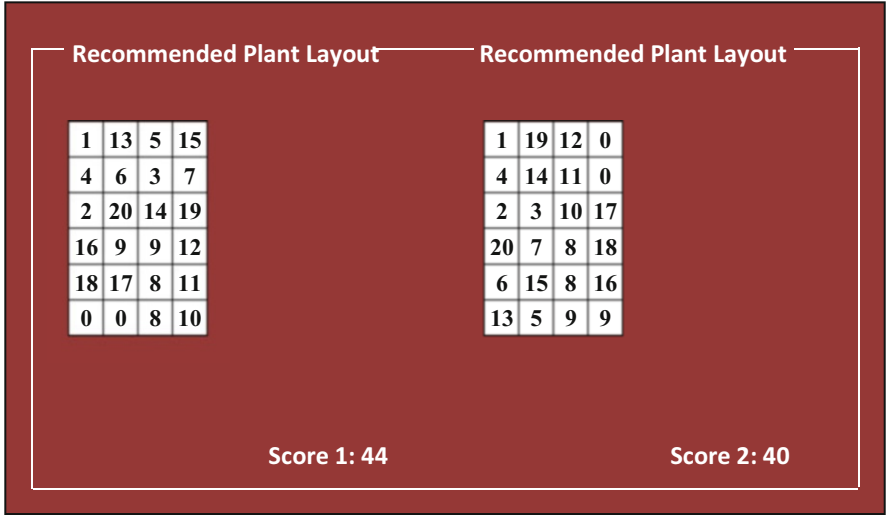


Fig. 6.8 FLAP alternatives

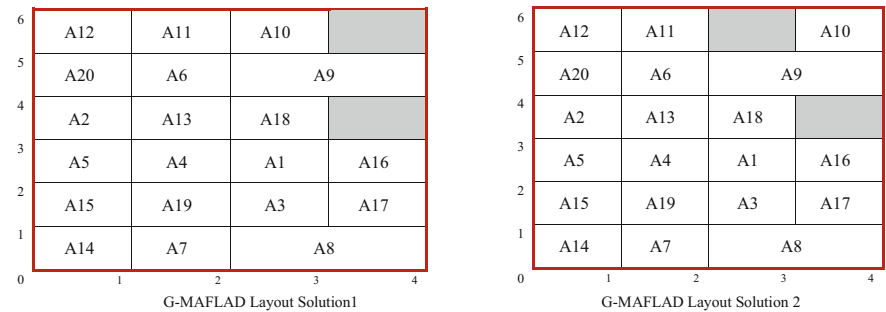


Fig. 6.9 GMAFLAD alternatives

illustrates a planar graph with an additional node—a Steiner node—representing the circulation area within a facility designed to handle the intermediate flow of customers from the source node or an activity node to another activity node.

A floor plan with a movement system can be described by a network with a Steiner node, where the nodes represent departments, facilities, or machines and the links (or arcs) represent connections of locations. The length of a link is the distance between the two adjacent locations connected by the link. The distance information is given by the distance matrix $\mathbf{D} = [\mathbf{D}_{kh}]$, where:

$$\mathbf{D}_{kh} = \begin{pmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{pmatrix}$$

Table 6.2 CRAFT generated departmental data

Department	Color	Area-required	Area-defined	x-centroid	y-centroid	Sequence
D 1	1	1	1	0.5	1.5	12
D 2	2	1	1	0.5	2.5	20
D 3	3	1	1	2.5	2.5	2
D 4	4	1	1	0.5	3.5	5
D 5	5	1	1	1.5	3.5	15
D 6	6	1	1	3.5	2.5	14
D 7	7	1	1	1.5	1.5	7
D 8	8	2	2	2	0.5	19
D 9	9	2	2	4	0.5	4
D 10	10	1	1	4.5	1.5	13
D 11	11	1	1	4.5	3.5	6
D 12	12	1	1	5.5	3.5	11
D 13	13	1	1	3.5	1.5	10
D 14	14	1	1	5.5	2.5	9
D 15	15	1	1	1.5	2.5	18
D 16	16	1	1	2.5	3.5	1
D 17	17	1	1	2.5	1.5	3
D 18	18	1	1	3.5	3.5	8
D 19	19	1	1	0.5	0.5	17
D 20	20	1	1	4.5	2.5	16

Here d_{kh} is the distance between location k and location h . If activity i is assigned to location k , then k is the permutation of activity i , $k = a(i)$. Similarly, h is the permutation of activity j , $h = a(j)$. Therefore, $d_{a(i),a(j)}$ indicates the distance between node i and node j .

The transition probability matrix, generally referred to as the *transition matrix*, $\mathbf{P}$, describes the probability of a customer going from node i to node j , that is,

$$\mathbf{P}_{ij} = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{pmatrix}$$

Similarly, $p_{a(i),a(j)}$ indicates the probability of a customer going from a facility at location k to a facility at location h . This is an alternative way to indicate that a facility is assigned to a location.

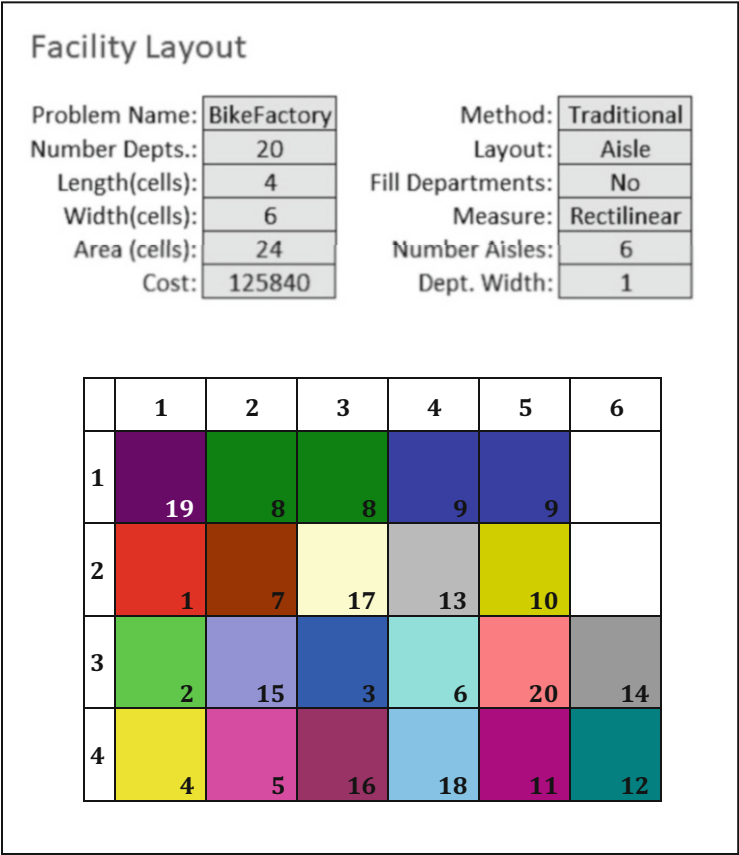
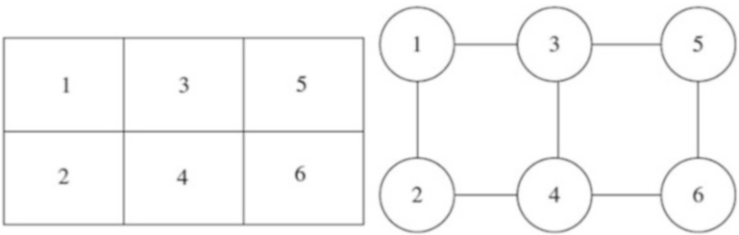


Fig. 6.10 CRAFT final layout



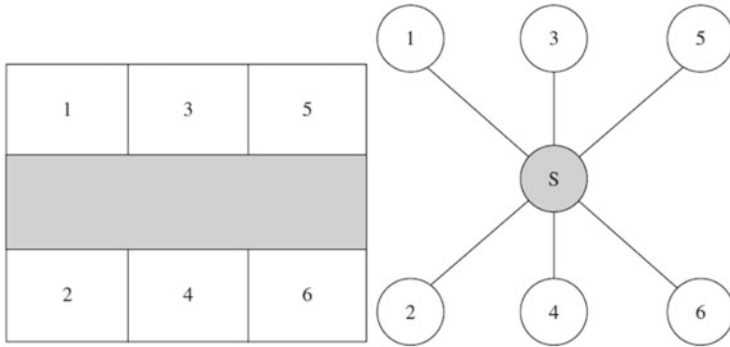


Fig. 6.12 A floor plan and its $G(V, A)$ representation

6.7.2 Assumptions, Notation, and Special Terminology

We present a formulation of the QAP where the number of customers in the Steiner node is minimized.

Assumptions

1. During the time interval $(t, t + \Delta t)$ the number of customers arriving at a circulation passage independent and stationary, and the probability of one customer arrival is equal to $\lambda \Delta t$, that is, $P(N(\Delta t) = 1) = \lambda \Delta t$ and $P(N(\Delta t) > 1) = 0$. It is assumed that customers arrive according to a Poisson process with rate equal to λ .
2. Each customer needs an amount of work t_{ij} , following an arbitrary probability distribution G .
3. The systems to be designed are in the steady state. This is more relevant in the design than in the control of facilities, steady-state mathematical models are more appropriate than transient-state ones for location and layout design [37].

Notation

v average walking speed of customers.

d_{ij} distance between node i and node j .

t_{ij} service time for a customer moving from node i to node j , that is, d_{ij}/v .

p_{ij} probability of a customer moving from node i to node j .

r_j arrival rate of customers at j from outside the system, $r_j \geq 0$.

λ_j arrival rate of customers at node j (same as rate of departure),

$$\lambda_j = r_j + \sum_{i=1}^k \lambda_i p_{ij}.$$

λ arrival rate of customers at Steiner node, $\lambda = \sum_{i=1}^n \lambda_i$.

$\frac{1}{\mu_i}$ service time mean for customers in node i , $\frac{1}{\mu_i} = \sum_{j=0}^n p_{ij} \frac{d_{ij}}{v}$.

Special Terminology

1. Traffic flow into node i is called *flow in*. For example, the *flow in* for node 1 is $\sum_i \lambda_i p_{i1} t_{i1}$
2. Traffic flow out from node j is called *flow out*. For example, the *flow out* for node 1 is $\sum_j \lambda_1 p_{1j} t_{1j}$

6.7.3 Facility Layout with an $M/G/\infty$ System

Consider the case where there is an infinite server in the Steiner node. That is, as soon as customers enter a movement system, each one has a server and receives an amount of service which is a function of the distance traveled in the layout. In other words, the queue behaves as if each occupant owns a server and the occupants are delayed independently of each other. One can model this Steiner node as an $M/G/\infty$ queuing system [36, 37].

In an $M/G/\infty$ queuing system, the average sojourn time is equal to the average service time in the queue [16]. Actually, the average sojourn time in the system is the time a customer spends in the Steiner node, and the average service time required is the time needed to travel the distance from activity i to activity j in the facility. Since the average sojourn time in the Steiner node for customers from node i is $1/\mu_i = \sum_j p_{ij} t_{ij}$ by applying Little's law, we know that the average number of customers in the Steiner node who are from node i is, thus, the total number of customers in the system is λ_i/μ_i . Thus, the total number of customers in the system is

$$L = \sum_{i=1}^n \frac{\lambda_i}{\mu_i} \quad (6.8)$$

$$= \sum_{i=1}^n \sum_{j=1}^n \lambda_i p_{ij} t_{ij} \quad (6.9)$$

$$= \sum_{i=1}^n \sum_{j=1}^n q_{ij} \frac{d_{ij}}{v} \quad (6.10)$$

where $q_{ij} = \lambda_i p_{ij}$, $i = 1, \dots, n$; $j = 1, \dots, n$. Now, to assign departments to rooms in order to minimize the number of customers in the movement system, we minimize the function formulated in (6.11):

$$\text{Minimize } \frac{1}{v} \sum_{i=1}^n \sum_{j=1}^n q_{ij} d_{a(i), a(j)} \quad (6.11)$$

The minimization in (6.11) can be achieved through a standard QAP formulation, as indicated in Eqs. (6.12)–(6.13).

$$\text{Minimize } \frac{1}{v} \sum_{i=1}^n \sum_{j=1}^n \sum_{k=1}^n \sum_{h=1}^n q_{ij} d_{kh} x_{ik} x_{jh} \quad (6.12)$$

subject to

$$\begin{aligned} \sum_{i=1}^n x_{ik} &= 1, & k &= 1, \dots, n \\ \sum_{k=1}^n x_{ik} &= 1, & i &= 1, \dots, n \\ x_{ik} &= 1, 0 & k &= 1, \dots, n \end{aligned} \quad (6.13)$$

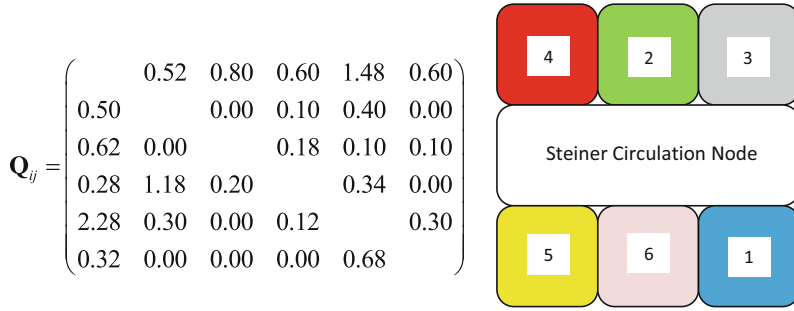
This is a stochastic version of the QAP, that is, an SQAP model. Notice that matrix $\mathbf{Q}$ is asymmetric and $\sum_i \sum_j q_{ij} = \lambda$.

6.7.4 Stochastic Example

Consider a layout with six possible locations where six activities are to be located in a double-loaded aisle system, as in Fig. 6.12. The distance matrix $\mathbf{D}_{kh}$, transition probability matrix $\mathbf{P}_{ij}$, arrival rate vector, flow matrix $\mathbf{Q}_{ij}$, and optimal locations for the six activities are shown below. The corresponding value of the objective function is 13.88 persons in the Steiner circulation node of the layout.

$$\mathbf{x} = (4, 5, 2, 6, 3, 1)$$

$$\mathbf{D}_{kh} = \begin{pmatrix} 0 & 1 & 1 & 2 & 2 & 3 \\ 1 & 0 & 2 & 1 & 3 & 2 \\ 1 & 2 & 0 & 1 & 1 & 2 \\ 2 & 1 & 1 & 0 & 2 & 1 \\ 2 & 3 & 1 & 2 & 0 & 1 \\ 3 & 2 & 2 & 1 & 2 & 0 \end{pmatrix} \quad \mathbf{P}_{ij} = \begin{pmatrix} & 0.13 & 0.20 & 0.15 & 0.37 & 0.15 \\ 0.50 & & 0.00 & 0.10 & 0.40 & 0.00 \\ 0.62 & 0.00 & & 0.18 & 0.10 & 0.10 \\ 0.28 & 0.18 & 0.20 & & 0.34 & 0.00 \\ 0.76 & 0.10 & 0.00 & 0.40 & & 0.10 \\ 0.32 & 0.00 & 0.00 & 0.00 & 0.68 & \end{pmatrix}$$



6.7.5 Algorithm

There are many heuristic procedures for solving the QAP. Some recent notable ones are documented in references [31, 32]. The *Sample Test Pairwise Exchange Procedure* (STEP) was designed specifically for solving the SQAP.

Sampling Test

A *sample* is defined as a subset of the terms in the total cost function. In this algorithm, in an assignment A of facilities to locations, the locations of two facilities u and w are exchanged to obtain a new assignment A' . Then the difference of the total costs $T(A) - T(A')$ is computed to determine if the exchange yields a reduction in the total cost. This difference can be calculated as shown below:

$$\delta = T(A) - T(A') \quad (6.14)$$

$$\begin{aligned}
 &= \sum_{\substack{i \neq u \\ i \neq w}} q_{iu} d(a(i), a(u)) + \sum_{\substack{i \neq u \\ i \neq w}} q_{iw} d(a(i), a(w)) \\
 &\quad - \sum_{\substack{i \neq u \\ i \neq w}} q_{iu} d(a(i), a(w)) - \sum_{\substack{i \neq u \\ i \neq w}} q_{iw} d(a(i), a(u)) \\
 &\quad + \sum_{j \neq w} q_{uj} d(a(u), a(j)) + \sum_{j \neq u} q_{wj} d(a(w), a(j)) \\
 &\quad - \sum_{j \neq u} q_{uj} d(a(w), a(j)) - \sum_{j \neq w} q_{wj} d(a(u), a(j))
 \end{aligned} \quad (6.15)$$

The terms in (6.15) require extensive calculations. Hence, we will take a sample of them and consider only the first four terms of representing the flow into facilities. This consists of the product of two truncated vectors of matrices $\mathbf{D}$ and $\mathbf{Q}$, as will be

shown later. The last four terms representing the flow out of facilities also could be taken as a test sample. In this algorithm, the first four terms are chosen. This quantity is shown in (6.16):

$$\begin{aligned}
 e_{uw} = & \sum_{\substack{i \neq u \\ i \neq w}} q_{iu} d(a(i), a(u)) + \sum_{\substack{i \neq u \\ i \neq w}} q_{iw} d(a(i), a(w)) \\
 & - \sum_{\substack{i \neq u \\ i \neq w}} q_{iu} d(a(i), a(w)) - \sum_{\substack{i \neq u \\ i \neq w}} q_{iw} d(a(i), a(u))
 \end{aligned} \tag{6.16}$$

We evaluate this sample and determine whether there is a possible exchange which will reduce the total cost. The rationale for this will be described in more detail in the following subsection.

Column and Row Vectors

$\overline{D}_j = (d_{1j}, \dots, d_{j-1,j}, d_{j+1,j}, \dots, d_{nj})$	Column j of matrix $\mathbf{D}$ with $n - 1$ elements
$\overline{Q}_j = (q_{1j}, \dots, q_{j-1,j}, q_{j+1,j}, \dots, q_{nj})$	Column j of matrix $\mathbf{Q}$ with $n - 1$ elements
$\underline{D}_i = (d_{i1}, \dots, d_{i-1,j}, d_{i+1,j}, \dots, d_{in})$	Row i of matrix $\mathbf{D}$ with $n - 1$ elements
$\underline{Q}_i = (q_{i1}, \dots, q_{i-1,j}, q_{i+1,j}, \dots, q_{in})$	Row i of matrix $\mathbf{Q}$ with $n - 1$ elements

Steps of the Procedure

In this algorithm, given a distance matrix $\mathbf{D}$, a probability matrix $\mathbf{Q}$, and a chosen initial assignment A , for all pair-wise exchanges of facility locations (there are $n(n-1)/2$ possible pair-wise exchanges) compute the cost of $n(n-1)/2$ samples instead of the total assignment cost and find one that will lead to decreasing the total cost, make this exchange, and revise the assignment, and then repeat the process until the total cost cannot be further decreased. The procedure is now explicitly stated:

Step 1. Find an initial assignment and its total cost.

Given distance matrix $\mathbf{D} = (\mathbf{D}_{a(1)}, \dots, \mathbf{D}_{a(n)})$ and probability matrix $\mathbf{Q} = (\mathbf{Q}_1, \dots, \mathbf{Q}_n)$
 Compute

$$d_j = \sum_{i=1}^n d_{ij} \quad j = 1, \dots, n \tag{6.17}$$

$$q_j = \sum_{i=1}^n q_{ij} \quad j = 1, \dots, n \tag{6.18}$$

Let $\mathbf{D}_{.r} = (d_{.r_1}, \dots, d_{.r_n})$, obtained by ordering the elements of $d_{.j}$ so that they are nondecreasing; let $\mathbf{D}_{.s} = (q_{.s_1}, \dots, q_{.s_n})$ obtained by ordering the elements of $q_{.j}$ so that they are nonincreasing. Then the assignment of facilities to locations is:

$$a(s_1) = r_1 \quad a(s_2) = r_2 \quad \dots \quad a(s_n) = r_n$$

Revise the matrix $\mathbf{D}$ according to this new assignment vector and compute its related cost, T , the initial assignment cost. For the $M/G/\infty$ and $M/G/C/C$ models the algorithm uses the particular objective function to calculate these total costs.

Step 2. Create matrix $\mathbf{Z}$.

$$\mathbf{Z} = \begin{pmatrix} \mathbf{Z}_{12} & \mathbf{Z}_{13} & \dots & \mathbf{Z}_{1n} \\ \mathbf{0} & \mathbf{Z}_{23} & \dots & \mathbf{Z}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{Z}_{n-1,n} \end{pmatrix}$$

$\mathbf{Z}_{ij}$ is a vector with $n-2$ elements obtained from $\bar{Q}_i - \bar{Q}_j$ after ignoring row i and row j . Thus, $\mathbf{Z}_{ij} = (z_{ijk})$, $z_{ijk} = q_{ik} - q_{jk}$, $k \neq i, j$; $i < j$, $i = 1, \dots, n-1$; $j = 2, \dots, n$

Illustration

$$\mathbf{Q} = \begin{pmatrix} * & 0.12 & 0.12 & 0.16 \\ 0.14 & * & 0.02 & 0.04 \\ 0.15 & 0.03 & * & 0.12 \\ 0.04 & 0.06 & 0.10 & * \end{pmatrix}$$

$$\bar{Q}_1 = \begin{pmatrix} * \\ 0.14 \\ 0.15 \\ 0.04 \end{pmatrix} \quad \bar{Q}_2 = \begin{pmatrix} 0.12 \\ * \\ 0.03 \\ 0.06 \end{pmatrix} \quad \bar{Q}_1 - \bar{Q}_2 = \begin{pmatrix} \\ 0.12 \\ -0.02 \end{pmatrix} \quad \mathbf{Z}_{12} = \begin{pmatrix} 0.12 \\ -0.02 \end{pmatrix}$$

Step 3. Main steps

3.1 Compute

$$e_{ij} = \sum_{\substack{l \neq i \\ l \neq j}} (d_{a(i)l} - d_{a(j)l}) z_{ijl}, \quad i > j, \quad i = 1, \dots, n-1; \quad j = 2, \dots, n$$

3.2 Let $K=1$.

- (a) Find the K th largest $e_{ij} > 0$.
- (b) If $e_{ij} < 0$, stop. T is the best result. Otherwise, proceed to Step 3.3.

- 3.3 Compute $e'_{ij} = (D_{a(i)} - D_{a(j)}) (Q_i^T - Q_j^T)$ for all $i \neq j$.
- 3.4 $\delta = e_{ij} + e'_{ij}$; if $\delta < 0$, $K = K + 1$, go to step 3.2b.
- 3.5 $T = T - \delta$.
- 3.6 Revise assignment A by exchanging the locations of facilities i and j , and return to Step 3.2.

6.7.6 The Concept of Sampling Test

Sampling tests or acceptance sampling plans are commonly used in statistical quality control (SQC). In SQC, the acceptance sampling plan for attributes is a lot-inspection procedure. The purpose of the sampling plan is simply to accept or reject lots in order to ensure that the output of a process conforms to requirements. A random sample of size n is selected from a lot and then tested under the rule that if c or less defectives are found in a sample, then the lot is accepted. Otherwise, the lot is rejected. The important concept involved in the acceptance sampling plan is Bayes' theorem [7]. Because a relationship exists between the sample and the remainder of the lot, the acceptance sampling plan works well.

In this algorithm, the concept of an acceptance sampling plan has been adopted. If Eq. (6.15) is regarded as a lot, then its computation is 100% inspection. Equation (6.15) is unduly complicated and needs extensive computing time—in other words, to do 100% inspection is too expensive—hence, we select a sample set of terms, namely Eq. (6.16), which will provide the most information about this pairwise exchange, and then calculate its cost. The reason to choose Eq. (6.16) as a test sample is that in some cases one-half the size of the lot contains the lot [25]. If the problem is symmetric then $\mathbf{Q}$ is also symmetric and then Eq. (6.16) provides exact information about the pairwise exchange; if the problem is not symmetric, $\mathbf{Q}$ is not symmetric either and then Equation (6.16) calculates two columns for the exchanged pair. Equation (6.16) provides most of the information contained in Eq. (6.15). If there is a reduction in Eq. (6.16), then this pair is a potential candidate to be exchanged. Otherwise, this pair will not be considered further. This procedure obviously entails less computing time and also provides effective solutions, as will be demonstrated in the next subsection.

6.7.7 Computational Results

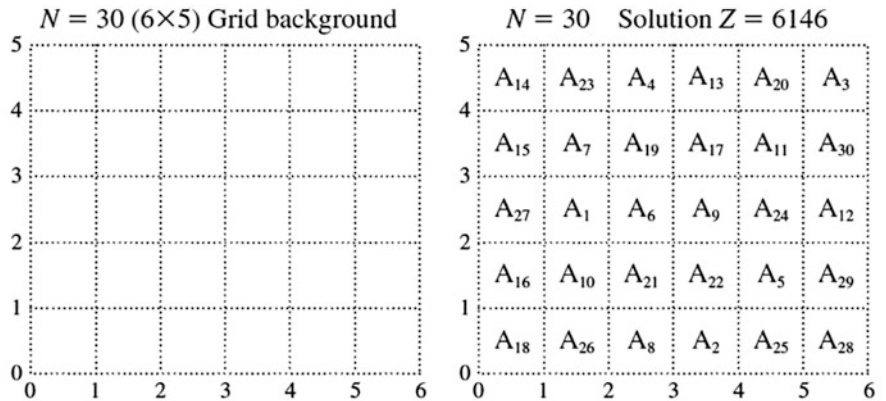
The heuristic algorithm STEP is coded in Fortran-77 and runs on many different platforms. The particular implementation described below was run on a Windows XP PC. The basic comparison of the heuristic in relation to other heuristics and the library of test problems is found in reference [26]. Its performance as compared to many of the competitive heuristics in its class has been shown to be very acceptable,

Table 6.3 Comparison of heuristic and optimal solutions

Nugent file (<i>N</i>) QAP Library	Optimal	Heuristic	% Deviation
Nug12	578	578	0.00
Nug14	1014	1022	0.79
Nug15	1150	1162	1.04
Nug 16a	1610	1636	1.60
Nug 16b	1240	1240	0.00
Nug17	1732	1734	0.12
Nug18	1930	1930	0.00
Nug20	2570	2570	0.00
Nug21	2438	2442	0.16
Nug22	3596	3596	0.00
Nug24	3488	3488	0.00
Nug25	3744	3744	0.00
Nug36	6124	6146	0.36
Average			0.31
Std. dev.			0.51

and its running times are also very reasonable as *N* (the number of activities) grows in size.

Table 6.3 summarizes results from STEP for selected deterministic problems available in the QAP Library with *N* ranging from 12 to 30. These are some of the classical QAPs available in the literature. According to Table 6.3, the heuristic generates solutions which on average are within less than 1% of the optimal solution. The maximum number of iterations was set equal to 100. Perhaps better results can be anticipated if this number is increased. Program STEP is included on the textbook website along with a user manual and sample inputs and outputs.



6.7.8 A Factory Project Example

In this subsection we present a factory example where STEP is used to generate the planar graph decomposition. In this example, there are a total of 14 activities within the factory. This factory layout was designed for producing an incandescent torchiere lamp [5]. The net assignable area is 21,800 ft². A non-assignable area of 6500 ft² is added to the net assignable area to have a total requirement of 28,340 ft². The departmental area requirements in ft² and activity relationship chart are given below.

1. Receiving (RE) (3500)	
2. Stamping (ST) (300)	
3. Compression molding (CM) (2000)	
4. Injection molding (IM) (500)	
5. Blow molding (BM) (1500)	
6. Die casting (DC) (700)	
7. Lathes (LA) (3000)	
8. Painting (PA) (600)	
9. Band saw (BS) (200)	
10. Cleaning (CL) (500)	
11. Assembly area (AS) (1500)	
12. Packaging (PK) (500)	
13. Shipping (SH) (2000)	
14. Offices (OF) (5000)	

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	-	I	O	O	O	E	O	I	U	U	I	U	U	U
2		-	U	U	U	U	U	U	U	I	U	U	U	U
3			-	U	U	U	U	U	U	O	U	U	U	U
4				-	U	U	U	U	O	O	U	U	U	U
5					-	U	U	U	U	O	U	U	U	U
6						-	O	U	E	U	U	I	U	U
7							-	I	E	O	U	U	U	U
8								-	U	U	U	U	U	U
9									-	A	U	A	U	U
10										-	I	U	U	U
11											-	A	U	U
12												-	A	U
13													-	O
14														-

The STEP program generates the planar graph decomposition shown in Fig. 6.13a and the schematic layout given in Fig. 6.13b. A rectangular layout is assumed to build the distance matrix. To generate the flow matrix cardinal utility values of A(7–9), E(5–7), I(3–5), O(1–3), and U(0) are used for flow mapping. The layout must also include a material handling system. The analysis and design of this system are the subject of Chaps. 7 and 8.

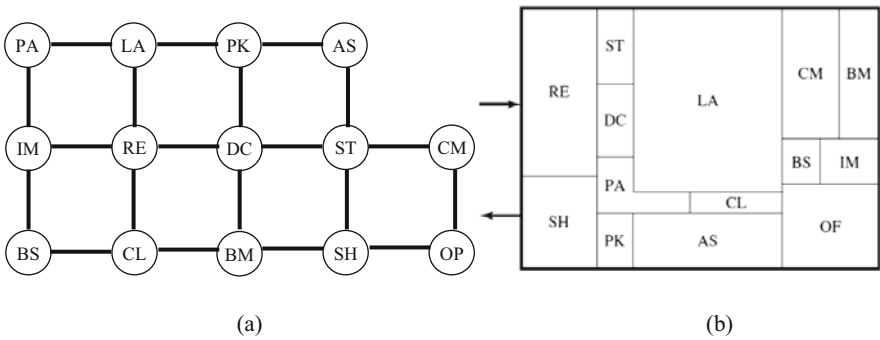


Fig. 6.13 Planar graph decomposition (a) and final layout (b)

6.8 Summary

This chapter has presented the basic planning issues underlying the development and use of computerized layout procedures. This topic has been covered at a level that serves to complement the students' knowledge on the fundamental principles and procedures for an effective layout design. This chapter demonstrated both optimal and heuristic solution procedures for the facility layout problem.

In particular, several traditional layout procedures were described emphasizing input requirements, procedural steps, output results and pros and cons for each algorithm. The topic of software integration was illustrated to support its use in the development of factory layouts using FLAP, GMAFLAD, and CRAFT.

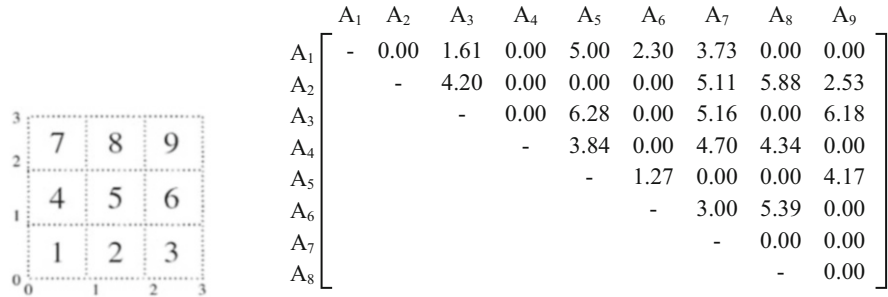
A non-traditional heuristic procedure called STEP was also described which achieves a suboptimal solution, but can solve larger problems. An application example was presented to illustrate the application of the procedure.

In closing we want to emphasize that a number of software development companies offer a diversity of products that let you plan and validate factory layouts for efficient equipment placement to improve production performance. However, most of these products focus more on factory and manufacturing management and much less on the actual design of a layout. Also, we have included in the list of bibliographical references at the end of the chapter many suggested additional references for those students interested in related topics not covered in this chapter.

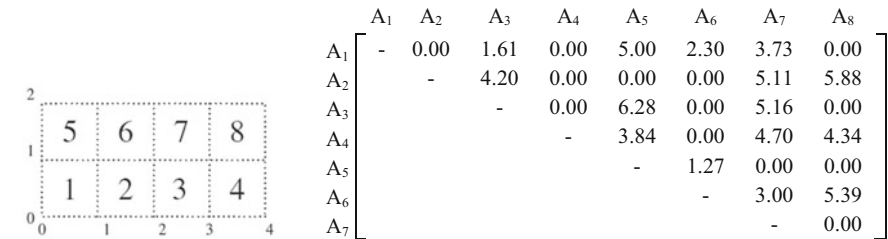
6.9 Exercises

- 6.1. What are the primary benefits of using computerized layout procedures vs. SLP procedures done by hand (see Chap. 4)?
- 6.2. What are the primary differences between construction and improvement procedures in computerized layout planning procedures? Among the traditional heuristic procedures described in this chapters, which ones are construction or improvement procedures?
- 6.3. What is the difference between an optimal layout algorithm and a heuristic layout algorithm? When do you think it is wise to recommend a heuristic solution vs. an optimal one?
- 6.4. What are the most relevant software issues discussed in this chapter? Provide a brief description of each one.
- 6.5. If you were to lay out a facility with 50 activities, what approach or approaches would you recommend to generate the layout solution? What type of data gathering would you recommend, and do you think there might be a way to decompose the problem into smaller units or sets of activities?
- 6.6. In the example of Sect. 6.6 use CRAFT to develop an improved solution based upon the first alternative generated by FLAP. Repeat this considering the second alternative (which has a lower score than the first alternative).

- 6.7. In the factory project example of Sect. 6.7 consider a rectangular area of 15 by 15 cells, each cell being a square with area equal to 100 ft². Use FLAP to recommend a layout. Discuss the differences between the FLAP layout and the STEP layout (Fig. 6.13b).
- 6.8. Consider a nine-activity problem on a 3 × 3 grid. The placement value is a constant of 1 for all cells, and the flow matrix is given below. Run GMAFLAD and print out the four best solution values.



- 6.9. This is the famous Nugent ($N = 8$) problem. GMAFLAD will generate solutions slightly different from the original Nugent solutions, because it is maximization instead of a minimization problem.



- 6.10. For the Nugent problem given in Exercise 6.9 use the STEP algorithm to generate a solution. STEP should generate the same solution as the original Nugent solution, since it is minimizing the objective function.
- 6.11. Consider a 4 × 3 grid where each of the activities can be in any of the 12 locations. Using the given place values for the different alternatives and flow matrix, run GMAFLAD to find the best arrangements.

3

9

10

11

12

2

5

6

7

8

1

1

2

3

4

0

0

1

2

3

4

Placement values matrix for N= 12

1

2

3

4

5

6

7

8

9

10

11

12

A₁

4.28

2.90

4.80

2.14

1.58

4.67

7.63

9.80

7.56

8.44

9.17

1.83

A₂

6.64

3.36

2.44

9.68

7.52

5.54

4.76

5.48

6.86

2.67

1.84

4.06

A₃

1.26

1.36

4.75

1.46

3.04

6.94

7.13

4.36

2.59

5.55

3.90

1.16

A₄

8.54

7.15

4.18

6.56

5.85

2.53

4.42

6.02

3.14

2.72

7.43

7.40

A₅

1.73

2.39

7.91

5.93

3.36

2.14

8.25

5.11

1.01

3.17

3.21

2.15

A₆

9.96

7.87

1.02

6.17

1.24

6.04

2.21

4.93

6.15

6.83

2.22

1.68

A₇

8.73

8.89

2.75

1.73

8.45

5.15

9.99

4.63

1.17

6.26

4.39

9.36

A₈

6.05

7.88

2.97

1.49

2.47

3.92

4.39

4.30

7.55

5.33

5.10

6.75

A₉

6.93

4.82

6.59

7.52

2.71

7.40

3.99

7.74

9.24

9.60

2.92

6.53

A₁₀

5.48

6.67

9.71

5.81

8.16

4.52

1.64

3.46

5.21

4.36

3.92

6.53

A₁₁

6.13

1.50

7.75

2.54

6.99

9.80

8.84

9.95

3.18

1.14

3.69

5.96

A₁₂

7.52

3.40

7.52

2.87

1.13

3.57

2.87

1.94

8.29

6.50

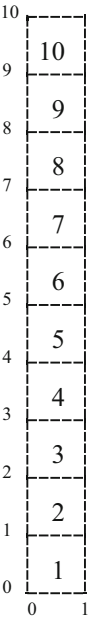
6.80

3.59

												Flow values matrix for N= 12											
												A ₁	A ₂	A ₃	A ₄	A ₅	A ₆	A ₇	A ₈	A ₉	A ₁₀	A ₁₁	A ₁₂
A ₁	-											-	2.63	0.0	0.0	3.04	0.0	0.0	3.65	1.60	1.10	2.95	0.0
A ₂													-	1.19	0.0	1.15	0.0	0.0	2.57	3.58	0.0	3.92	0.0
A ₃														-	0.0	1.65	0.0	2.19	1.01	3.40	1.63	0.0	0.0
A ₄															-	0.0	3.03	0.0	0.0	1.01	1.25	3.72	0.0
A ₅																-	0.0	1.05	1.52	0.0	3.80	2.27	0.0
A ₆																	-	0.0	2.20	1.22	0.0	0.0	2.79
A ₇																		-	0.0	2.16	2.49	0.0	2.08
A ₈																			-	1.87	1.99	1.65	0.0
A ₉																				-	0.0	0.0	0.0
A ₁₀																					-	0.0	0.0
A ₁₁																						-	0.0

6.12. *High-rise building floor assignment problem.* Consider a 10-story high rise building where you are interested in assigning retail shops activity A_1 fixed to the bottom floor, the mechanical room space activity A_{10} fixed to the top floor, and the other activities to the various floors according to the flow matrix provided below. We assume that there is an elevator-stairwell core in the center of the building to connect the traffic flow between floors. (a) Generate a heuristic solution manually. (b) Check your solution with the GMAFLAD code. All activities have an equal placement value for each floor.

	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆	A ₇	A ₈	A ₉	A ₁₀
A ₁	-	7.24	0.0	0.0	3.04	2.22	1.94	9.89	0.0	5.41
A ₂		-	7.00	9.00	0.0	0.0	7.90	0.0	0.0	5.70
A ₃			-	0.0	9.32	7.20	9.90	9.03	0.0	0.0
A ₄				-	7.81	0.0	0.0	3.01	0.0	3.61
A ₅					-	9.92	1.67	0.0	0.0	3.90
A ₆						-	0.0	7.88	0.0	2.51
A ₇							-	4.58	0.0	2.89
A ₈								-	0.0	0.0
A ₉									-	0.0



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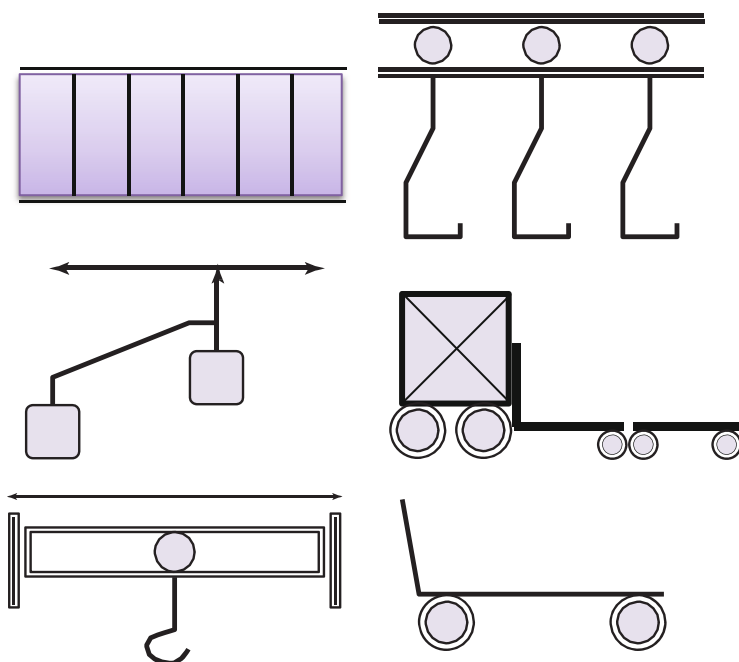
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Chapter 7

Material Handling Principles, Equipment, and System Design



7.1 Introduction

From an engineering point of view, *materials handling* is defined as the art and science involved in the moving, packaging, and storing of substances in any form. A *materials handling system* is defined as a series of related equipment elements or devices designed to work in concert or in sequence to accomplish the movement, storage, and control of materials in an operating environment and with designated materials. This chapter addresses the important concepts of materials handling, equipment, and systems design. The drawings below the chapter title illustrate the range of possible material handling equipment encountered in factory design. The next chapter addresses some of the details of material handling system design and analysis and their integration with the layout through quantitative techniques. Of key importance at this point in the factory project is to conjoin the layout and the material handling system. According to the Material Handling Institute (MHI),

material handling embraces all of the basic operations involved in the movement of bulk, packaged, and individual products in a semisolid or solid state by means of machinery, and within the limits of a place of business.

First, material handling involves the movement of material in a horizontal (transfer) and vertical (lifting) direction, as well as the loading and unloading of items. Second, materials moved include raw material to workstations, semifinished products between workstations, and finished products to their storage locations. Third, the selection of equipment is an important activity of designing a material handling system. Fourth, the term “bulk” indicates that materials are moved in large, unpacked volumes (such as sand, sawdust, and coal). Fifth, using machinery for handling material is the preferred method, although the investment might be high. The objectives of material handling may be summarized as follows [10]:

1. Increase efficiency of material flow
2. Reduce material handling cost
3. Improve facility utilization
4. Improve safety and working conditions
5. Facilitate the manufacturing process
6. Increase productivity

Material handling can account for 30–75% of production costs and can reduce operational costs by 15–30%. It affects building requirements, departmental arrangements, and production time. We shall discuss the various equipment types and their functions in subsequent sections of this chapter. A very general reference is the *Materials Handling Handbook* [8].

This chapter has three major parts:

1. Fundamental principles of materials handling
2. Material handling equipment selection
3. Material handling system design

We discuss the fundamental scope of the chapter and basic definitions in Sect. 7.2, the principles of material handling in Sect. 7.3, an outline of the procedure for conducting material handling system design in Sect. 7.4, the equipment used in material handling in Sect. 7.5, a decision-support tool for material handling equipment selection in Sect. 7.6, the corresponding computerized program in Sect. 7.7, material handling requirements and costs in Sect. 7.8, and Section III of the factory design project in Sect. 7.9. Finally, Sect. 7.10 summarizes and concludes the chapter.

In Chap. 8 detailed design tools and techniques are described for material handling system design, such as is available with open queuing networks, conveyor design and analysis, closed queuing network models for transfer lines, and discrete-event simulation tools for cellular network design and layout.

7.2 Scope and Definitions

There is a very strong correlation between the design of facilities and the design of the material handling system (MHS). In fact, it is fundamentally a symbiotic relationship. Certain facilities are probably best configured once one knows and understands the material handling system, while for others, the MHS can be determined only after the facility layout design is well established. In the best of all worlds, the design of the MHS and the facility layout should be done simultaneously. This is a demanding task, but one which should be seriously considered.

Examining the sample manufacturing plant layout in Fig. 7.1, one sees that there is a spatial/hierarchical relationship involving the vehicles and equipment required in the MHS design.

Level 1: Certain MHS equipment will bring in raw materials and deliver finished goods to and from the boundary of the facility. (Normally the spatial area over which the MHS equipment works here is very expansive.)

Level 2: Other MHS equipment will move raw materials and completed parts and subassemblies between departments. (Normally the area of extent is much smaller.)

Level 3: Other MHS equipment will be utilized to move parts and components between the specified workstations and individual machines. (Here, point-to-point movement within a fairly restricted area is needed.)

Semitrailer trucks, railcars, forklifts, conveyors, dollies, hand trucks, and people movement all must work together in a coordinated systemwide effort. Thus, within this particular factory design there are at least three levels of movement. This is typical in a manufacturing layout problem. There must be some way to coordinate the movements of the MHS equipment between the levels in the facility, if it is to function effectively. These hierarchical levels relate directly to the queuing network model to be discussed in Chap. 8, which is based on nested types of material handling transfers.

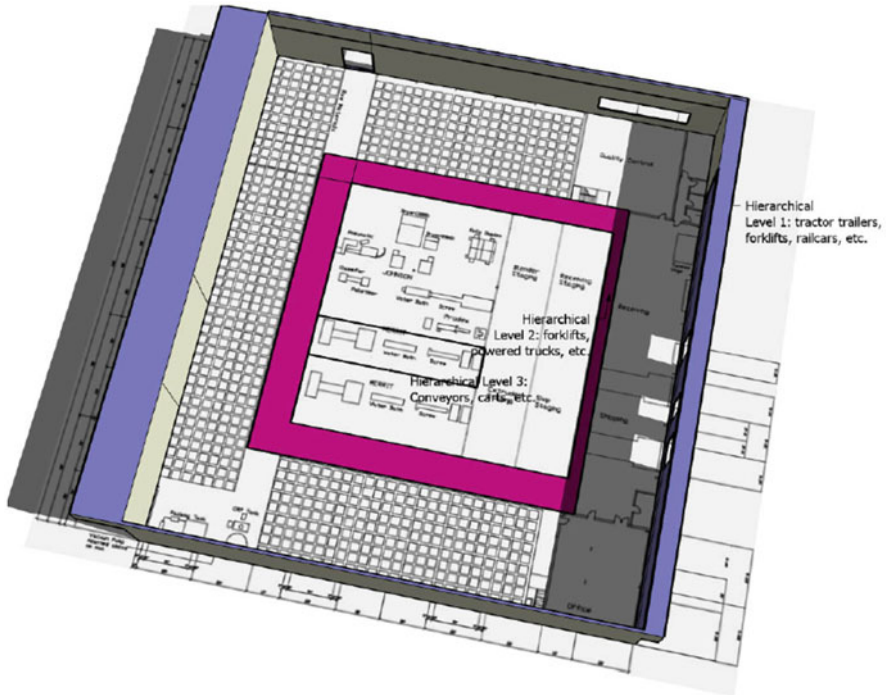


Fig. 7.1 Manufacturing floor layout with hierarchical MHS levels

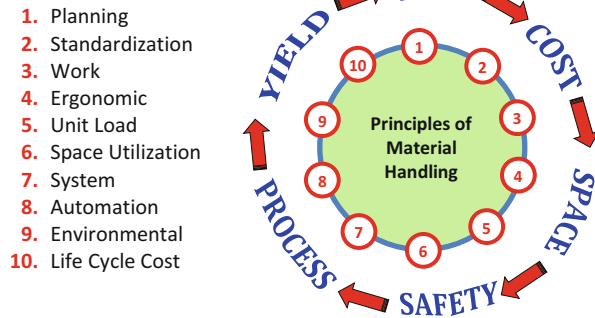
7.3 Principles of Material Handling

As noted in Chap. 1, a principle is a general rule, fundamental concept, or statement of an observable fact. In the field of material handling, various principles can be invoked to analyze, plan, and manage material handling systems.

In 1968, the College–Industry Committee for Material Handling Education (CIC-MHE) [2] published a preliminary set of principles, which since then have undergone a sequence of reorganizations and redefinitions, based on additional knowledge generated by practitioners in the field. In essence, the material handling systems can be considered as general guidelines that can be used to compare and evaluate material handling systems. Figure 7.2 lists the 10 most important principles used today in the field. These principles impact the flow, cost, space utilization, safety, process and yield (productivity) of a manufacturing operation.

1. *Planning Principle:* A material handling facility should be the result of a cohesive and structured unit of specific courses of action (i.e., a plan) to determine what material needs to be moved, when and where it will be moved, and how it will be done.

Fig. 7.2 Material handling principles



2. *Standardization Principle:* Methods, equipment, control devices, and software should be standardized without reducing the level of performance and the need for flexibility.
3. *Work Principle:* Material handling flow should be as low as possible within the requirements demanded by the effectiveness and efficiency of a material handling system. "The best flow is no flow."
4. *Ergonomic Principle:* Material handling activities should be designed and proper equipment chosen after taking into consideration human capabilities and limitations to enhance the level of safety and working conditions.
5. *Unit Load Principle:* The amount of material to be moved or stored as a unit should be sized and configured according to the specific needs and objectives of the material handling facility.
6. *Space Utilization Principle:* The cubic space should be used as effectively and efficiently as possible.
7. *System Principle:* A material handling system consists of a collection of elements working and interacting together as a unit to perform a common function. Alternatively, material handling activities and facilities are integrated to form a coordinated operational system including receiving, inspection, storage, production, assembly, packaging, load unitizing, order selection, shipping, transportation, and returns handling.
8. *Automation Principle:* The level of mechanization and automation depends on the specific operational requirements and financial capabilities of each situation.
9. *Environmental Principle:* Environmental impact and energy consumption should be important factors in the selection of a material handling system.
10. *Life Cycle Cost Principle:* In the economic analysis of a material handling system all cash flows need to be considered along the service life of the system.

7.3.1 Unit Load Principle

The standardization principle is an important notion in material handling. Often it influences the application of the *unit load principle*. Basically, the larger the unit load handled, the smaller the cost per unit handled [2]. A *unit load* is defined as an individual item, multiple items, or a mass of bulk material too large for manual handling, that can be picked up and moved as a single object and, once released, will retain its initial arrangement for subsequent moves [2]. Most unit loads are handled by some type of pallet or skid.

Once the unit load is defined for a manufacturing facility, it will begin to dictate the type, size, and configuration of material handling equipment needed. While the unit load has many advantages, it has some disadvantages related to the cost of unitizing and deunitizing, equipment and space requirements, the problem of returning empty pallets and skids, and the lack of equipment on either or both ends of the move [2]. It can be a difficult problem to define the unit load in practice.

For the factory project the selection of a unit load may be rather straightforward, since normally the parts moving in the factory will not be very large and will be moved in some cases manually, so that no significant material handling problems are anticipated.

7.4 Designing Material Handling Systems

Designing the material handling system (MHS) for a facility is a major undertaking. This section provides a brief overview of the process of material handling systems (MHS) design as it relates especially to the factory project. Section 7.6 provides a detailed guide for the design and selection of material handling equipment. This guide is closely related to the factory design project.

The activity areas within the plant are not static entities, because they always contain dynamically moving parts, people, or equipment. Within a department of the plant, there usually is a collection of machines with (1) an entry point, (2) a staging area, (3) processing, (4) finishing, (5) shipping, and (6) exit points. The sequence of materials flow is fairly typical of most manufacturing plants, and most facilities in general have prespecified sequences of operations within.

Figure 7.3 illustrates a typical department with its subactivities. In general, each department maintains a well-defined hierarchy of activities with a number of sub-areas or activities wherein the flow of materials is channeled. The nodes in the diagram represent activities and the arrows represent potential MHS moves. Possible equipment and manual moves are indicated on the diagram. Often certain conveying or transportation equipment is needed in order to move the parts, subassemblies, and finished goods according to this predefined sequence of operations through the department. Thus, the entire plant can be conceived as a hierarchical collection of departments with subactivities and an associated MHS for transferring the parts,

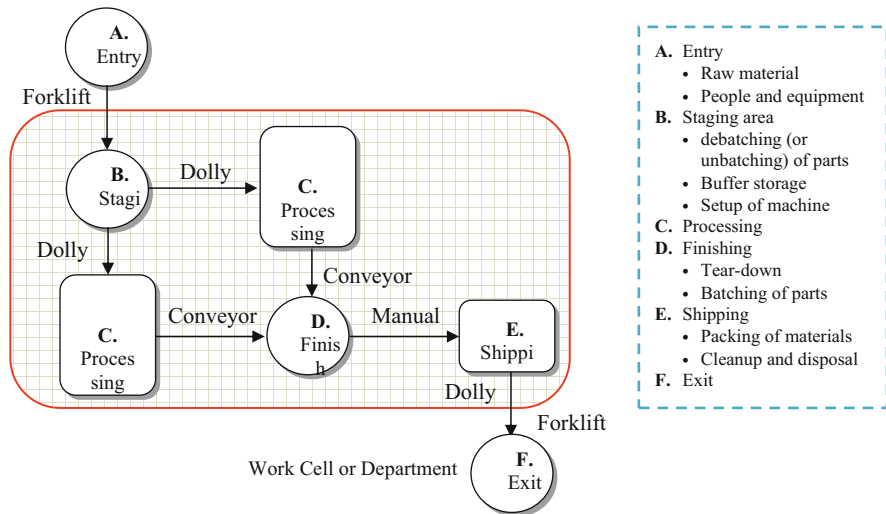


Fig. 7.3 Hierarchical department representation

people, and equipment between them. The main issue is, how to identify, organize, and structure this hierarchical system of activities into one overall functional system. This is a crucial design issue in facility planning. In Chap. 8, we describe a queuing network planning tool to design and analyze this hierarchical MHS system design.

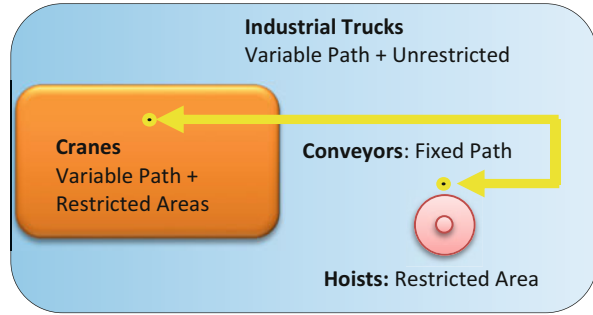
Also, in the factory project stages, once the route sheets and standard times are completed and the quantities of material, equipment, and personnel are determined, one should develop the *layout planning sheets* which describe the fundamental relationship between the facility layout and the MHS. These layout planning sheets provide one of the detailed inputs for the MHS system design process. See Chap. 4 for an example of a typical layout planning sheet and Sect. 7.7 for the integration of all sheets in the factory project (Section III).

7.5 Material Handling Equipment

We now provide a brief description of the types of material handling equipment often encountered in a factory project, as listed in Fig. 7.4. The figure shows a layout with specified locations for typical material handling equipment. The figure illustrates the point that industrial trucks have wide-area access to the entire plant, cranes and hoists have a limited area extent, and conveyors have point-to-point accessibility.

Most material handling equipment can be characterized using the following classification system:

Fig. 7.4 Diagram of key material handling equipment and factory plan [5]



$$\text{Input load/transfer mechanism/output of load} = \text{UB/TOI/AN}$$

Input Load: The product or item can normally be considered as a unit load (U) or a bulk (batch) load (B).

Transfer Mechanism: The location of the MHS equipment can either be on top of the ground or floor (T), overhead (O), or embedded in the floor (I).

Output of Load: The type of queuing system for which the MHS equipment deposits the load can either be accumulating (A) or non-accumulating (N). Accumulating refers to the fact that the load will queue up on the device or at a workstation. Non-accumulating can be thought of as no queue at all, since when the material handling equipment stops, the load is dispatched individually, with no queue forming along the material handling equipment.

Figure 7.5 illustrates the range of equipment involved in MHS design. Section 7.6 provides a detailed description of the decision-support tool that is included in the textbook to help the students choose the most appropriate type of material handling device for their factory layout project. The descriptions provided below offer an overview and introduction of the type and range of material handling devices included in the decision-support tool but are not meant to be an exhaustive description. We shall highlight certain pieces of equipment that commonly occur in factory layouts, providing a sketch, a brief description, and a summary evaluation of the equipment according to the following criteria: initial cost, maintenance cost, frequency of use, load distance moved, and volume of material moved.

7.5.1 Conveyors

Conveyors are typically used for point-to-point and department-to-department movement, assembly operations, and for integrating production departments with automated storage and retrieval systems along fixed paths. As indicated by Konz [6], the American Material Handling Society lists 57 types of conveyors. Conveyors move materials continuously over a fixed path. There must be a sufficient flow volume between the connection points of the conveyor in order to justify its use.

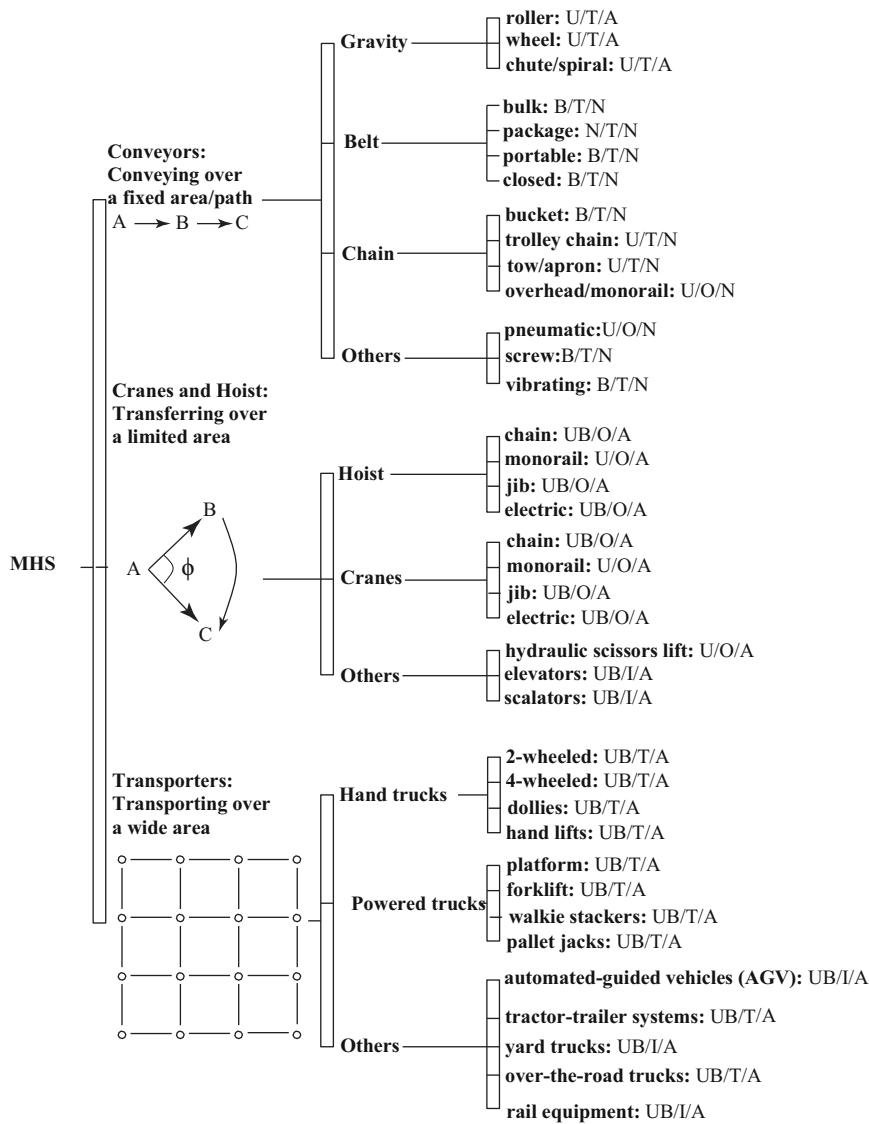


Fig. 7.5 MHS icons

Conveyors are best used for high-volume items for a fairly constant flow along a fixed route. Most conveyor systems are tailored to fit the specific manufacturing and warehousing function they are intended to serve.

Some advantages of conveyors are [10] as follows: (1) their high capacity permits a large volume of items to be moved; (2) they have adjustable speeds; (3) processing and inspection activities can be integrated; (4) they can be used throughout the entire

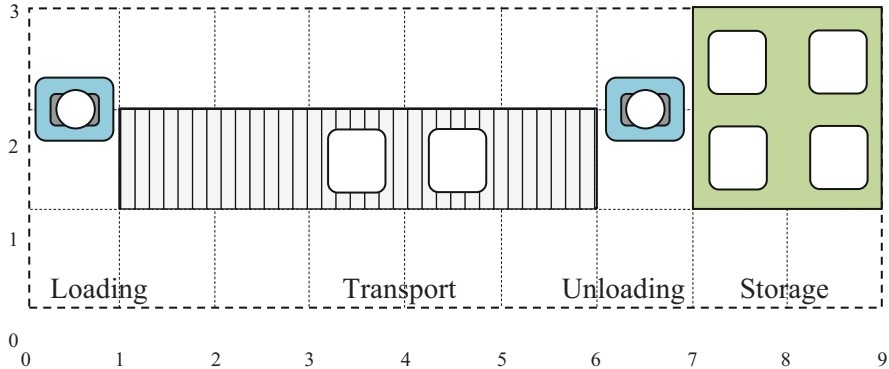


Fig. 7.6 Typical conveyor setup

horizontal and vertical spaces of the factory; (5) load transfer can be automatic without an operator; (6) curvilinear path movement is possible. Another characteristic of conveyors that has made them valuable for materials handling is that they are relatively easy to equip with automatic control devices and identification tag systems. Baggage handling at airline terminals and package handling in large postal centers make extensive use of automatic sorting conveyor systems.

The main disadvantages of conveyors are [10] as follows: (1) they have a point-to-point fixed area of movement, instead of a wide area as in other handling devices; (2) bottlenecks can develop in the system; (3) breakdowns will halt the entire production line; (4) they impede the movement of other material handling devices because of their fixed position in the layout.

The typical functions of conveyors are represented in Fig. 7.6 and include (1) transportation, (2) storage, and (3) pacing. Conveyors have adjustable speeds, their capacity is high, they can combine transferring with processing and inspection and can serve as temporary storage facilities between workstations, can be controlled automatically, and allow the utilization of the cube through the use of overhead conveyors. However, they can serve only limited areas because of the fixed paths, can generate bottlenecks if not properly controlled, and hinder the movement of mobile equipment on the factory floor.

One important difference in the modeling of conveyors is whether or not the loads on the conveyors can accumulate or not. This is important in simulation modeling of conveyors. For the most part we discuss open-loop conveyors in this chapter and closed-loop conveyors in Chap. 8. Table 7.1 is useful for selecting conveyors. The guidelines in this table are for two purposes: (a) deciding when to use each specific type of equipment, and (b) providing several choices of the equipment.

In our equipment descriptions we use the six icons shown in Fig. 7.7 to represent hooks, platforms, pallets, powered devices, wheels, and skid boxes. These icons may be used on the layout planning sheets to characterize the MHS and provide a visual way to design the MHS system. They were inspired by the work of Muther International [9].

Table 7.1 Guidelines for selecting conveyors

Purpose	Material move conditions	Types of equipment
Use conveyors	Loads are uniform. Materials move continuously. Rate of movement, unit loads, and location of routes are not likely to vary. Conveyors can bypass cross traffic.	Gravity, roller, wheel, spiral, live roller, belt, chute, trolley chain, floor chain, apron, pusher bar, vertical tray, reciprocating, pneumatic, automatic, and portable.

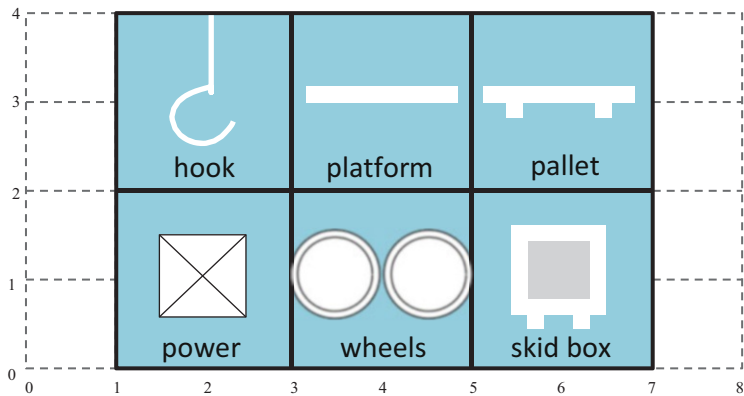


Fig. 7.7 MHS icons

For each material handling type of equipment (conveyors, cranes, hoists, and trucks) included in this chapter, an illustrative figure, a plan or elevation view, and a table with relevant criteria are provided as part of a brief description.

When one needs to connect multiple levels of a manufacturing facility and the product can move by gravity, then an inexpensive and flow efficient method of connecting multiple floors with limited space is a spiral chute. A chute conveyor is a slide, generally made of metal (steel or aluminum), which guides materials as they are lowered from a higher-level to a lower-level workstation [10]. It can be a low-cost and low-maintenance solution because it uses gravity. Items are in direct contact with the steel or aluminum chute with no wheels or rollers necessary. The shape of the chute can be straight or spiral in order to save space.

Figure 7.8 demonstrates a vertical spiral chute designed to connect multiple manufacturing levels in a layout. One concern is to make the conveyor wide enough so that there are no blockages or jams as the packages move down the chute. Also, the chute will generally link two other conveyors or workstations on the adjoining floors. For the spiral chute conveyor, Table 7.2 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

When one needs an economical conveyor for light-duty applications that is flexible and expandable for various situations, then a *wheel conveyor* is very

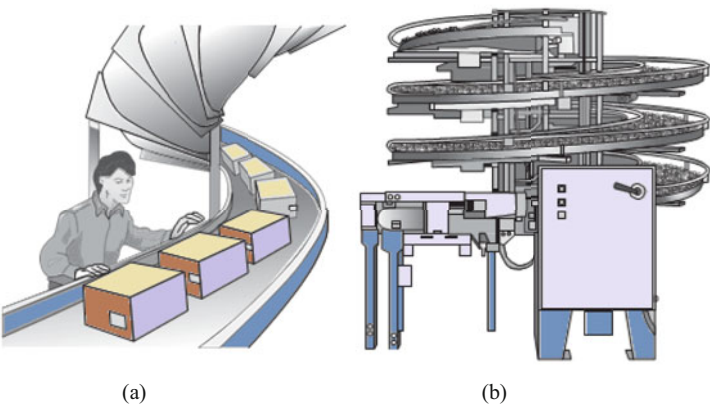


Fig. 7.8 (a) Spiral chute, (b) spiral conveyor

Table 7.2 Spiral chute conveyor

Spiral conveyor plan view

Criteria	Lowest	Medium	Highest
Initial \$	**a		
Maintenance \$	**b		
Frequency of use		**	
Load distance	**		
Material volume			**c

a Economical use of space [2]

b Very inexpensive [10]

c Depends on the factory situation

appropriate. The wheel conveyor can be gravity operated or power driven. Figure 7.9 illustrates a wheel conveyor that allows for accumulating loads. It consists of skate wheels—small steel, aluminum, or plastic wheels that turn on ball bearings or sleeves—attached to side rails supported by a steel frame. The load is carried on the wheels, each of which rotates about a fixed axis. The conveyor may be laid horizontally, and loads are manually pushed along, or else it may be declined and gravity powered. The conveyor line is normally built in standard straight and curved sections, from 5 to 20 feet long.

Most flat-bottomed surfaces will convey satisfactorily on a wheel conveyor. If the part does not have a flat surface, it may ride in a box or on a small pallet. The wheel conveyor is less expensive than a roller conveyor [2]. For the wheel conveyor, Table 7.3 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and value of material.

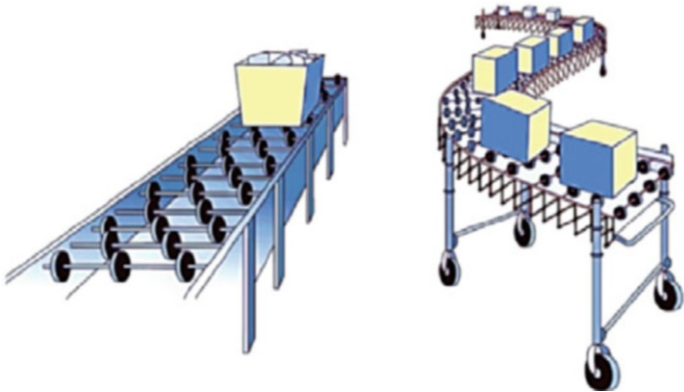


Fig. 7.9 Wheel conveyor

Table 7.3 Wheel conveyor

	Criteria		
	Lowest	Medium	Highest
Initial \$	**a		
Maintenance \$	**b		
Frequency of use	**c		
Load distance	**		
Material volume		**	
a Easy to install [2]			
b Minimum maintenance and long life [2]			
c Easy to install [2]			

If one allows accumulating loads so that they move independently of each other and not all at the same speed along the conveyor, then a *roller conveyor* (Fig. 7.10) may be appropriate. A roller conveyor is an alternative to the wheel conveyor that can be gravity operated or power driven. It consists of rollers attached to side rails supported by a steel frame. Materials must have a rigid riding surface. The load is carried on the rollers, each of which rotates about a fixed axis. The diameter of a roller, which extends across the full width of the conveyor, is generally from 1 to 3 inches. The material (steel, rubber, or wood) and the spacing of rollers depend on the type of load to be carried. Gravity-operated conveyors have a slight downward slope (pitch), commonly 3–6 inches per 10-foot section [10]. On a power-driven conveyor, some of the rollers are driven by chains or belts to impart motion to the material. As can be seen in Fig. 7.9, the spiral roller conveyor incorporates the concept of the chute conveyor with that of the roller conveyor, although the footprint of this device must obviously be larger to accommodate the large unit load and to make sure that the unit load as it descends the levels is oriented so that it does not jam

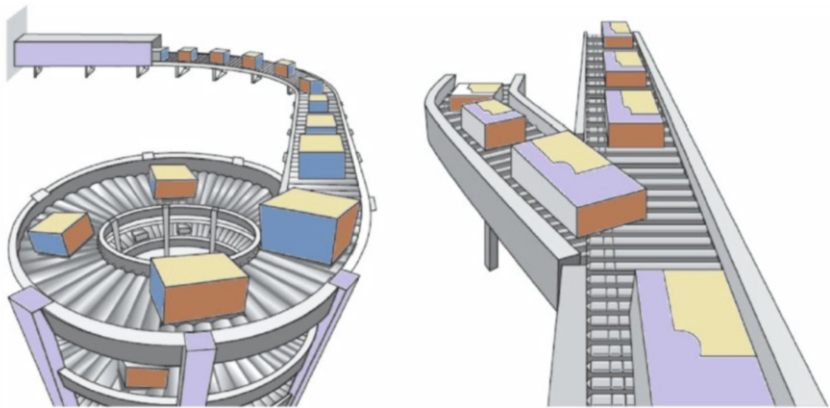


Fig. 7.10 Roller conveyor

Table 7.4 Roller conveyor

2

1

0

0

1

2

3

4

5

6

Roller conveyor plan view

Criteria	Lowest	Medium	Highest
Initial \$	*** ^a		
Maintenance \$	*** ^a		
Frequency of use	**		
Load distance	**		
Material volume			*** ^b

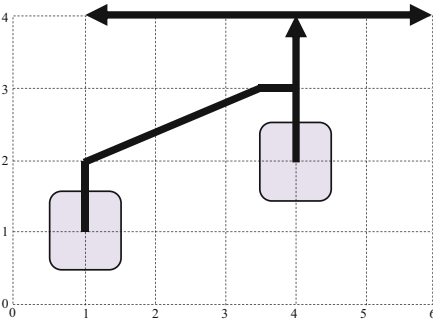
^a Similar \$ to wheel conveyor [2]
 ^b Width can be from 7 to 51 inches; capacity from 460 to 20,000 pounds [10]

or collide with the sides of the chute. For the roller conveyor, Table 7.4 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

When one needs a system for transporting small, lightweight objects over a complex pathway network that may connect the entire facility with a potentially high volume, then a *pneumatic conveyor* (Table 7.5) or tube system may be appropriate. It consists of either a cylindrical device in which small tools, messages, dies, or other small items are sent over a predetermined path by compressed air or vacuum [10]. A major advantage is that the unit load is completely enclosed in the cylindrical device, so it is easy to implement turns and vertical moves along the conveying pathway [5].

Lightweight (bulk) objects can be sent throughout the facility. The requirement for a constant pressure or vacuum results in high operating and maintenance costs for large, complex multibranch networking systems with many stations [10].

Table 7.5 Pneumatic conveyor system



Criteria	Lowest	Medium	Highest
Initial \$			***a
Maintenance \$			**b
Frequency of use			**
Load distance		**	
Material volume			**

a Initial cost may be very high
b Requirements for constant pressure or vacuum makes system very expensive to maintain [10]

Pneumatic conveyor elevation view

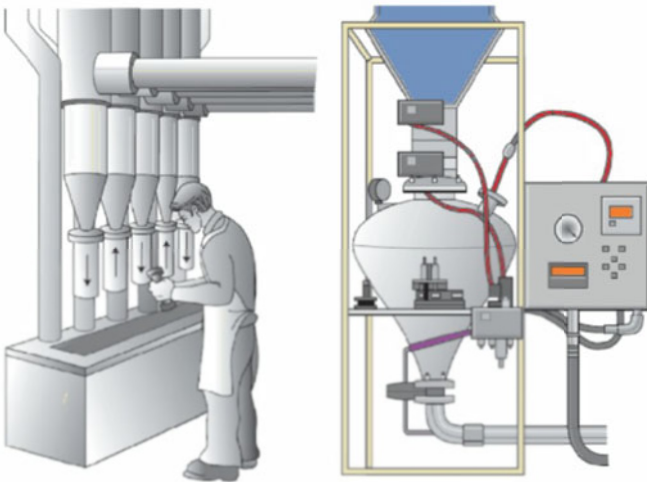


Fig. 7.11 Pneumatic conveyor system

Figure 7.11 illustrates, on the right, a pneumatic conveyor system, and on the left, one for transporting messages or manufacturing items. There are even flexible pneumatic systems that provide a very useful way of sending material throughput a plant. Pneumatic systems are widely used in the banking industry to transfer account information and customer transactions. For the pneumatic conveyor, Table 7.5 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

When one has light- to medium-weight loads moving between departments, then a *belt conveyor* might be appropriate, since the orientation and placement of the part

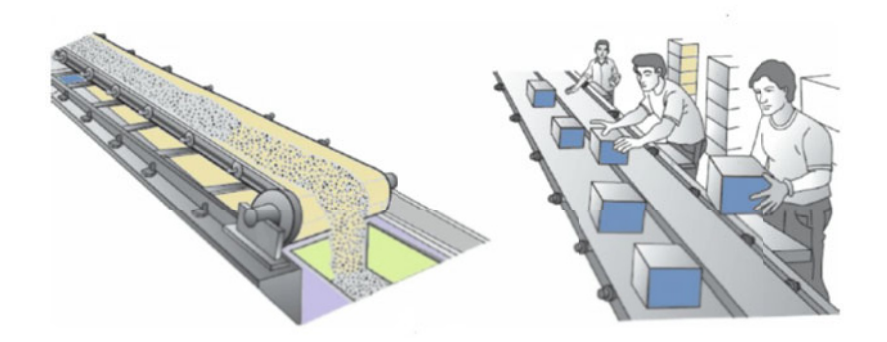


Fig. 7.12 Belt conveyor

Table 7.6 Belt conveyor

Criteria		Lowest	Medium	Highest
Initial \$		***a		
Maintenance \$		***b		
Frequency of use				**
Load distance				***c
Material volume				**
a		Cost in terms of floor space is low to medium [2]		
b		Easy to maintain, since both side wear equally [5]		
c		Relatively unlimited distance [2]		

on the belt are easily controllable. A belt conveyor is an endless, continuous belt, driven by power rollers or drums at one or both ends and supported by flat beds or rollers [10]. These rollers can provide a flat belt or a trough conveyor. The belt type is probably the most versatile of all conveyors; it can be used to move non-unit-load materials such as sand, gravel, bags, small cartons, large packages, and almost any other materials. Figure 7.12 shows an illustration of a belt conveyor.

The belt conveyor moves the unit load at a constant rate of travel, so that no accumulation is possible. The belt must be stopped and restarted at each workstation or when there are complications. The belt is made of rubber, woven wires, metal, or fabric [10]. Occasionally it can be magnetic.

Portable belt conveyors are so popular that they come in standard units. Also, belt conveyors will operate on level and on an incline up to 28 degrees or downgrade [2]. For the belt conveyor, Table 7.6 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

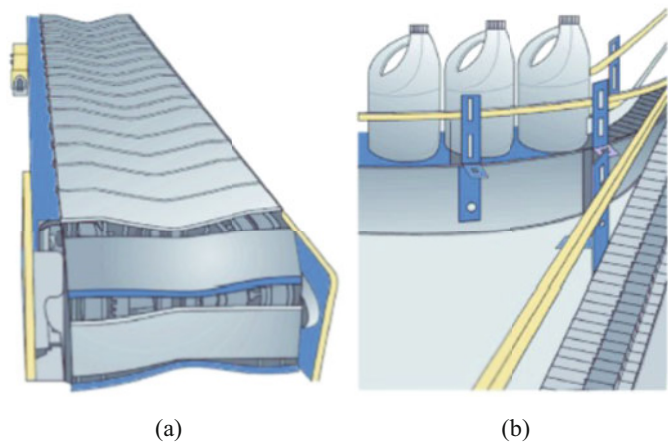


Fig. 7.13 (a) Gull wing and (b) chain conveyor

Table 7.7 Chain conveyor

The diagram illustrates a chain conveyor system in plan view. It consists of eight vertical bars, each representing a chain link. The bars are arranged in a horizontal line, with the first bar on the left and the last bar on the right. The bars are labeled with numbers 0 through 6 along the bottom axis, indicating their position. The leftmost bar is labeled 0, and the rightmost bar is labeled 6. The bars are also labeled with numbers 0 through 2 along the left axis, indicating their height or width. The bars are labeled 0, 1, 2, 3, 4, 5, and 6 from left to right. The bars are labeled 0, 1, and 2 from bottom to top. The bars are labeled 0, 1, and 2 from left to right. The bars are labeled 0, 1, and 2 from top to bottom. The bars are labeled 0, 1, and 2 from right to left. The bars are labeled 0, 1, and 2 from bottom to top. The bars are labeled 0, 1, and 2 from left to right. The bars are labeled 0, 1, and 2 from top to bottom. The bars are labeled 0, 1, and 2 from right to left. 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A *chain conveyor* employs one or more endless chains upon which loads are carried directly. The chain transmits power from a motor to a carrying surface or unit [5]. The carrying load can be quite varied. Specific examples of chain conveyors are flight conveyors (flights are “blades” attached perpendicular to the chain), apron conveyors, bucket conveyors, and slat conveyors. Figure 7.13a illustrates a gull-wing chain conveyor where the unit load is slanted inward to maintain its position and orientation. This provides for more control over the unit load. Figure 7.13b represents a typical application of a chain conveyor in a bottling or canning plant, where wet conditions, temperature variations, and cleanliness concerns must be addressed [5]. For the chain conveyor, Table 7.7 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

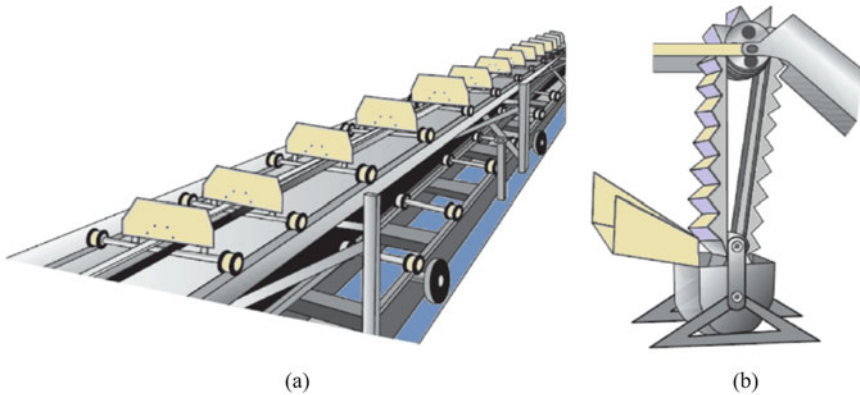


Fig. 7.14 (a) Flight-and-drag conveyor, (b) continuous bucket conveyor

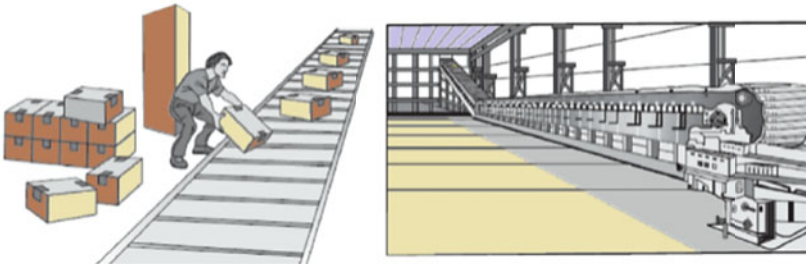


Fig. 7.15 Apron conveyors

Figure 7.14 shows illustrations of flight and bucket conveyors. A special type of chain conveyor is the *trolley* or *tow conveyor* (a powered trolley on a rail). The trolley is connected to a motor by a chain or cable.

When heavy loads and their orientation and placement on the conveyor need to be controlled, then an *apron* or *slat conveyor* is appropriate [5]. Figure 7.15 illustrates an apron conveyor. For this type of conveyor, Table 7.8 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

The slats of the conveyor are made of metal or wood and connected to two lines of motor-driven chain [10]. An apron conveyor is similar to a slat conveyor, the only difference being the partial overlapping of the slats in the apron conveyor to provide a continuous moving surface.

Table 7.8 Apron conveyor

Apron conveyor plan view

Criteria	Lowest	Medium	Highest
Initial \$		**	
Maintenance \$	**		
Frequency of use			**a
Load distance			**
Material volume			**b

^a Operation can be horizontal or inclined [10]
^b Used for heavy loads, wet or hot [2]

7.5.1.1 Conveyor Control

As indicated by Konz [6], the conveyor control system has four basic elements: input interface, logic, memory, and output interface. The input interface takes voltages or currents from switches, relays, and temperature or pressure sensors and transforms them into power levels suitable for the control system logic device. The logic takes the input and actuates devices in specific sequences. The output electromechanical devices and motors generally need line voltage; the output interface boosts the low-powered logic commands.

7.5.1.2 Accessories

This brief description of accessories is adapted from work by Sule [10]. A variety of accessories is available for the successful integration of an effective conveyor system. Among the most widely used are pallets, boxes, tote pans, skids, and optical code or bar code readers.

A *pallet* is a platform on which material can be stacked in unit loads and handled by lifting equipment such as the forklift. A *box* is a portable container (11.5 × 2.75 × 2.75 inches to 71 × 18 × 19 inches) in which parts or material can be stored in unit loads. Material can be stored in unit loads. Boxes are made of cardboard, wood, plastic, or metal.

A *tote pan* is a portable container (16.75 × 10.75 × 3 inches to 46 × 34 × 33 inches) that is smaller than a box. It is used to carry small parts. Tote pans are made of plastic, metal, or wood. They can be moved by either power-driven or hand-operated devices.

A *skid* is similar to a pallet, except that its construction does not permit stacking of loaded skids on top of each other. Skids are made of metal or heavy wood and are used to store and move heavy and/or bulky materials. They can be moved manually or mechanically and can be made portable by attaching two wheels on one end and a carrying dolly at the other.

Table 7.9 Unit loads on conveyors^a

Item	Approximate weight (lb)	Conveyor pitch (in./10 ft)
Barrels	—	5
Baskets	—	5
Boxes, wood	15–25	6.25
	25–50	5
	50–100	3.75
	100–250	3.12
Brick	—	5
Cans (milk)		
Empty	5	
Full	6.25	
Cartons	3–6	8.75
	6–12	7.5
	12–25	6.25
	25–30	5
Crates	—	5–6.25
Drums	150–300	2.5–3.75
Lumber	—	5
Tote pans	—	2.5–5

^a*Guidelines for Pitch on Gravity Conveyors* (1982). Avoid loads over 200 lb

An *optical* or *bar code* reader is a hand-held device that can read an optical code to identify the product or handling device on which the code is affixed. It can be used to keep track of inventory or products as items are moved from station to station. Radio-frequency identification devices (RFID), tags, and transponders and their technology are also an important aspect of product identification.

Table 7.9 shows how the weights of unit loads on conveyors are related to conveyor pitch. It is adapted from a publication by the *General Electric Company*. More details of this type of decision-making process are included in the Decision Support System presented in Sect. 7.6.

In general, for products to roll on a gravity feed conveyor line, the conveyor must be pitched downward. Pitch recommendations vary in Table 7.9 vary from 2.5" to 8.75" in each 10' section. The pitch depends on the type of unit load, the number of rollers under the product and the type of lubrication used on the rollers.

7.5.2 Monorails, Hoists, and Cranes

Hoists and cranes, along with lift trucks and conveyors, constitute one of the three principal types of equipment for material handling in manufacturing and warehousing. Transporters and trucks provide versatile handling from the wide-area floor surface, and conveyors provide fixed point-to-point transfer at any elevation. Hoists and cranes provide versatile handling overhead within a constrained

Table 7.10 Guidelines for selecting cranes and hoists

Purpose	Material move conditions	Type of equipment
Use cranes or hoists	Where and when [1] Intermittent movements occur within a limited or constrained area. Material loads are of variable size and weight. Movement of materials is free from concern about conveyor cross traffic on the ground. Unit loads are not uniform.	Hoists are commonly divided into three classes: Chain, air, and electric hoist. Electric hoist has the widest application because its high speed results in economic operation. Common types of cranes: Portable crane, jib crane, stacker crane, monorail, derrick, gantry, overhead traveling bridge.

area. These types are important for manufacturing and warehousing operations, each performing certain types of handling best.

Cranes and hoists are overhead equipment for moving unit loads of variable size and weight intermittently within a limited area. Advantages derived from using them include the following: (1) they are not encumbered by the manufacturing or warehouse floor area, (2) aisles are not needed, and (3) they utilize the vertical space for materials movement within the plant. Bridge cranes, jib cranes, stacker cranes, monorail cranes, and hoists are examples. Lifting equipment is also generally capable of transferring material, although it might be confined to one major location. It can handle very heavy loads, and it can be used for loading as well as unloading.

Some disadvantages associated with the use of cranes and hoists are that [10] (1) they can be very expensive; (2) they serve only a limited area and because of their straight travel cannot make turns; (3) utilization may not be very high; (4) they provide more flexibility in moving items than conveyors but less flexibility than industrial trucks [5]; (5) they require an operator for most operations.

Table 7.10 lists specific types of hoists and cranes to be used for some typical functions. The guidelines in this table are for two purposes: (a) deciding when to use each specific type of equipment, and (b) providing several choices of the equipment.

An *overhead monorail*, illustrated in Fig. 7.16, has a track to transport carrying devices such as trolleys and hooks. The track itself can form a closed loop. Often an overhead monorail is used in transporting units to spray paint booths or baking ovens. Generally, it is placed at 8–9 feet from the floor. The overhead monorail is similar to a conveyor because it transports unit loads overhead with potential accumulation. A telfer is a light car suspended from and running on aerial cables. Usually, telfers are propelled by electricity. For the overhead monorail, Table 7.11 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

A *hoist* is a lifting device attached to monorails, cranes, or a fixed point. It can be powered manually or by electric or pneumatic motors. Figure 7.17 shows illustrations of hoists and some of their applications. For hoists, Table 7.12 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material. A hoist is frequently named by the kind of

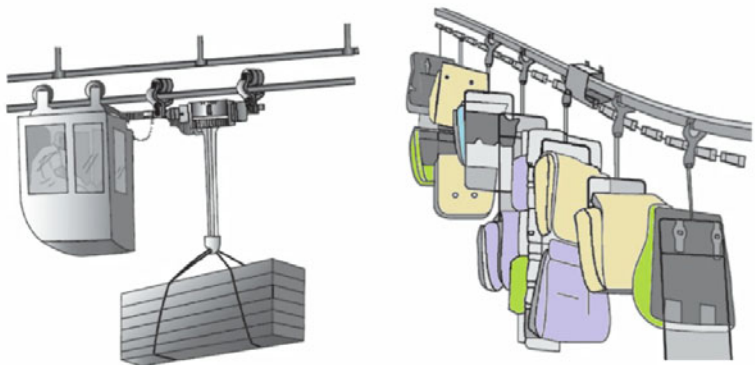
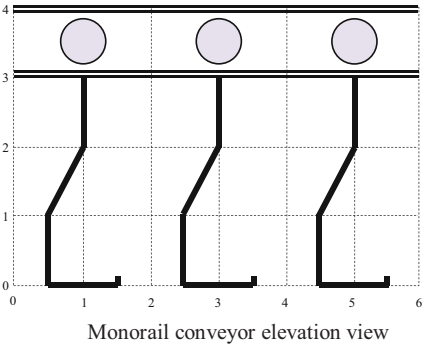


Fig. 7.16 Overhead monorail

Table 7.11 Overhead monorail



Criteria	Lowest	Medium	Highest
Initial \$		** ^a	
Maintenance \$	** ^b		
Frequency of use			**
Load distance		**	
Material volume	**		

^a Removes traffic from floor space [2]
^b Low installation and maintenance costs [2]

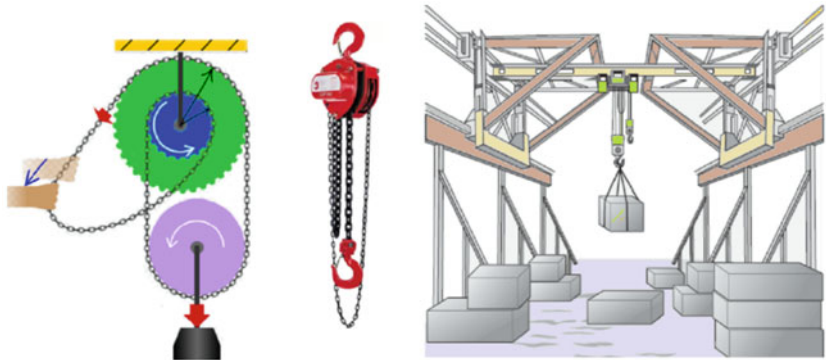
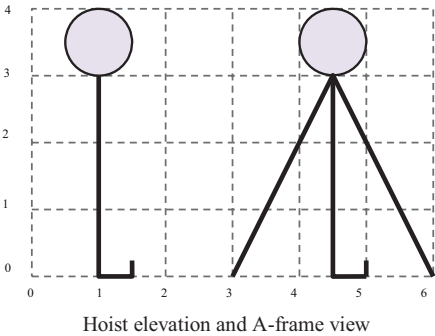


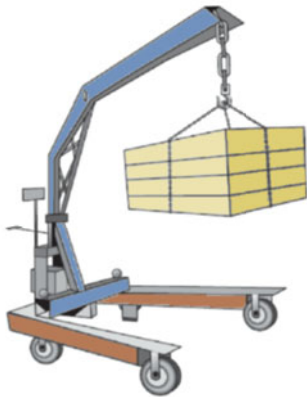
Fig. 7.17 Hoists and their uses

Table 7.12 Hoist and A-frame

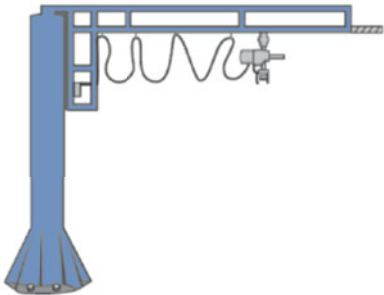


Criteria	Lowest	Medium	Highest
Initial \$	***		
Maintenance \$	**		
Frequency of use	**		
Load distance		**	
Material volume	**		

^a Inexpensive [2]



(a)



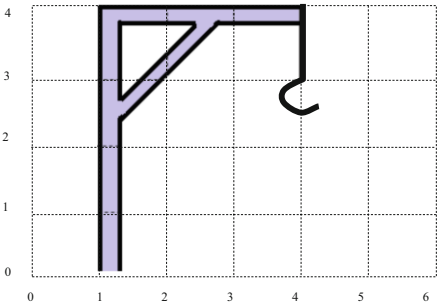
(b)

Fig. 7.18 (a) Portable and (b) fixed jib crane

crane to which it is attached. There are three major types: *chain hoist* (serves a fixed spot directly beneath the hoist), *monorail hoist* (free to move along an overhead rail), and *jib hoist* (serves any area circumscribed by the jib in a 360-degree rotation).

A *crane* is a piece of overhead equipment consisting of a boom or bridge along which a handling device, such as a hoist, traverses. A *jib crane* consists of a lifting device (hoist) traveling on a horizontal boom mounted on a vertical mast (pillar jib crane, bracket jib crane, and cantilever jib crane). The arm can rotate 360 degrees and the hoist can move along the arm, as is shown in Fig. 7.18. The horizontal boom can rotate to achieve a wide range of coverage. For the jib crane, Table 7.13 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

Table 7.13 Jib crane

	Criteria	Lowest	Medium	Highest
	Initial \$	***		
	Maintenance \$	**		
	Frequency of use	**		
	Load distance		**b	
	Material volume	**		

^a Inexpensive and very versatile [2]

^b Can also handle large loads (>350 tons) [2]

Jib crane elevation view

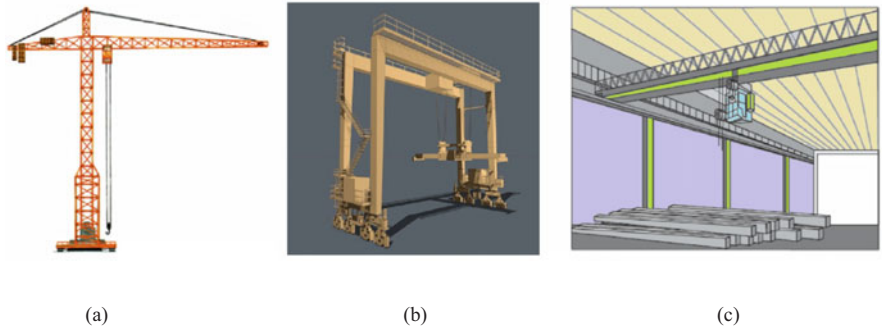


Fig. 7.19 (a) Tower crane, (b) Gantry crane, (c) bridge crane

A *tower crane* (Fig. 7.19a) consists of a hoist that travels on a horizontal boom attached at one end to a vertical post, the other end of the boom being supported by a guy line to the top of the post. A *gantry crane* (Fig. 7.19b) is basically a bridge crane with the boom supported at one or both ends by a vertical gantry leg traveling on rails installed at ground level (instead of on an overhead runway). A *monorail crane* consists of a beam supporting a carrying device mounted on wheels, which run along the beam. A *stacker crane* is one with a vertical beam suspended from a carriage, mounted on a device similar to a bridge crane, and fitted with forks or a platform to permit it to place items into or retrieve items from storage racks on either side of the aisle it traverses. It is essentially a moving forklift solution [5].

A *bridge crane*, illustrated in Fig. 7.19c, consists of a lifting device mounted on a bridge, which is supported at each end by tracks riding on or suspended from runways installed at right angles to the bridge. It enables the unit load to move in (x, y, z) space within the area served by the bridge crane, which yields a great deal of flexibility. Variations include stacker crane, tower crane, and gantry crane. For the

Table 7.14 Bridge crane

Bridge crane elevation view

Criteria	Lowest	Medium	Highest
Initial \$			** ^a
Maintenance \$	**		
Frequency of use			**
Load distance	**		
Material volume	** ^b		

^a Can be very expensive and is designed by specialists [2]

^b Low to medium volume [2]

bridge crane, Table 7.14 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

7.5.3 Industrial Trucks

These are carrier designed to transport materials within a factory area with maximum flexibility in making moves. Most industrial trucks permit mechanized pickup and deposit of the loads, eliminating manual work in lifting as well as transporting. They are very flexible in routing items and versatile for movement from small to very large loads. They also can provide vertical movement if they have lifting capabilities. They are ubiquitous in manufacturing systems. In general, they can be manually operated or power-driven. Industrial trucks and forklifts are among the most common forms of material handling equipment in warehouse and manufacturing settings.

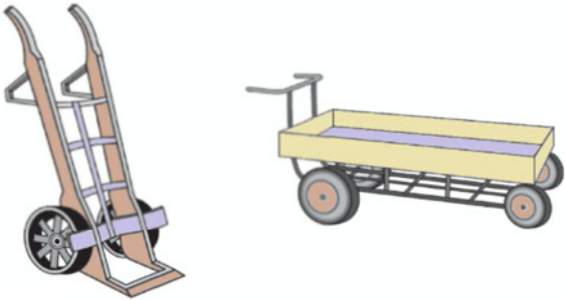
Table 7.15 is a useful characterization of the purpose and use of wide-area trucks. The guidelines in this table are for two purposes: (a) deciding when to use each specific type of equipment and (b) providing several choices of the equipment. There are many adaptations of industrial trucks, each designed to accomplish a specific type of job. They are so flexible in operation that the integration of the industrial truck system with crane or conveyor systems satisfactorily answers most materials handling problems.

The purpose of these trucks is to carry loads over varying paths. There are a number of types, such as lift trucks, hand trucks, fork trucks, trailer trains, and automated guided vehicles. Several types are capable of loading, unloading, and lifting as well as transferring. Major advantages of trucks are as follows: (1) their wide area of reach and pickup, transfer, and routing; (2) 3D flexible capabilities in

Table 7.15 Guidelines for selecting industrial trucks

Purpose	Material move conditions	Type of equipment
Use industrial trucks	Where and when [1] Materials must be picked up and moved intermittently over various routes. Materials are either of mixed size and weight or of uniform size. Distances are moderate. Cross traffic would prohibit the use of conveyors. There are suitable running surfaces and clearances. The operation itself is principally handling. Unit loads are utilizable.	Hoists are commonly divided into three classes: Chain, air, and electric hoist. Electric hoist has the widest application because its high speed results in economic operation. Common types of cranes: Portable crane, jib crane, stacker crane, monorail, derrick, gantry, overhead traveling bridge.

Fig. 7.20 Handcart or hand truck

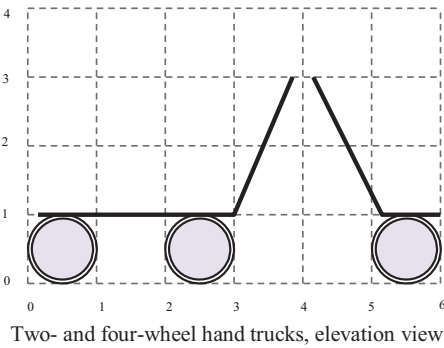


loading, transfer, and unloading; and (3) achievement of high utilizations due to their wide-area reach [10]. Some of the disadvantages of trucks are as follows: (1) they cannot handle extremely heavy loads; (2) they have limited capacity per trip; (3) aisles are required, which can interfere with people and other equipment; (4) they cannot be combined with processing and inspection activities, as in conveyors; and (5) they are operator driven [10].

The handcart or hand truck (Fig. 7.20) is one of the oldest pieces of equipment for material handling. It can be either two-wheeled or four-wheeled. It is a wheel-mounted platform fitted with handles by which it can be manually pushed or pulled. Often it is used to move material short distances with frequent stops for loading and unloading as well as temporary storage [10]. It is inexpensive, versatile, and used for low-frequency moves, short distances, narrow aisles, and crowded areas [2]. For two-wheel hand trucks, Table 7.16 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

When one needs a universal, flexible, one-person manual transport device for moving small or large items, then a dolly is a very affordable and practical device (Fig. 7.21). It is considered to be a hand truck consisting of a small rectangular,

Table 7.16 Two-wheel hand truck



Criteria	Lowest	Medium	Highest
Initial \$	**		
Maintenance \$	**		
Frequency of use	***a		
Load distance	**		
Material volume	***b		

^a Low-frequency and low-volume movement [2]

^b Platform capacity from 200 to 10,000 lb [10]

Fig. 7.21 Rectangular and circular dolly

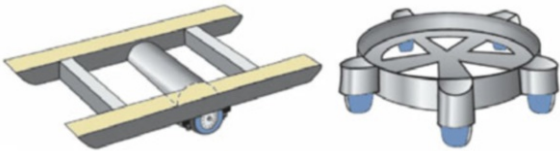
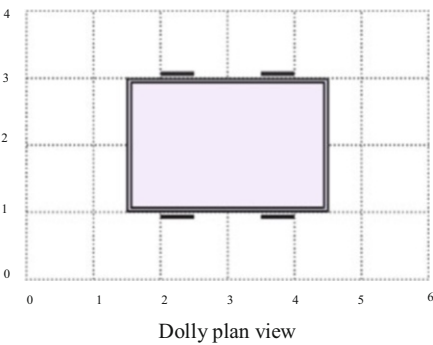


Table 7.17 Dolly



Criteria	Lowest	Medium	Highest
Initial \$	***a		
Maintenance \$			
Frequency of use			**
Load distance	**		
Material volume	***b		

^a Inexpensive to purchase and maintain

^b Load capacity from 500 to 4,000 lb

triangular, or circular load carrier with one or more rollers, casters, or wheels attached to the underside. It is mainly used for transporting relatively light weights and low volumes over short distances [10].

In general, dollies are also much larger and more commonly used for bulkier, heavier items, while hand trucks are usually small and best-suited to stacking boxes

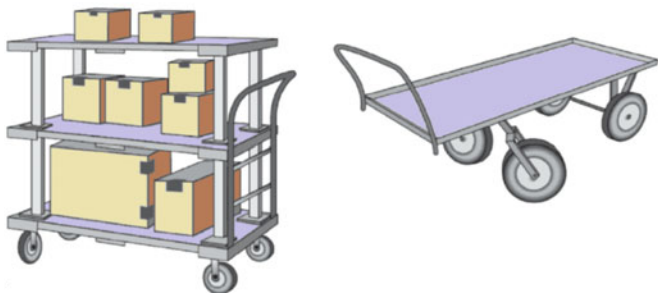
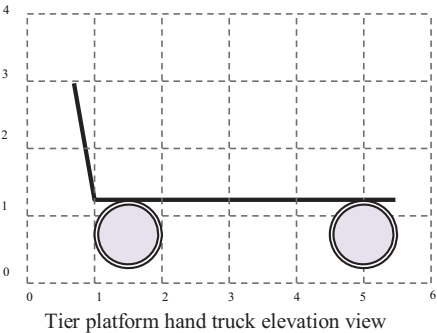


Fig. 7.22 Tier platform truck

Table 7.18 Tier platform truck



Criteria	Lowest	Medium	Highest
Initial \$	**		
Maintenance \$			
Frequency of use		**	
Load distance	**		
Material volume	*** ^a		

^a From one to five trays with 150 to 1800 lb capacity [10]

or vertical loads. Table 7.17 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

A tier platform truck (Fig. 7.22) is a hand truck with one or more additional tray platforms stacked vertically. It can be powered or manually moved [10]. For tier platform trucks, Table 7.18 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

A hand lift truck (Fig. 7.23) is a hand-operated truck, designed to be rolled under a pallet or skid, that can raise loads hydraulically or mechanically to clear the floor before transporting them to the desired destination [2, 10]. It is better for heavier objects than a simple hand truck, and it is low-cost, lightweight, compact, and relatively simple to operate [2]. Table 7.19 summarizes relevant remarks regarding purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material for hand lift trucks and pallet jacks.

A power-driven hand truck (Fig. 7.24) is similar to a hand lift truck, except that it is driven by a battery-operated electric motor [10]. Sometimes it is called a walkie truck. For power-driven hand trucks, Table 7.20 summarizes relevant remarks

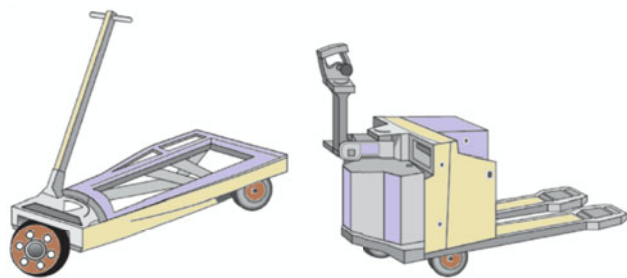
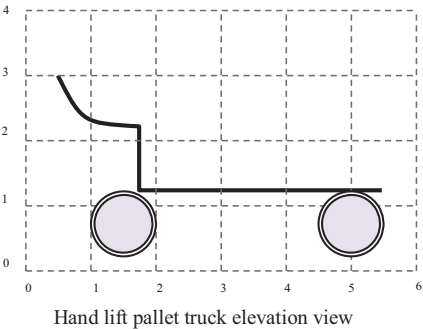


Fig. 7.23 Hand lift truck/pallet jack

Table 7.19 Hand lift truck/pallet jack



Criteria	Lowest	Medium	Highest
Initial \$			
Maintenance \$			
Frequency of use			
Load distance	**	***a	
Material volume	**		

^a Moderate distances (50 – 200 ft) [2]

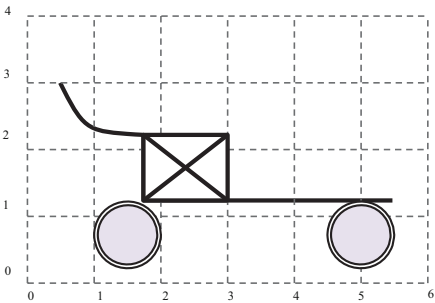


Fig. 7.24 Power-driven hand truck

related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

A power-driven platform truck (Fig. 7.25) is a much larger device than a power-driven hand truck. It is used for narrow aisles and is generally a one-person operation [2]. It carries both load and operator, with power supplied by a diesel or gasoline

Table 7.20 Power-driven hand truck



Power-driven hand truck elevation view

Criteria	Lowest	Medium	Highest
Initial \$		**	
Maintenance \$	**		
Frequency of use	**		
Load distance		***a	
Material volume	**b		

^a Longer distances than hand truck (150 – 300 ft) [10]

^b Load capacity from 500 to 6000 lb [10]

Fig. 7.25 Power-driven platform truck

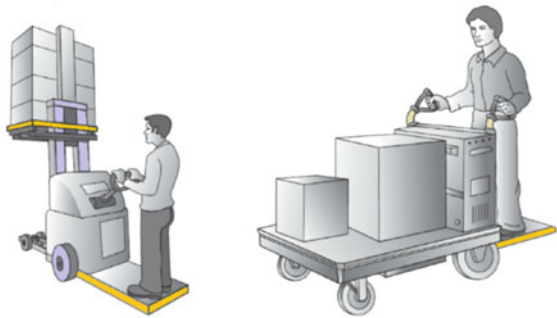
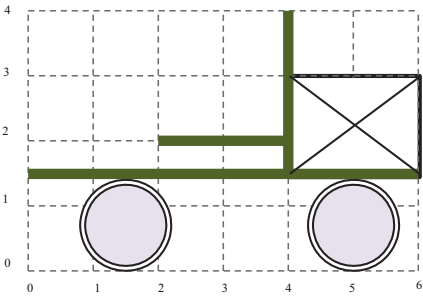


Table 7.21 Power-driven platform truck



Criteria	Lowest	Medium	Highest
Initial \$		**	
Maintenance \$	**		
Frequency of use	**		
Load distance		***a	
Material volume	**b		

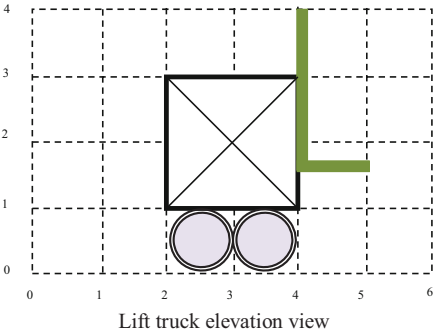
^a About 400 – 500 feet is a normal application [10]

^b Load capacity from 200 to 2000 lb [10]

Fig. 7.26 Powered lift truck



Table 7.22 Lift truck



Criteria	Lowest	Medium	Highest
Initial \$			***a
Maintenance \$		**	
Frequency of use		**b	
Load distance		**	
Material volume	**c		

^a Can be expensive
^b Intermittent moves
^c Low to medium volume; used for heavy loads up to about 100,000 pounds; can lift load up to 25 feet

engine or and electric motor [10]. Truck width equals load width plus about 3 feet [2]. Table 7.21 summarizes relevant remarks regarding purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material for power-driven platform trucks.

Powered lift trucks are one of the most versatile single pieces of material handling equipment used in manufacturing and warehousing operations (Fig. 7.26). These trucks are self-propelled, self-loading, counterbalanced, wheeled vehicles carrying an operator, and having a fork or other type of attachment fastened to a telescoping mast mounted on the vehicle [2]. They can move loads horizontally and vertically, travel over wide areas with a wide variety of attachments and can pick up, turn, push, and pull all types and shapes of loads (1000–100,000 lb) on skids or pallets [10]. For

Fig. 7.27 Tractor-trailer train

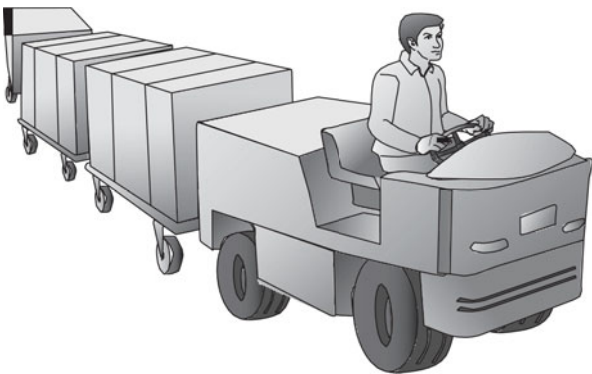
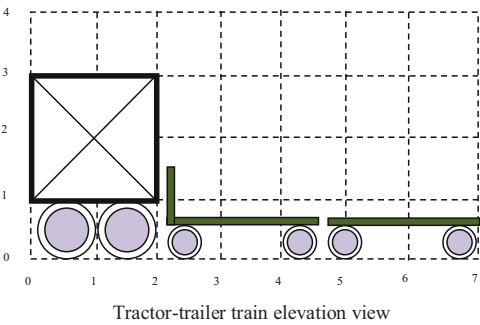


Table 7.23 Tractor-trailer train



Criteria	Lowest	Medium	Highest
Initial \$		**	
Maintenance \$	**		
Frequency of use	**		
Load distance		**a	
Material volume		**b	

^a Distance of 200 – 300 ft [2]
^b Greater volume than a forklift [2]

lift trucks, Table 7.22 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

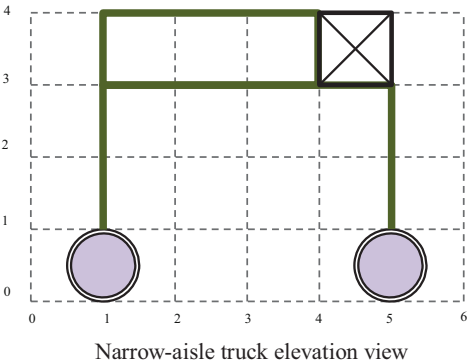
A tractor-trailer train, depicted in Fig. 7.27, is a series of carts pulled by either an operator-controlled or self-propelled tractor. It is mainly used for stop-and-go operations carrying loads within 200–300 feet [2]. For this type of vehicle, Table 7.23 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

A narrow-aisle truck (Fig. 7.28) is an industrial truck specifically designed for narrower aisles (5–6 feet) [10], depending on the capacity of the lift truck and the dimensions of loads carried, where the conventional truck requires, say, 9- to 14-feet wide aisles. The main advantages of narrow aisle trucks are that they have a much shorter turning radius; therefore, aisles can be narrower, permitting greater utilization of manufacturing warehouse storage space. The narrow-aisle truck is powered by electricity or gas [10]. Variations include side-loader truck (forks on the side rather than the front), straddle truck (with outriggers to balance loaded truck), reach truck (fork truck with telescoping forks to reach loads that are set back), order-picker

Fig. 7.28 Narrow-aisle truck



Table 7.24 Narrow-aisle truck



Criteria	Lowest	Medium	Highest
Initial \$		**	
Maintenance \$	**		
Frequency of use			**
Load distance		**	
Material volume	***a		

^a Capacity from 1000 to 100,000 lb with lift height up to 30 ft [10]

truck (with a platform that lifts the operator), turret truck (with forks that can rotate left or right to place or pick up a load without the truck having to turn in an aisle). For narrow-aisle trucks, Table 7.24 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

There are many variations of narrow-aisle trucks. One of them is called a straddle truck—a lift truck with outriggers to counterbalance loads. The short wheelbase of the straddle-arm lift truck does not provide the balance necessary to reach as high as the conventional counterbalance lift truck. Because of this balancing problem, most straddle-arm trucks are limited to lift heights of less than 25 feet. To increase the versatility of the truck, a telescopic mechanism is added to extend the fork unit out 3 or 4 feet to pick up loads.

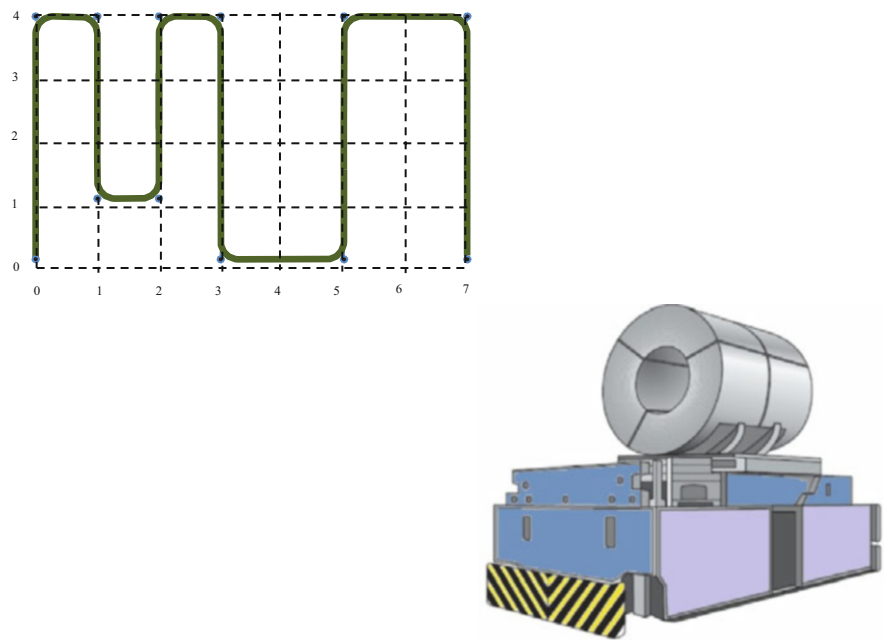


Fig. 7.29 Automated guided vehicle (AGV)

Table 7.25 AGV systems

Criteria	Lowest	Medium	Highest
Initial \$			**a
Maintenance \$			**
Frequency of use			**
Load distance			**
Material volume			**b

a

Adaptable to existing facilities [7]

b

Up to 10 tons are common [10]

An automated guided vehicle (AGV) is a computer-controlled vehicle that moves along a predetermined path and performs certain duties, according to instructions sent by a system operator located at a station. Barret Electric introduced the first AGV (“driverless tractor”) in 1953. Figure 7.29 illustrates a heavy-load AGV and Table 7.25 summarizes relevant remarks related to purchase cost, maintenance cost, frequency of use, load moving distance, and volume of material.

The AGV was originally designed as a towing tractor that followed a guide wire and was used primarily in warehouses. AGVs were introduced into the United States from Europe in the mid-1970s and were used almost exclusively to interface with automated storage and retrieval systems (discussed in Chap. 9). The early AGVs were designed to follow a wire embedded in the floor as guidance and were able to make only the simplest routing decisions. This wire path option was the only viable one until the early 1980s. Two general categories of guidance systems have evolved since then: (1) guide paths such as reflective tape, which are easy to apply and modify and (2) dead reckoning along with reference markers, such as magnets embedded in the floor, rather than a path. These new technologies allow installation of AGV systems in areas where buried wire would have been impractical or impossible. AGV systems have typically been used to move large, heavy loads.

Traditional applications of AGV systems have primarily involved moving pallet loads throughout distribution warehouses and highly automated manufacturing facilities, especially in the automotive industry. These have been followed by applications using smaller AGV systems in light manufacturing and assembly facilities (delivering raw materials, totes, and work-in-process), as well as in office and other industrial applications (moving items as diverse as mail, laundry, and hospital meals). AGVs have moved from the largest companies to smaller companies in simple, but effective, applications. The benefits of AGV systems are flexibility, space utilization, safety, and overall operating cost.

7.6 Decision Support System for Material Handling Equipment Selection

This section presents the design and illustrates the use of a decision-support system (DSS) for determining the material handling equipment for the factory design project. The DSS was developed and computerized by B. Velapula [11] as a VB program named DSS-MHE and is available on the website of the textbook. This section consists of the following components:

- Architecture of the application
- Developing the knowledge base
- Developing the decision-support system
- Developing inference chains
- Advantages of the DSS
- Two-step approach
- Limitations of existing expert systems
- Decision-support system for material handling equipment selection (DSS-MHE)

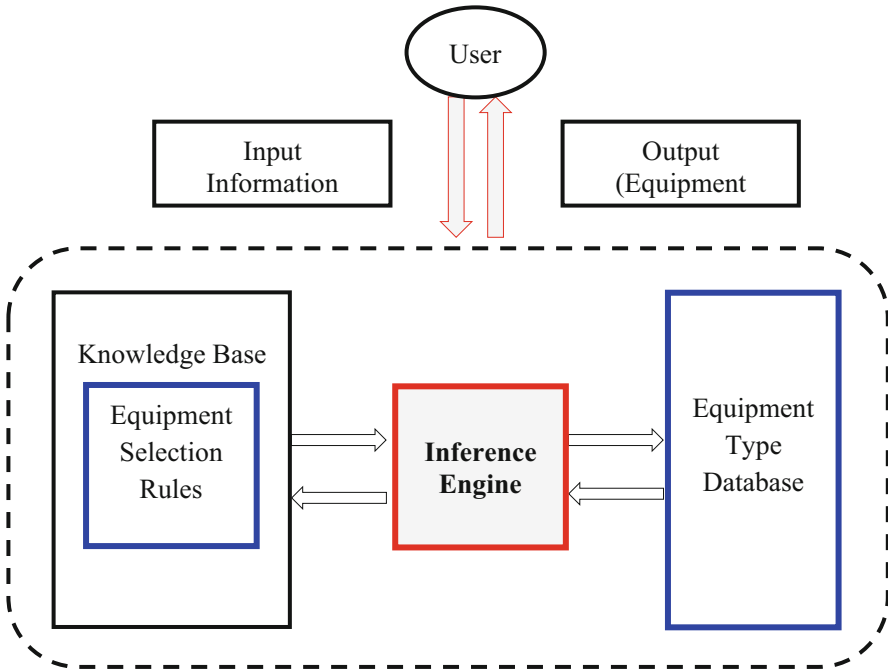


Fig. 7.30 Architecture of DSS

7.6.1 *Architecture of the Application*

The architecture of the application is shown in Fig. 7.30 [11]. The application is coded in Visual Basic, Version 6.0. It is comprised of numerous forms and modules. It is also readily interfaceable with other commonly used tools such as Excel and Access.

7.6.2 *Developing the Knowledge Base*

The first stage in creating a knowledge base is to study and understand the particular application. In confining attention to the three basic material handling types, the categories of containers and supports and of “auxiliary equipment” have been omitted; otherwise, the knowledge base would have become excessively large.

The knowledge base in the DSS consists of equipment information compiled from published literature. A survey of the literature on the selection guidelines for material handling equipment identified three equipment categories: (1) conveyors, (2) industrial trucks, and (3) cranes and hoists, as the major types used for present-day material handling. All the pertinent attributes of the equipment types were

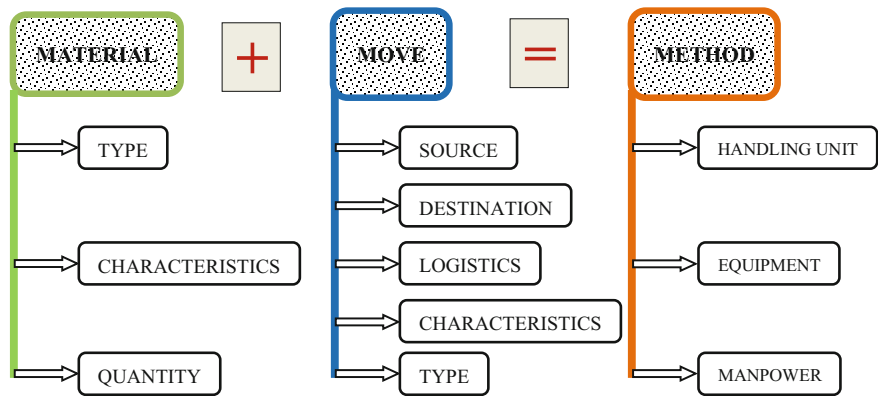


Fig. 7.31 Material handling equation

identified and included in the knowledge base, with the aim of supporting the selection of a suitable equipment type for a given material handling system. These attributes were subsequently classified as (1) the MOVE attribute, or (2) the characteristic of the MATERIAL to be handled. In general, making an appropriate choice for a given material handling problem involves extensive matching of the attributes of MOVE, MATERIAL with the capabilities of equipment. Figure 7.31 [11] shows the main factors that need to be considered to design material handling methods.

7.6.3 Developing the Decision-Support System

Given an equipment selection problem, the DSS generally asks a series of questions and progressively works toward the selection of a particular equipment type. For example, a material handling task could have the following characteristics: (1) the function type is move; (2) the move type involves movement between specific points over a fixed path; and (3) the floor space is available. A possible line of reasoning could be as follows. Since the function type is MOVE, the MOVE type is conveying, and since the floor space is available, then the equipment category could be a conveyor. Additional requirements such as the move direction, the material nature, the need of flow control, and the material weight could narrow the choice to a specific equipment type. The decision or *inference chain* in the decision support system thus involves a directed line of reasoning that uses the attribute information to progressively reduce the search space for equipment alternatives.

The next step in DSS development was the incorporation of expert guidelines from published literature. These are represented as selection rules, written in terms of the attributes and values identified in Table 7.26. Starting from a set of facts and progressively inferring a conclusion is referred to as *forward chaining*. Inference chains were developed for typical equipment types. Several problems appeared in

Table 7.26 Attributes and values for determining basic material handling type

Attribute	Conveyors	Trucks	Cranes/Hoists
MOVE TYPE			
Transportation			
Loading/Unloading			
Lifting			
MATERIAL SIZE			
Uniform			
Nonuniform			
Unit load			
FREQUENCY OF MOVEMENT			
Regular/Continuous			
Irregular			
Intermittent			
MATERIAL PATH			
Fixed			
Variable			

the development of the inference chains: (1) determining the attributes that should be considered, (2) determining the sequence in which they should be considered, and (3) determining the equipment options suitable for a set of attributes. In general, not all the attributes are relevant for all the equipment categories under consideration. Even for a particular equipment category such as conveyors, not all the attributes may be required to arrive at a recommendation of a particular equipment type; a single attribute may sometimes suffice.

7.6.4 Developing Inference Chains

The following approaches were used for developing the inference chains:

1. The set of attributes that are important for each equipment type was identified.
2. A value or set of values appropriate to an equipment type was identified.
3. Lines of reasoning were identified to determine the sequence in which attributes should be considered in order to reduce the number of equipment options.

7.6.5 Advantages of DSS

The approach for inference-chain development has two advantages. First, each recommendation requires consideration of a limited set of attributes. Second, the attributes in the inference chain are always pertinent to the equipment category being considered by the system. For instance, if an initial rule infers that the equipment category is conveyors, subsequent questions will be focused only on those attributes which are important to conveyors.

7.6.6 Two-Step Approach

The DSS system processes two major stages. Stage I includes the selection of material handling equipment type. Stage II focuses on the selection of the most favorable equipment, using a decision-support software application.

Stage I: The first stage involves the user input values for the attributes Move Function, Material Size, Material Frequency, and Material Path. Weights are assigned to the basic equipment types listed in Table 7.26.

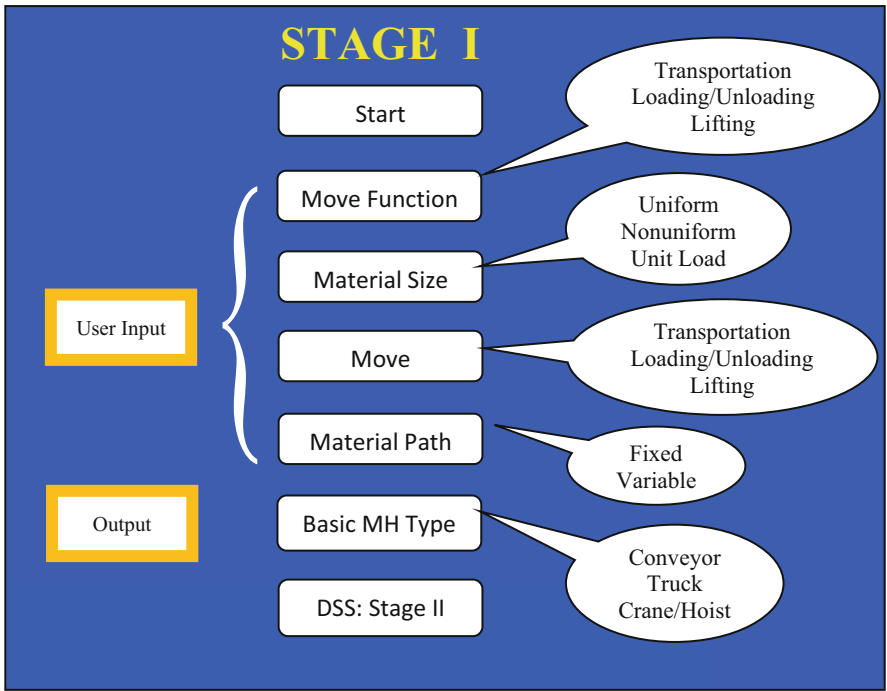


Fig. 7.32 Determination of basic material handling type

The flowchart for Stage I is given in Fig. 7.32. The output is the basic material equipment type to be used, either conveyor, truck, or crane.

Stage II: Depending on the output of the basic material handling type in Stage I, we proceed with the inference chain of that particular type. Figure 7.32 shows the inference chains used in the development of this decision-support system.

7.6.7 Limitations of Existing Expert Systems

Existing expert systems for selection of material handling equipment have several limitations. Most of them are incomplete prototypes that consider only a limited number of equipment types and attributes. Also, they lack flexibility in dealing with selection criteria such as economic and strategic attributes. Different companies might assign different weights to different criteria; however, none of these systems provides the means for users to select their own weightings.

7.7 DSS-MHE Program

This VB computerized system was developed by B. Velapula [11]. It provides the user with a comprehensive approach to the material handling equipment selection process. Fewer user inputs and easy guidance through the process are very important features of the handling system. Additionally, a picture database is coupled with the back end of the software to provide the user with a real-time view of the handling equipment. The executable file for this program is named **DSS-MHE-UTK.EXE** and it is available through the website link for the book. A sample run of this program is illustrated in Fig. 7.38 at the end of this subsection.

7.7.1 Flow of the Application

This decision-support system application has two stages.

DSS Stage I: As illustrated in Fig. 7.32, Stage I starts off by seeking a move decision input from the user in a (Move decision form). The user can choose one of three options for the move function—Transportation, Loading/Unloading, or lifting. (If there is no input, then the form will prompt the user for one.)

The form appearing next (Material Size decision) asks the user to specify whether the material size is Uniform, Nonuniform, or Unit Load.

The third step in Stage I is the Move Frequency decision. The user chooses whether the move frequency is Irregular, Regular/Continuous, or Intermittent.

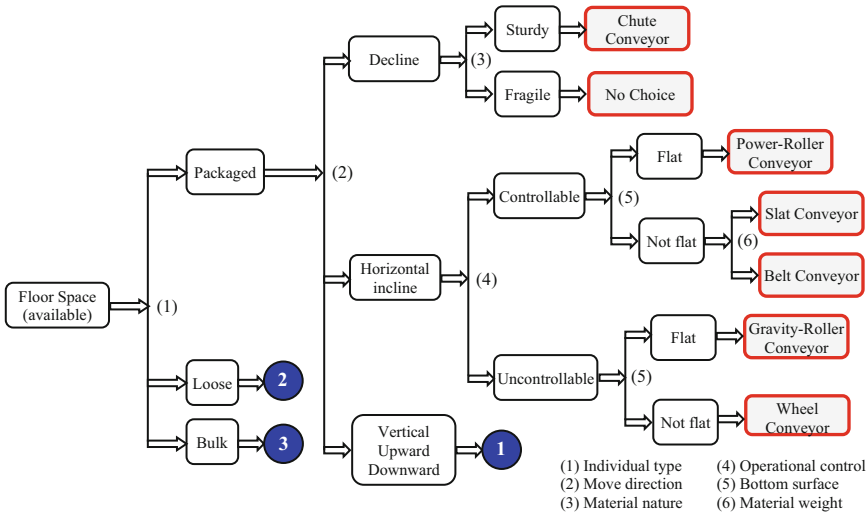


Fig. 7.33 Inference chain for conveyors (available floor space)

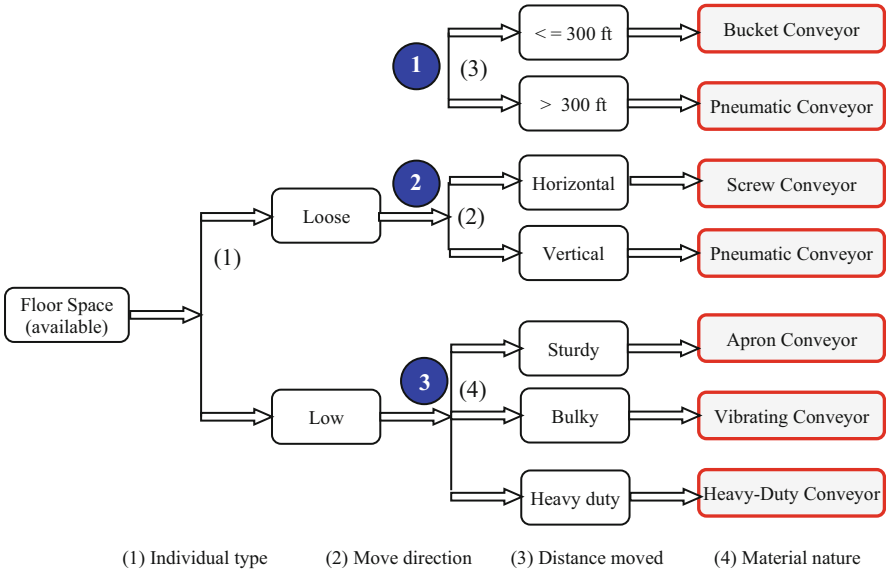


Fig. 7.34 Inference chain for conveyors (available floor space)

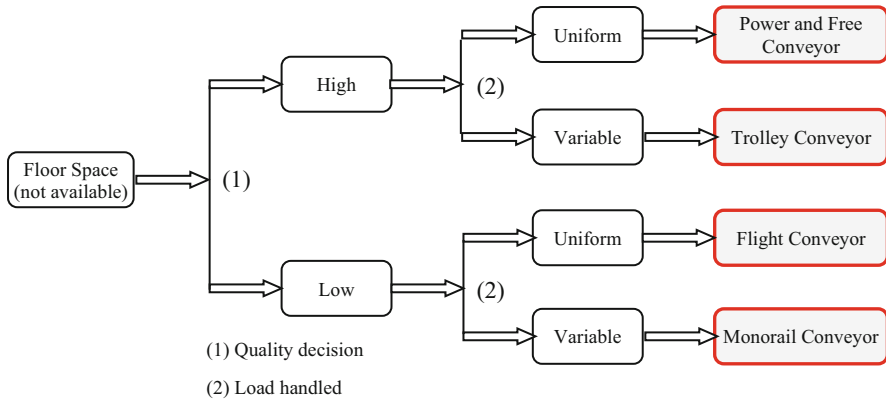


Fig. 7.35 Inference chain for conveyors (floor space not available)

The next form (Material Path) asks the user whether the material path is Fixed or Variable.

This is the end of Stage I. On verifying the information and submitting the form, the user can see what equipment is best suited for the stated requirements. It can be conveyors, trucks, or cranes.

DSS Stage II for Conveyors: After the basic material handling equipment type has been determined, the DSS application follows an inference chain for that type. If the Stage I result is conveyors, the application flows as shown in Figs. 7.33 and 7.34 [4, 11].

Conveyor Stage II starts off by seeking input from the user in a Floor Space decision form. The user can choose one of two options—namely, whether there is floor space or not. (If there is no input, then the form will prompt the user for one.)

If user selects “yes” for floor space available, a Conveyor Equipment decision form appears. The user chooses individual material type as Packaged, Loose, or Bulk, and chooses Move direction as Decline, Horizontal, or Vertical.

If user selects “Packaged” and “Decline,” the Material Nature form appears next. The user can choose either Sturdy or Fragile.

If user selects “Packaged” and “Horizontal” in the Conveyor Equipment decision form, another Equipment decision form appears. The form elicits information about Operational Control and Bottom Surface. If user selects “Controllable” and “Not flat,” the Material Weight form appears. The user can either choose Material Weight either ≥ 100 kg or < 100 kg.

If user selects “Packaged” and “Vertical” in the Conveyor Equipment decision form, the Distance decision form appears. The user can choose either under 300 feet or over 300 feet.

If the user selects “No” to floor space available in the first form of conveyor Stage II, the Material Direction and Material Nature form appears. The inference chain for conveyor selection is shown in Fig. 7.35 [4, 11].

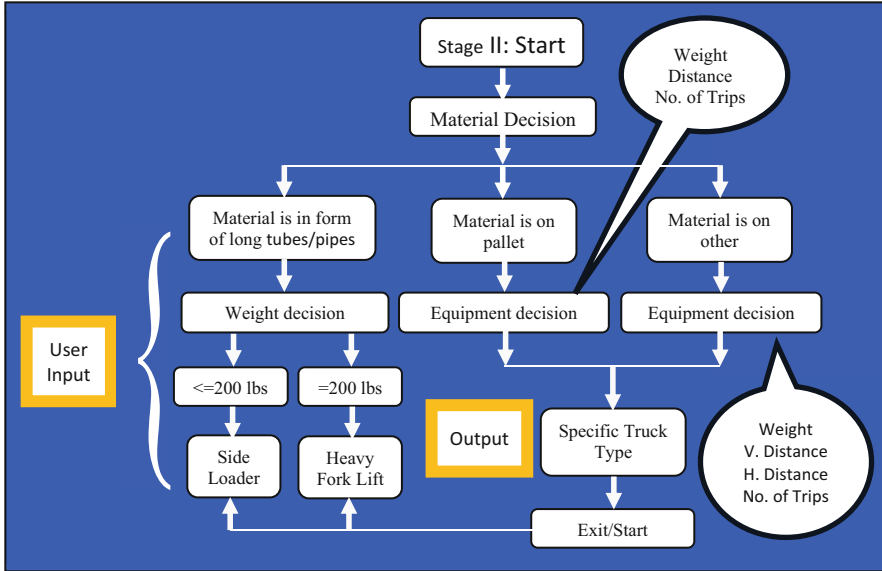


Fig. 7.36 Inference chain for trucks

DSS Stage II for Trucks: If the Stage I result is trucks, the application will flow as indicated in Fig. 7.36. Truck Stage II starts off by seeking move decision inputs from the user in a Material decision form. The user chooses whether the material to be transferred is in the form of long tubes or in pallets, or otherwise. Once this choice is made, the user is directed to the specified form.

Long Tubes: The long-tubes equipment decision has two options: whether the weight to be transported is less than 200 lb or greater than 200 lb. The result follows.

Pallets: If pallets are involved, distance and trip decisions are to be made. The user has to select one from each of three option categories to proceed to verify results in the next form and then see what equipment is best suited for his/her requirements.

Other: The “Other” form has options like those for pallets, except that the number of trips changes based on the weight of the material to be carried, as shown in the form.

DSS Stage II for Cranes: If the Stage I result is cranes, the application will flow as indicated in Fig. 7.37. Cranes Stage II starts off by seeking inputs from the user in an Equipment decision form. If pallets are involved, there are distance and trip decisions to be made. The user has to select one from each of the three options categories to move to the next form.

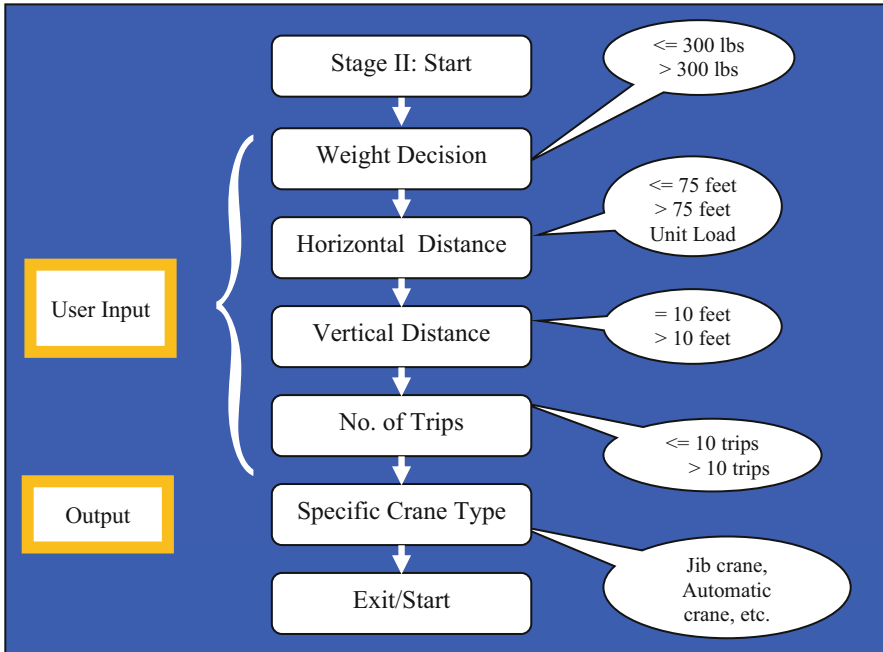


Fig. 7.37 Inference chain for cranes

The second Equipment decision form has two options: whether the Quantity is low or high, and whether the Load handled is uniform or variable. Making these choices leads to the result.

7.7.2 Sample Run of DSS-MHE-UTK.EXE Program

A complete run of the program generates ten computer screens, as illustrated in Fig. 7.38.

7.7.3 Final Synthesis

The DSS application has been successfully developed, tested, and validated for students' use. It easily integrates with any manufacturing DSS tool for layout design. It was created to be user friendly, helpful, and flexible, keeping in mind that its main users are students, whose primary aim is to get a first-hand feel for a professional tool, which they might be encountering in their jobs outside school.

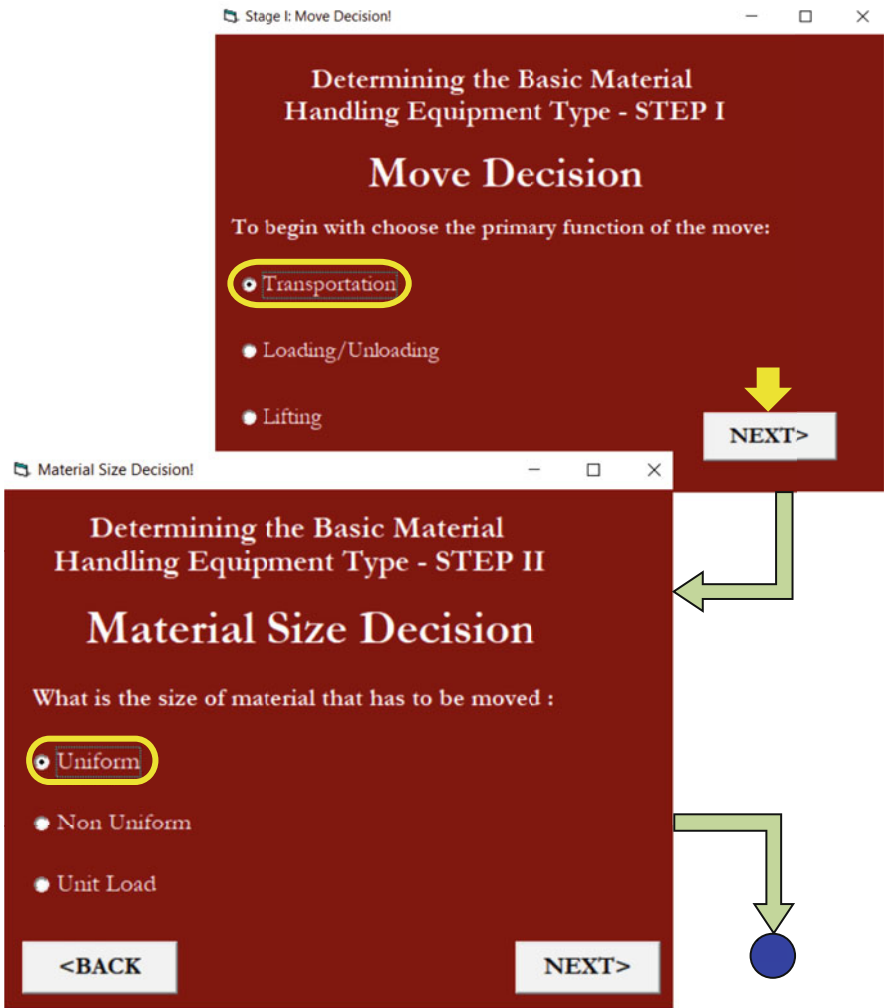


Fig. 7.38 Sample run of DSS-MHE-UTK.EXE

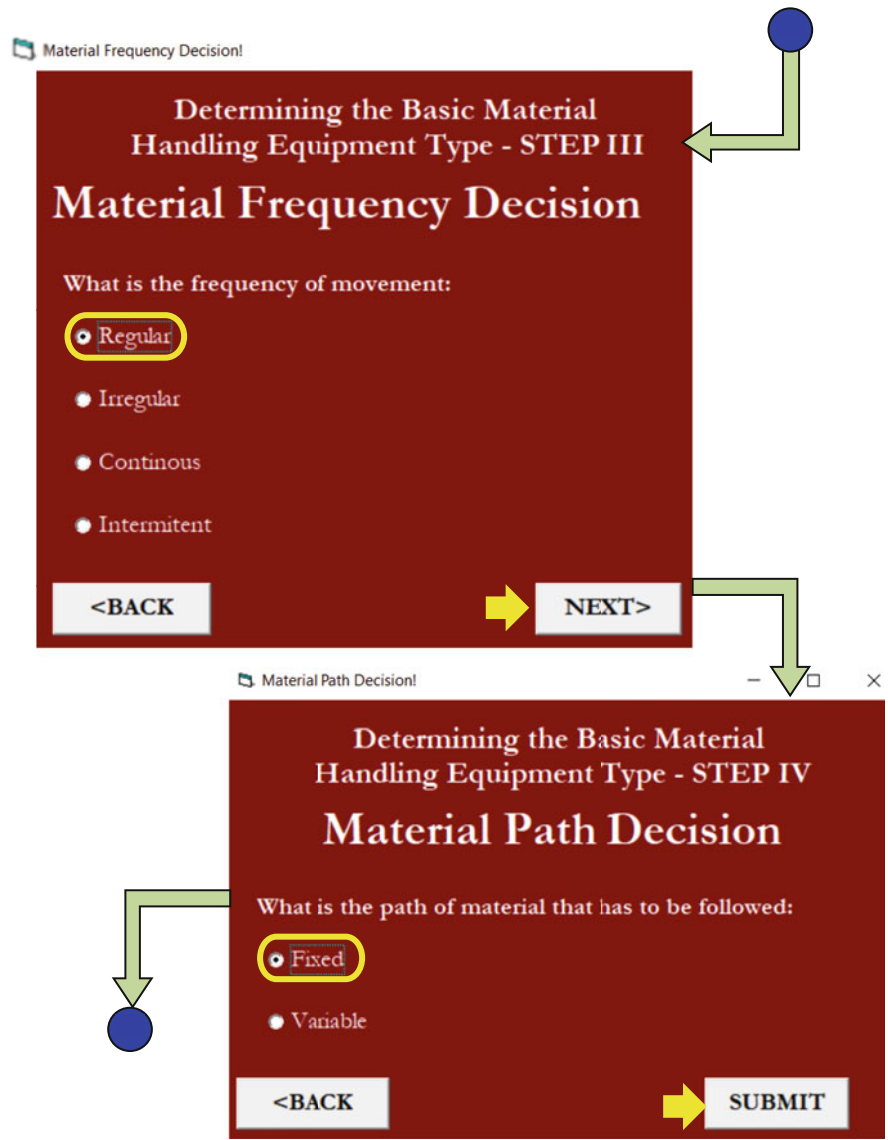


Fig. 7.38 (continued)

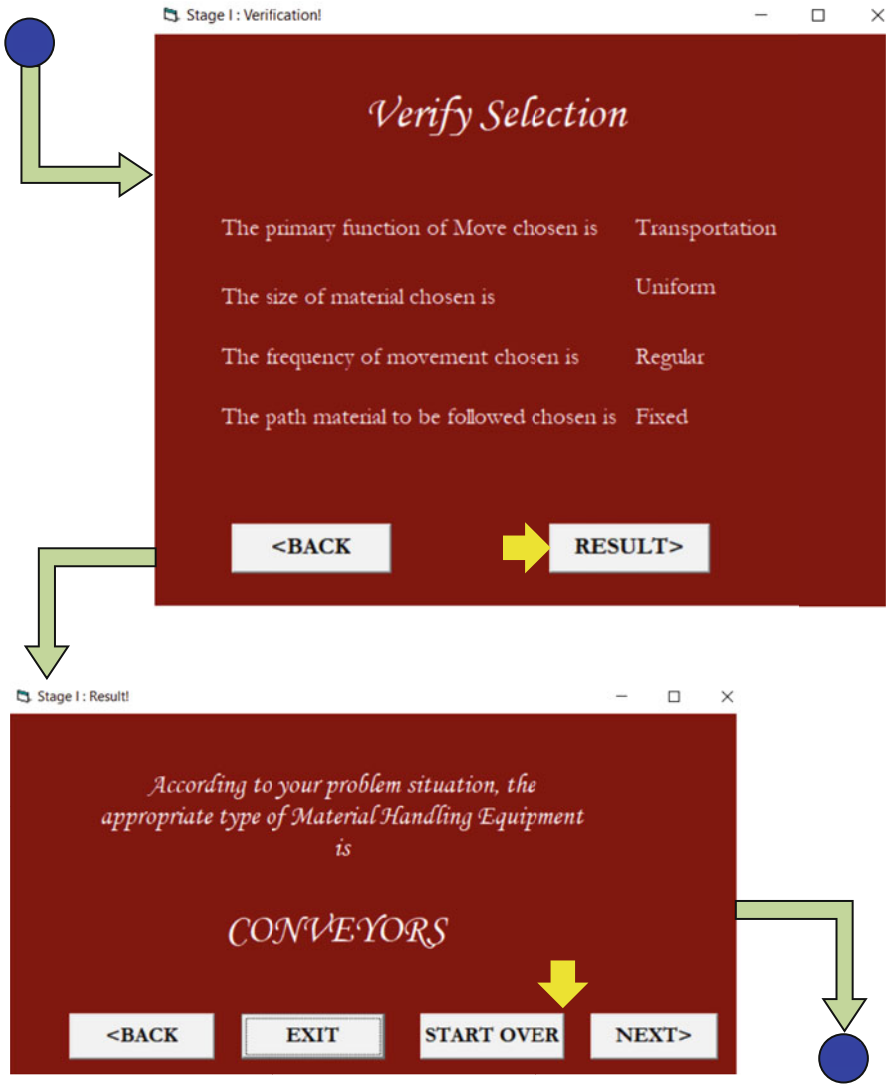


Fig. 7.38 (continued)

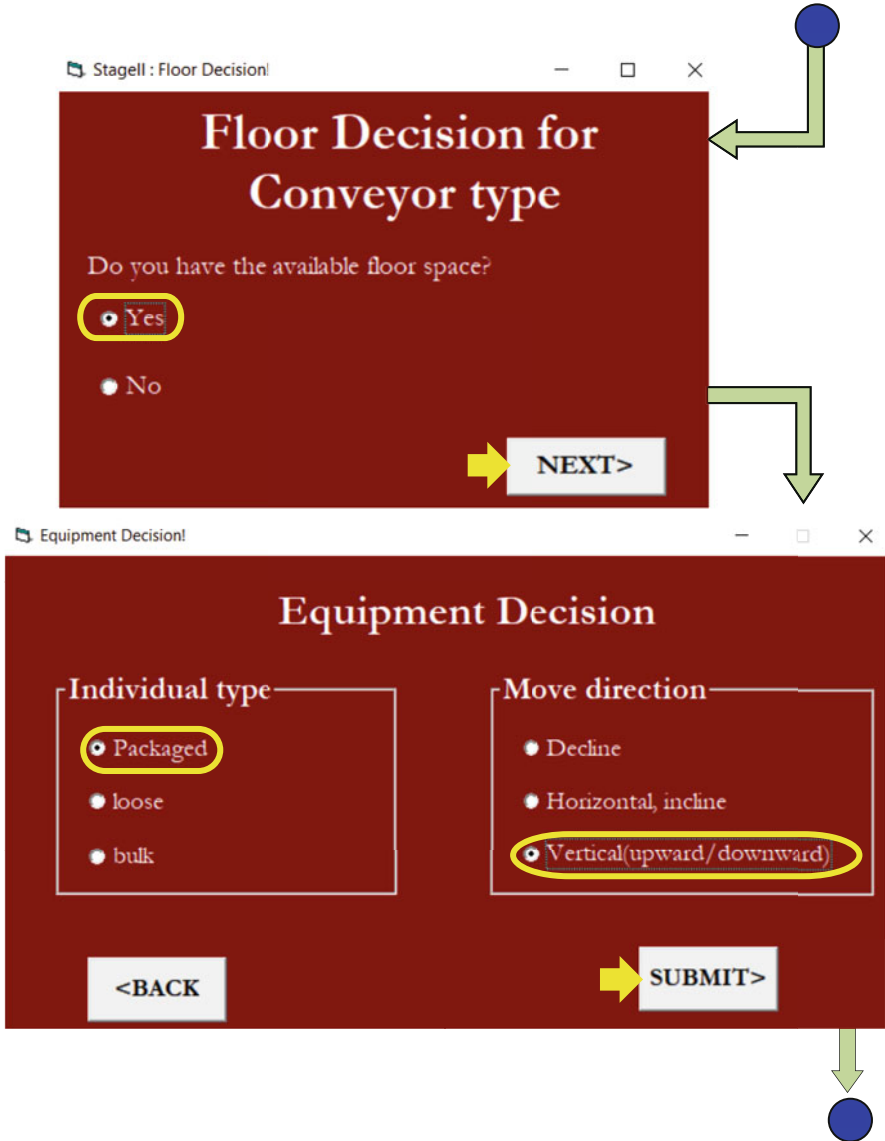


Fig. 7.38 (continued)

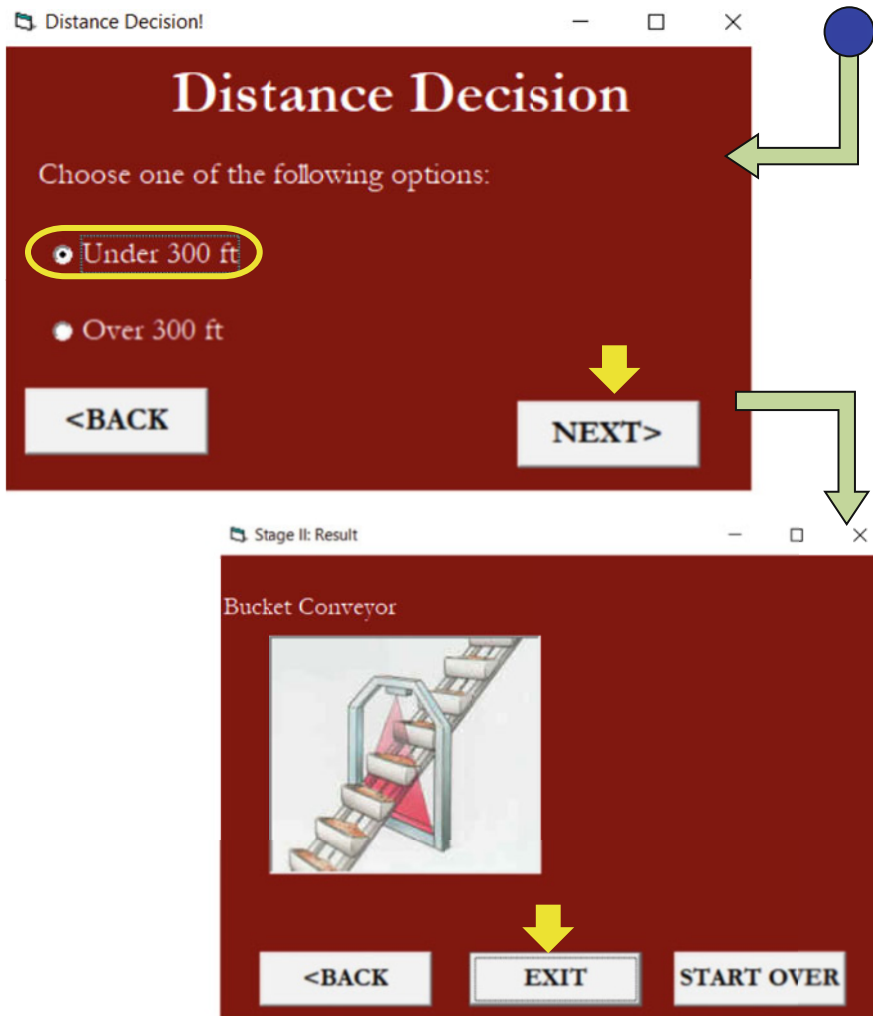


Fig. 7.38 (continued)

As a prototype test, the tool was evaluated by many students. With their input as a base, many improvements have been made to the original software and a lot of help features added. The decision-support system has passed some of the rigorous tests performed by students and faculty. More features and additional design changes can always be included in the main software, because of its basic design and suppleness.

7.8 Material Handling Requirements and Costs

To determine material handling requirements and costs initial undertaking is to design a plant layout on which the material handling system will perform as a facilitator of the manufacturing activities. Brown et al. [3] developed the factory project for the revolving desktop organizer. Their proposed initial layout for the factory manufacturing this product was designed using CRAFT. This section summarizes their work on this particular component of the overall factory design project.

The first step was to input the desired size for the entire factory. This was based upon the size of the individual departments and includes assumed dimensions for storage and raw materials, as well as inspection and final assembly. The areas needed for the 14 departments are as shown in Table 7.27. The total area requirement is 7341 ft². A rectangular factory floor of dimensions 80' × 100' was selected for the factory layout.

The dimensions for the raw materials were created to include at least a half-week supply of wood and an extra 250 ft² to allow movement of the forklift. Room for receiving was also included. The storage department was created on the opposite side of the factory and likewise includes room for shipping. The storage department was given enough capacity to hold 10 days' worth of products.

The from-to chart for the revolving desktop organizer is shown in Table 7.28. The entries of the table correspond to number of trips per day. Aside from the department areas, the from-to chart was input into the CRAFT program in order to construct a proper layout based on the flow relationships between departments. The measure of effectiveness used was defined as the total material handling distance traveled.

The output from CRAFT is shown in Fig. 7.39. The labels 1, 2, . . . , 14 correspond to the department names shown in Table 7.27, which provides departmental areas. The area of each department is represented in this figure as an aggregate of 2' by 2'

Table 7.27 Departmental areas

Departments	Number of workstations	Area (ft ²)
1. Raw material	1	1000
2. Table saw	6	780
3. Radial saw	3	240
4. Drilling	13	1170
5. Wood shaping	7	665
6. Portable routing	5	540
7. Sanding	1	68
8. Spraying	1	100
9. Drying	1	635.5
10. Injection molding	1	266.5
11. Subassembly	1	480
12. Final assembly	1	546
13. Inspection	1	50
14. Storage	1	800

Table 7.28 From-to chart

From/To	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Raw material (RM)		102	6						6					
2. Table saw (TS)			30	36	36									
3. Radial saw (RS)				18			30							
4. Drilling (DR)					24		42			6				
5. Wood shaper (WS)			18			42		10						
6. Portable router (PR)				12			30							
7. Sander (SA)								78			24			
8. Sprayer (SP)									88					
9. Dryer											78		10	
10. Injection molding (IM)											6			
11. Subassembly (SA)					10							40		
12. Final assembly (FA)														12
13. Inspection (IN)												10		
14. Storage (ST)														

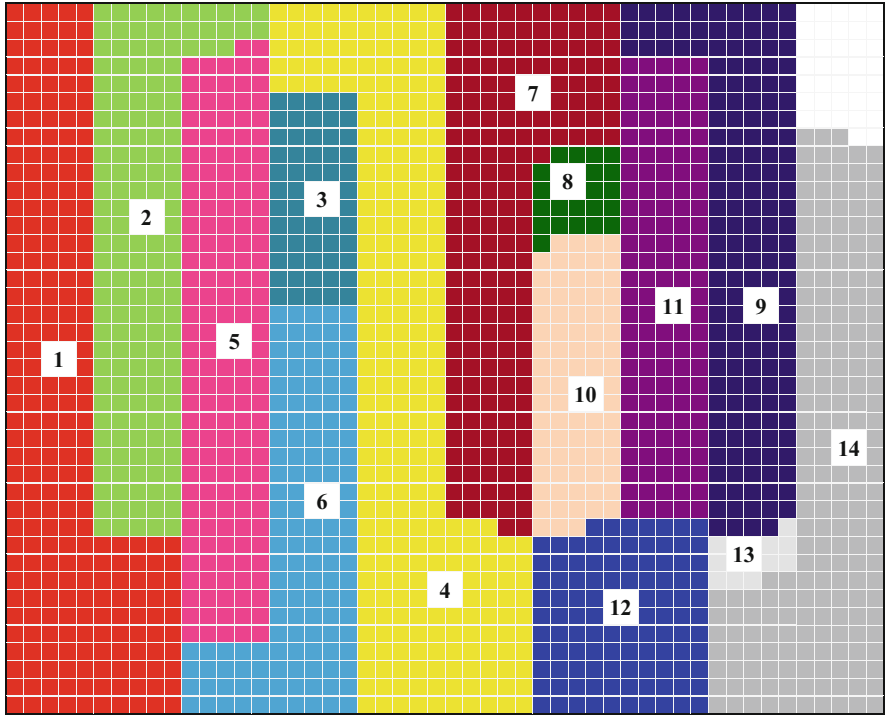


Fig. 7.39 CRAFT initial layout

cells. Note that this is an initial layout, which can be modified to transform it the final layout to be developed in Section VI of the factory design project (Section VI will be covered in Chap. 12).

In this part of the factory design project the following information was determined: (a) material handling equipment type, (b) material handling equipment quantity, (c) material handling equipment cost.

The basic material selected for the parts of the revolving desktop organizer is birch. Its light weight allows large quantities to be moved in batches having total moderate weight. Weight does become a factor when bulk supplies of wood are moved. These supplies are received on pallets and can be heavy. After considering the variation of routes within the factory, the moderate distances of the moves, and the presence of cross-traffic paths, several methods of transportation were studied. The analysis indicated that the use of industrial trucks was the most appropriate strategy, taking into consideration both the effectiveness and the cost of the material handling operations. Several types of industrial trucks were considered, and finally it was recommended to select hand carts and forklifts.

After each type of equipment was chosen, the next step was the determination of the number of pieces of equipment needed. The first operation is the movement of raw material onto the factory floor. For this operation it was decided to use one electric forklift. To arrive at this result, it was verified that the sum of all machine fractions documented on the layout planning was less than one and that no more than one move was required at a time. A forklift was purchased from Yale Products at a cost of \$11,000.

Afterward, it was decided to move materials within the factory using push carts. Using a standard size of push carts for all operations in the factory offered several advantages. Naturally, a cart has to be as large as a batch of the largest part transported, which in this project is subassembly SA1. The volume of this subassembly is $4.35 \times 3.95 \times 5.75 = 98.80 \text{ in}^3$. With 125 SA1 subassemblies being transported in the cart at a time, the total volume required for a batch is $98.80 \times 125 = 12,350 \text{ in}^3$. This calculation was adjusted to account for air space and other irregularities that may occur when filling the cart. An adjustment of 10% was made, resulting in a total requirement per batch equal to $13,585 \text{ in}^3$. A cart of this capacity will transport the largest batch of material and be more than enough to transport the smaller parts. Carts are being purchased from Merlin Industrial Co. These carts have a capacity of $15,561 \text{ in}^3$ and can be purchased for \$150 per cart.

In determining the number of carts needed, it was assumed that at least two carts were required at each workstation, one for incoming and another one for outgoing material. Furthermore, the analysis of requirements for the drying oven (which is the longest operation in the plant) and the sprayer indicated that two carts were needed for each. The spraying and drying operations are performed using a combination coater and conveyor oven. All relevant manufacturing operations were considered to determine the material handling requirement generated by each one. After the required number of carts for each different operation was established, an adjustment was necessary to account for factors not directly considered in the analysis, such as breakdowns, maintenance, and unexpected needs. Table 7.29 consolidates all

Table 7.29 Push cart requirements

Machine description	Number of machines required	Carts/Machine	Total number required
Table saw	6	2	12
Radial saw	3	2	6
Drilling	13	2	26
Portable router	5	2	10
Wood shaper	7	2	14
Sprayer	1	2	2
Drying oven	1	2	2
Injection molding	1	2	2
Sanding	9	2	18

requirements. Assuming an additional number of eight carts, the total number required is 100.

To determine the total material handling cost, shipping and installation costs were added to the equipment cost. For the industrial push carts, a \$10 shipping cost per unit was assumed. Furthermore, for the electric rider lift truck the shipping cost was assumed to be \$500, and the installation cost \$1000. The equipment cost is equal to \$27,500. Assuming a salvage value of 10% and a service life of 10 years, the straight-line depreciation method will result in a material handling cost of \$2475 per year [3].

7.9 Factory Design Project: Section III. Layout Planning and Material Handling

The purpose of this section is to generate an initial factory layout and choose appropriate cost-effective material handling equipment to facilitate the overall manufacturing operation. The question to be answered is, how are parts and materials to be moved efficiently within the plant? This section provides an answer by way of a six-stage process, each stage having a specific objective, as outlined below:

1. Develop layout planning charts.
2. Identify material handling requirements.
3. Determine material handling costs.
4. Propose an initial layout.
5. Show sample calculations.
6. Report organization.

A brief description of each stage follows.

7.9.1 Layout Planning Chart

The format of the layout planning chart used in the factory design project was introduced in Chap. 3. The following information must be documented on each chart:

- (a) Chart heading
- (b) Flow process, including operations, transportation, storage, and inspection
- (c) Standard time for each operation (fabrication)
- (d) Machine types and requirements
- (e) Manpower types and requirements
- (f) Material types and requirements
- (g) Material handling equipment and costs
- (h) The flow process is documented by means of “moves” of individual parts (elements). The letters F, M, S, and I will be used to indicate the operations listed below:

F Fabrication
M Movement
S Storage
I Inspection

For each M the layout planning chart must document the following information:

- 1. Frequency or number of moves per part
- 2. Origin and destination of each move
- 3. Quantity being moved
- 4. Time per move

7.9.2 Material Handling Requirements

Each team must determine adequate answers to some general questions on the material handling activity, as well as some equipment-related questions. Typical general questions are formulated in (a), (b), and (c) in the list below, while typical equipment-related questions are formulated in (d) through (h). Several alternative answers are shown for (a) through (c); the team should consider these and decide which ones are most appropriate. The decision-support methodology for material handling equipment and costs will be extensively used in the development of this section of the factory design project.

- (a) How are the materials going to be moved? For each move indicate the distance. Also, provide any special remarks that will be useful. Relevant aspects to be considered are related to the following items:
 - 1. Manually
 - 2. Forklift

3. Truck
 4. Crane
 5. Conveyor
 6. Tow line
 7. Distance moved
 8. Special remarks
- (b) What type of containers will be used?
1. Pallets
 2. Tote boxes
- (c) What is the unit load size?
1. Total number of units of product
 2. Number of units per load
 3. Number of loads per pallet or per box
- (d) What types of material handling equipment will be chosen for the project?
- (e) What are the specific models of the pieces of equipment selected?
- (f) What is the size (what are the dimensions) of each piece of equipment?
- (g) What is the capability of each selected piece of equipment?
- (h) How many units of each type of equipment will be needed?

7.9.3 Material Handling Costs

In this section the following specific elements associated with the project must be determined:

- (a) Cost of each type of equipment.
- (b) Installation cost per unit.
- (c) Total cost per year (depreciation analysis using 10-year service life).
- (d) The total cost can be divided by the total number of product units per year to determine product cost in \$/unit.
- (e) Document results in the table of material handling requirements and costs.

7.9.4 Guidelines for Proposed Initial Layout

- (a) Use a computerized procedure such as CRAFT, FLAP, MAFLAD, or STEP.
- (b) Show major types of material handling paths (indicating type of equipment used).
- (c) The idea in this section is to focus on the big picture more than on details. Emphasis is on location of planning departments and material handling.

7.9.5 Sample Calculations

For convenience, this subsection shows again an illustrative example previously considered in Chap. 2 to illustrate the calculation of material handling cost per unit of product. Some details of the calculation are:

- (a) Equipment type: Tow line

Required: 900 feet

Cost per foot: \$210

Installation cost per foot: \$84 (assuming 40% of purchase cost)

- (b) Total cost = $$(900 \times 210) + (900 \times 84) = $(189,000 + 75,600) = $264,600$

Salvage value = $0.10 ($900 \times 210) = $18,900$ (installation cost was not considered)

Service life = 10 years

Annual cost = $$(264,600 - 18,900)/10 = $24,570$

- (c) Total cost for all equipment (including installation) = \$1,130,460

Total salvage value for all equipment = \$80,747

Material handling annual cost = $$(1,130,460 - $80,747)/10 = $104,971$

- (d) Production volume = 5000 units per week

Material handling cost per unit of product is equal to the annual cost divided by the number of units per year, $\$104,971/(52 \times 5000) = \0.40 per unit

7.9.6 Report Organization

The following organization is suggested for the final report. Figure 7.40 shows the checklist that will be used to grade the report documenting all the team's activities in Section III of the factory design project.

- (a) Introduction

1. Background
2. Scope
3. Organization of report

- (b) Layout Planning Charts

1. Introduction
2. Charts (with brief discussion of each)

Group No _____	Product Description	Grade _____	Date _____
Names 1. 2. 3. 4.			
Organization and style [10]			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Introduction of report is lacking ☐ Technical English style can be improved ☐ Organization can be improved			
Layout Planning Charts [10]			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Missing information ☐ Description of charts should be more effectively done ☐ Calculations of distance moved are incorrect ☐ Operation descriptions are inadequate ☐ Sheets are not complete (at least 3 per student)			
Material Handling Requirement and Cost [10]			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Equipment choice can be more specific ☐ Unrealistic costs ☐ Annual cost analysis is not documented ☐ Appendix showing sample calculation is not included			
Proposed Initial Layout [10]			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ From-to chart is not included ☐ Computer output (from CRAFT, FLAP, MAFLAD, or STEP) not included ☐ Neatness of drawings can be enhanced ☐ Lacking or insufficient discussion of proposed layout			
Comments			

Fig. 7.40 Checklist for Section III**(c) Proposed Initial Layout**

1. Introduction
2. Alternative solutions (one per student) using a computerized procedure (CRAFT, FLAP, MAFLAD, or STEP)
3. Discussion of alternatives and selection of layout
4. Sketch of layout (emphasis on material handling) and discussion

(d) Material Handling Requirements

1. Introduction
2. Equipment needed

(e) Material Handling Costs

1. Introduction
2. Table (with brief discussion)

(f) Summary, Conclusions, and Recommendations

(g) Appendix showing sample calculations

Group No _____	Product Description	Grade _____	Date _____
Names			
1.			
2.			
3.			
4.			
Organization and Style [10]			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Introduction of report is lacking ☐ Technical English style can be improved ☐ Organization can be improved			
Layout Planning Charts [10]			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Missing information ☐ Description of charts should be more effectively done ☐ Calculations of distance moved are incorrect ☐ Operation descriptions are inadequate ☐ Sheets are not complete (at least 3 per student)			
Material Handling Requirement and Cost [10]			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Equipment choice can be more specific ☐ Unrealistic costs ☐ Annual cost analysis is not documented ☐ Appendix showing sample calculation is not included			
Proposed Initial Layout [10]			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ From-to chart is not included ☐ Computer output (from CRAFT, FLAP, MAFLAD, or STEP) not included ☐ Neatness of drawings can be enhanced ☐ Lacking or insufficient discussion of proposed layout			
Comments			

7.10 Summary and Conclusions

Material handling design and analysis is a key integration concept in the facility planning process. This chapter has presented an overview of basic definitions and fundamental principles of material handling that provide a foundation for designing,

improving and examining factory layouts. The major types of equipment were classified as conveyors, hoists/cranes, industrial trucks, and a diversity of accessories, highlighting their advantages and limitations, along with typical applications of each piece of equipment. A decision-support methodology and accompanying VB code for selecting material handling equipment were described in detail and illustrated with computer shots for a typical run of the program. This decision support system is available from the website and is a very useful tool for aiding the design of the MHS in the factory project. As previously done for Sections I and II of the factory design project, the scope of Section III was defined and illustrated using the revolving desktop organizer factory design project [3].

7.11 Exercises

- 7.1 What are the three basic categories of material handling systems? Give examples in each category. Create a table of advantages and disadvantages for each type of system, with at least three attributes for evaluation of each type of system.
- 7.2 What in your own words is a unit load? What factors influence the formulation of a unit load? Is the unit load concept appropriate in your factory design project?
- 7.3 Apple [2] suggests the following seven-step procedure to design a unit load:
 - (a) Determine whether the unit load concept is applicable.
 - (b) Select the unit load type (i.e., platform, sheet, rack, and container).
 - (c) Identify the most remote source of a potential unit load.
 - (d) Determine the farthest practical location/destination for the unit load.
 - (e) Establish the unit load size.
 - (f) Determine the unit load configuration.
 - (g) Determine how to build the unit load.

Use this procedure on your factory planning project.

- 7.4 There are seven products to be arranged on a 48" $\times$ 48" pallet.



Number of units	Product dimensions	Total area (sq ft)
2	2' $\times$ 2'	8
3	1' $\times$ 1'	3
1	1' $\times$ 3'	3
1	1' $\times$ 2'	2

Determine the best arrangement of products on the pallet, where the first two products need to be on the south side of the pallet for flow reasons and the three $1' \times 1'$ products should be adjacent to the first two products. Use GMAFLAD to help you find the optimal solution. Is there more than one optimal solution?

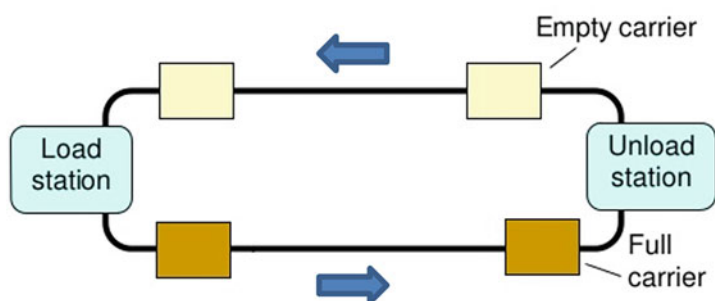
- 7.5 Give examples of applications of each of the eight principles of material handling as defined in this chapter.
- 7.6 Differentiate between the following material handling equipment items and give at least three advantages and disadvantages for each type.
 - Spiral chute vs. pneumatic conveyor
 - Belt conveyor vs. wheel conveyor
 - Roller conveyor vs. slat conveyor
 - Lift truck vs. overhead trolley conveyor
 - Hand truck vs. tractor-trailer train
 - Jib hoist vs. bridge crane
 - Automated guided vehicle vs. forklift truck
- 7.7 What factors should be considered in choosing the size of a pallet to be used in a factory setting?
- 7.8 Visit a local factory and describe the various material handling devices/systems that you observe. Use a digital camera to record the type of system and possibly include the pictures in your factory project report.
- 7.9 A warehouse uses forklifts to move pallets from receiving to shipping and back again. It takes a forklift around 1 minute to pick up and deposit a pallet and 6 minutes to travel from receiving to shipping and vice versa. The warehouse operates 5 days per week, 8 hours per day. At a minimum, the warehouse manager must be able to move 3000 pallets from receiving to shipping per week. Find the number of forklifts needed to meet the warehouse manager's pallet demand.
- 7.10 A factory produces 15,000 cellular phones per day. The dimensions of each cell phone are $5 \times 2.5 \times 2.5$ inches. Management wishes to have a 1-week (5-day) supply in stock. One hundred cell phones are packed in a carton, and cartons may be stacked seven high. Determine the floor space required in the warehouse to accommodate the 5-day supply of cell phones.
- 7.11 Use the DSS-MHE code to for three cases where the material handling equipment recommended is (a) a conveyor; (b) a crane; (c) a truck. Create appropriate inference chains for each case.
- 7.12 Modify the example in Fig. 7.37 to consider a case where the primary function of the move is to load or unload material. Design an appropriate inference chain for the case.

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Chapter 8

Material Handling Systems Analysis



8.1 Introduction

This chapter introduces the design, analysis, and integration of the flow of products and customers within a material handling system (MHS). Both deterministic and stochastic points of view are included. Quantitative models of material handling systems can be very complex, yet they are very desirable since the performance of the layout is dependent on the dynamic flow of products and customers within the layout system. Throughputs, bottlenecks, queues, utilization of machines, work-in-process (WIP), and overall congestion in the material handling system are important performance measures generated by the tools introduced in this chapter and available on the website.

8.1.1 Motivation

In most manufacturing and service systems, coupling the design of the layout with the dynamic flow of customers and products within the system in order to assess the performance of alternative layout designs is the most desirable property of a model. The fact that flow systems are dynamic (not static) and the interacting components are finite in number and size is crucial to the modeling problem.

It is important to know the dynamic performance of layout designs in order to assess the utilization of machines, utilization of the material handling system, congestion in these systems, potential bottlenecks, queues, and related performance measures, not the least of which is the work-in-process (WIP). How to accomplish this is the main focus of this chapter.

Three types of performance models are presented for analyzing material handling systems:

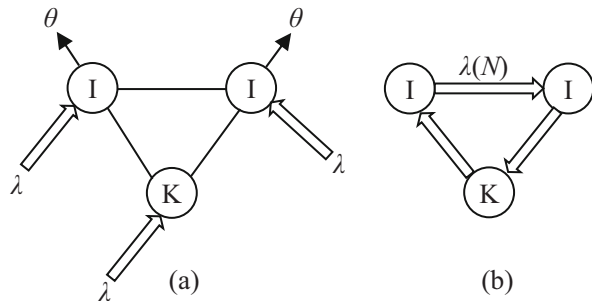
- Analytical open-system models
- Analytical closed-system models
- Discrete-event simulation models

In open-system models (Fig. 8.1), the products and commodities flowing through the material handling system enter the network at certain points, and then leave the network at others. Deterministic and stochastic models for open systems are possible. Deterministic models normally break up the time intervals of the planning horizon into discrete periods. This is an approximation to the continuous-time problem, but often a reasonable one. An open-system model based on a queuing network representation where time is continuous will be presented in this chapter.

In closed-system models, the products or commodities are finite and captured within the material handling system network. A deterministic model of a closed-loop conveyor and a closed queuing network model will be presented in this chapter.

A discrete-event (Monte Carlo) digital simulation model is a very general approach for modeling material handling systems. With this approach, both deterministic and stochastic simulation models are possible. Discrete-event simulation models generally are such that they can capture both closed and open systems. However, this generality comes at a price of computational complexity, statistical

Fig. 8.1 (a) Open system;
(b) closed system



analysis problems, and exceedingly long run times. Especially if one wants to use simulation as a design tool, then steady-state models are needed, and with simulation models, it is often very difficult to achieve steady-state conditions. A cellular layout case study is illustrated in this chapter with simulation in order to show the power and possible insights of simulation. Finally, a simulation model case study is included that effectively evaluates the lay-out and location of the warehouse and manufacturing components of a storage facility.

Certain deterministic models based on mixed integer programming seek to select the required type and quantity of manufacturing equipment as well as the MHS devices, the grouping of machines into cells, and the determination of the overall layout in a single model. Heragu [6] and Sule [20] provide a sample of models of this type. These models are very ambitious and are beyond our present scope. This is not to say that the models included in this chapter are trivial; however, we are not attempting here to create a single super model to solve everything at once.

8.1.2 Outline of Chapter

Section 8.2 describes the fundamental principles involved in the integration of material handling systems in the layout. A detailed example is included to help the reader understand the symbiotic relationship between the layout and the material handling or circulation system of a facility.

Section 8.3 provides an overview and describes the open queuing network for modeling the flow of traffic in open systems. It also includes a case study within which the queuing network tool was utilized.

Section 8.4 provides a brief introduction to the use of deterministic models for designing conveyors and also describes an analytical stochastic modeling approach based upon closed queuing networks. These closed queuing network models are very robust and appropriate for finite buffer material handling systems. The modeling approach is described in some detail along with the algorithms used to generate the performance measures. The optimization approach for optimizing these material handling and workstation design systems is included, and several examples demonstrate the computer package available with the book for carrying out the experiments.

Section 8.5 describes discrete-event digital simulation modeling and its importance for evaluating the integration of the layout design and the material handling system. Within this section, a case study of a cellular manufacturing system layout analysis and material handling system design is presented. The main focus here is to show the power and effectiveness of discrete-event simulation modeling rather than serve as a primer for simulation. Both the design of alternative layouts and the determination of the number of personnel necessary to work in a cellular manufacturing environment are examined.

Section 8.6 describes a case study of a simulation of a warehouse material handling system and how it affects the layout of the plant and the number of components in the plant. Section 8.7 concludes the chapter.

On the textbook website, open queuing network GQnet and closed queuing network model software Cnet are available. These tools are intended for the student's use in the factory project. In addition, video clips of the simulation models included in the textbook allow one to visualize the dynamic flow of materials and people through the facilities.

8.2 Integration of Layout and Material Handling System

This section describes the fundamental principles involved in the integration of the layout and material handling or circulation system of a facility. This is a challenging problem and one which makes facilities planning unique. While Chaps. 4, 5, and 6 describe the fundamentals of layout planning and Chap. 7 describes the components of material handling, this chapter integrates these concepts and gives the student some fundamental tools with which to analyze the integrated system.

8.2.1 Fundamental Integration Principles

The fundamental principles that comprise the integration of the facility layout and material handling system (MHS) are described through four distinct concepts. The key to the material handling analysis is to define the network topology of the MHS network; *then one can employ the analysis tools to model the flows in the layout.*

1. Tangential circulation flow network
 2. Circulation network polygon
 3. Steiner minimal tree network
 4. Circulation network flow analysis
1. **Tangential Circulation Flow Network:** The circulation or MHS flow network is tangential to the activities in the facility layout. Figures 8.2, 8.3, and 8.4 illustrate the concepts from the generation of the layout to the definition of the circulation or MHS network. The graph in Fig. 8.2 shows the evolution of the tangential network in the dark directed lines, where the activities are represented by the circles and the dotted lines represent the activity adjacency relationships.

Figure 8.2 also represents a planar graph diagram of a layout planning alternative. It was generated with a GTLN-style algorithm (Chap. 6). The circulation network should pass tangentially to all the activities in order to allow the traffic flow access to all the activities. Figure 8.3 illustrates the translation of the planar graph diagram into two block-plan realizations.

Fig. 8.2 Planar graph diagram

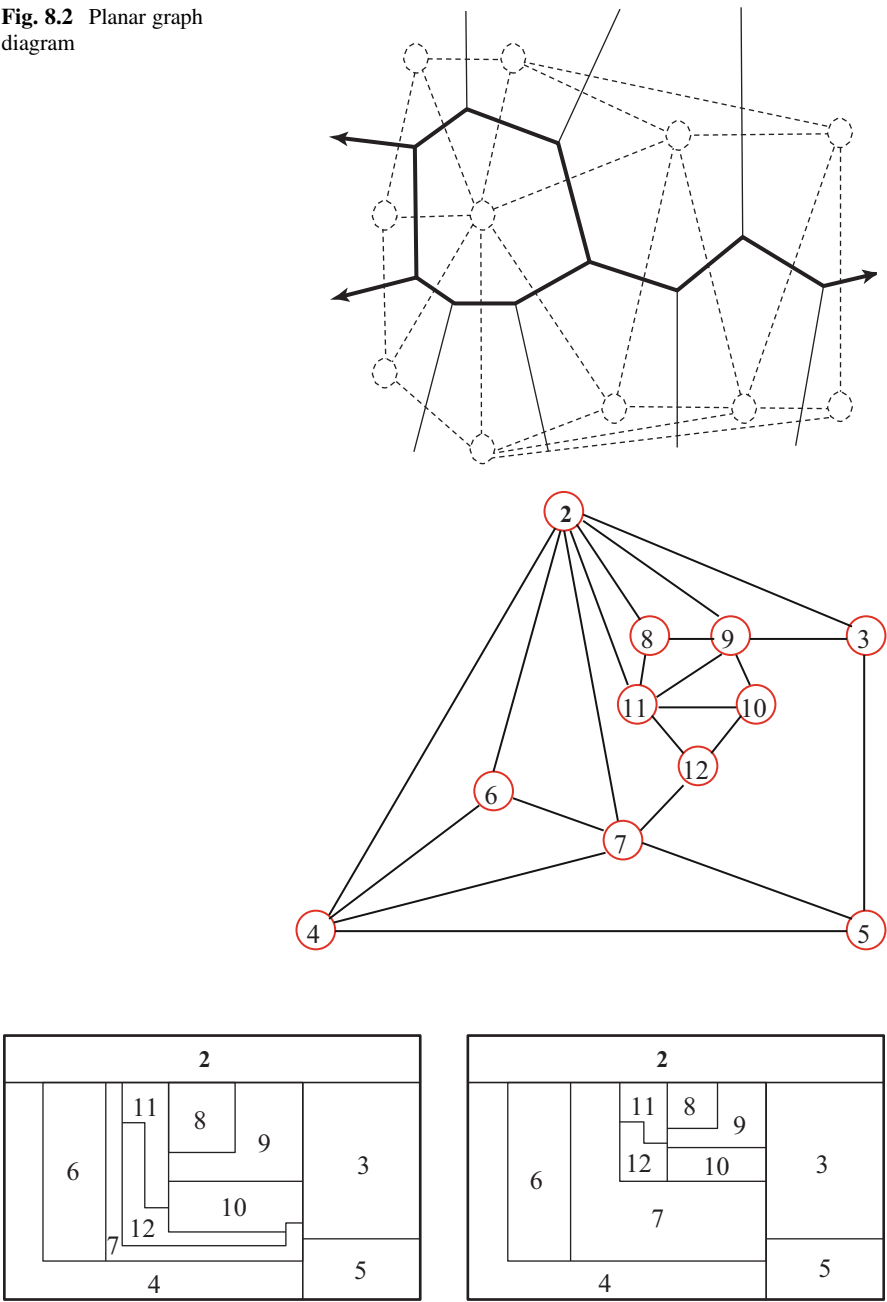


Fig. 8.3 Two block-plan realizations

Fig. 8.4 Circulation network realization

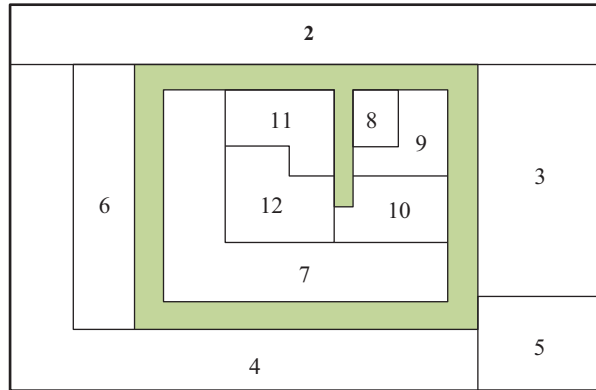


Figure 8.4 represents the integrated circulation or MHS network, where the traffic flow is tangential to the activity network of the alternative block plan of Fig. 8.3b. While the activities in the layout were located with a centroid-to-centroid distance rule, the traffic flows are tangential to the activities. It is important that the circulation or MHS network connects all the activities in the layout.

2. **Circulation Network Polygon:** The circulation network takes up an area in the layout and is actually a simple polygon having a varying width and overall length. The width, which is quite critical, represents the necessary accommodation of the traffic volume of pedestrians or vehicles (lift trucks, carts, conveyors, and so on) flowing through the circulation or MHS network. It is desirable to minimize the overall length of the circulation network subject to its ability to connect all the activities. The circulation network could either have a tree topology or a circuit topology. Figure 8.5 is an example of a circulation network in a hospital facility that has a tree topology. It is necessary for the circulation network to connect all the activities and allow the pedestrians in this case to visit any one of the activities within the layout. Once we define the circulation network, we can begin to quantify the traffic flows within it.
3. **Steiner Minimal Tree Problem on a Graph (SMTG):** The Steiner minimal tree (SMT) problem represents the minimal length network to connect a given set of N -terminals in the plane or higher dimensions. For the MHS solution, one would like to have minimal length, as this will provide an overall reduction in the MHS traffic flow costs.

Sometimes additional nodes called Steiner nodes are necessary in order to achieve the minimal length possible. The graphs in Fig. 8.6 indicate two alternative SMT solutions for connecting the $N = 10$ terminals, where diagram (a) is on the Euclidean metric and (b) is on the rectilinear metric. The terminals are the open circles, and the filled-in nodes are the Steiner points.

The circulation network (Fig. 8.7) connects the exterior perimeter of the facility with the interior in order to allow for access and egress of the occupants. The

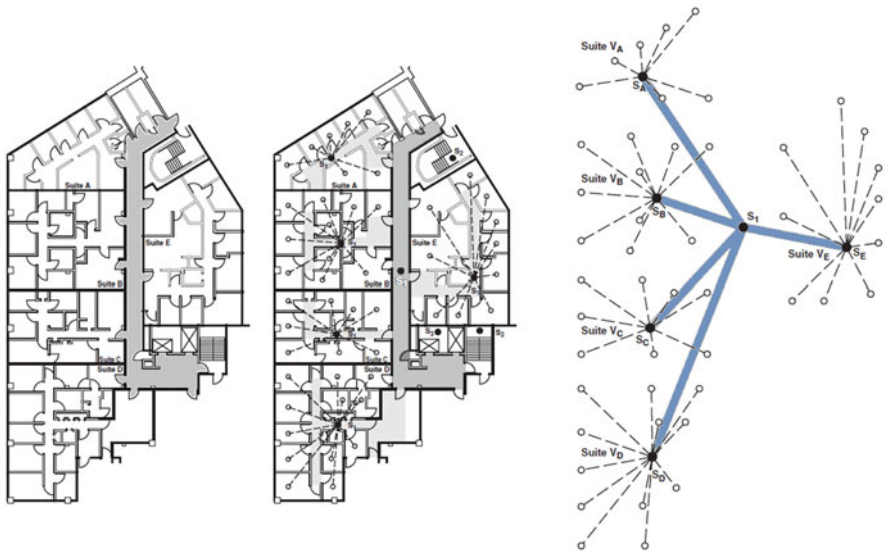


Fig. 8.5 Hospital facility circulation network polygon

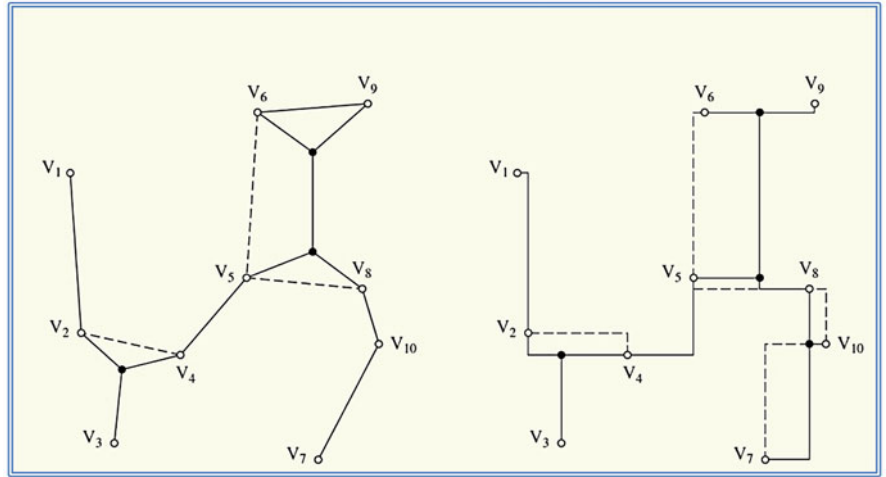


Fig. 8.6 SMT solutions

terminals on the interior and exterior form a set of given points from the set $\mathbf{Q} = \{Q_1, Q_2, \dots, Q_n\}$, which must be connected. The Q -points could represent receiving and shipping docks, exterior doors, parking areas, and other activities external to the facility.

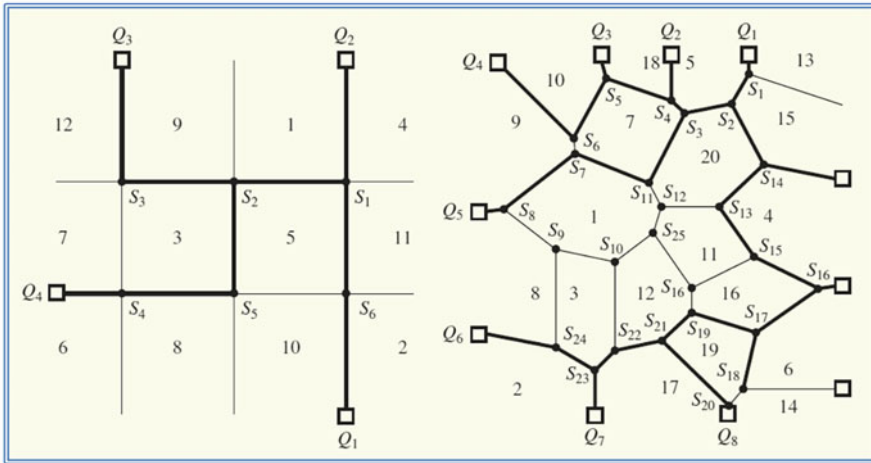


Fig. 8.7 Sample circulation network terminal realization

Some of the Q -terminals could also be interior to the facility, as they represent key terminus points or vertical travel connections such as stairs or elevators. In addition, a set of points called Steiner points, from the set $S = \{S_1, S_2, \dots, S_m\}$, are used to connect the Q -terminals. The S -points are usually interior to the facility. The Steiner points normally represent the three-way and four-way intersections of the circulation network. One may or may not use all the S -points.

In order to minimize the overall length of the circulation polygon, one would like to minimize its overall length. This will help minimize the material handling costs. This can be solved as the Steiner minimal tree problem on a graph (SMTG). The tree-network topology will normally act as a lower bound on the overall cost/length of the circulation network. Circuit topologies normally provide redundancy in the circulation network.

4. **Circulation Network Flow Analysis:** Once the planar graph layout geometry has been solved and the block diagrams generated, we should solve the SMTG problem to define the Steiner circulation polygon and size its width to accommodate the traffic volumes. In certain instances, some facilities may require us to solve the circulation network first because of the volume and complexity of traffic flows, then add the activities within the circulation network. Ideally, one should solve both networks simultaneously. Once we have the circulation network topology and geometry, then we can employ the analytical or simulation queuing network models to examine the flows in the layout.

In the next subsection, we illustrate the layout and material handling analysis principles in the design layout integration for a small factory.

8.2.2 Case Study

The case study presented here illustrates the evolution of the MHS network topology and its integration with the layout. Table 8.1 is a from-to chart for a small plant that makes plastic bottles. The commodity flowing through the plant is mainly plastic bottles, which are blow molded and then printed with various labels for a specific client. In addition, flows include cardboard packaging, pallets, and cartons for the bottles. Each entry in the matrix represents the percent flow from one department to another of the total flow of bottles within the plant. There are 11 key departments or activity areas.

Figure 8.8 illustrates a sequence of nonplanar graph decompositions generated from the from-to chart of the bottle-making plant. While these were manually generated from a direct analysis of the traffic matrix, a similar automatic generation would be carried out by one of the algorithms for the GTLN approach.

Figure 8.9 illustrates two alternative planar graph-theoretic layouts generated for the facility based upon the planar graph decomposition.

Building upon the from-to chart, the matrix of critical pair values was constructed for MAFLAD. Figure 8.10 at the top left represents the modular grid which was utilized to solve the layout problem with MAFLAD. Each cell represents a $25' \times 25'$ (625 sq ft) area module. The approximate area requirements for the individual activities are as follows:

- Molding dock (MD) 2500 sq ft
- Molding (M) 5250 sq ft
- Bottle storage (BS) 5000 sq ft

Table 8.1 From-to chart of product flows

Flows	MD	M	BS	P	PD	FS	FD	C	D	W	WD	Σ_i
Molding dock (MD)	0	≥ 1										≥ 1
Molding (M)	51	0	26	4						4		85
Blank storage (BS)			0	25				0.2	0.3			25.5
Printing (P)				0	13	20		≥ 1	≥ 1			≥ 35
Printing dock (PD)				6	0							6
Finished storage (FS)			0	14	3.5	2.5			20			
Finished dock (FD)							0					0
Coating (C)						4		0				4
Drive-in dock (D)									0			0
Warehouse (W)	1	12	1	2	1	1		1	1	0	4	24
Warehouse dock (WD)										15	0	15
Totals Σ_i	52	≥ 13	27	37	14	25	14	≥ 5.7	≥ 4.8	19	4	215.5

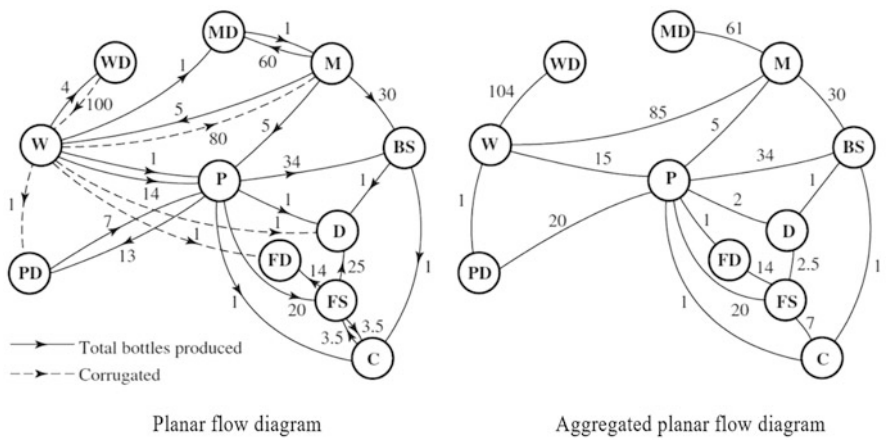


Fig. 8.8 Planar graph evolution

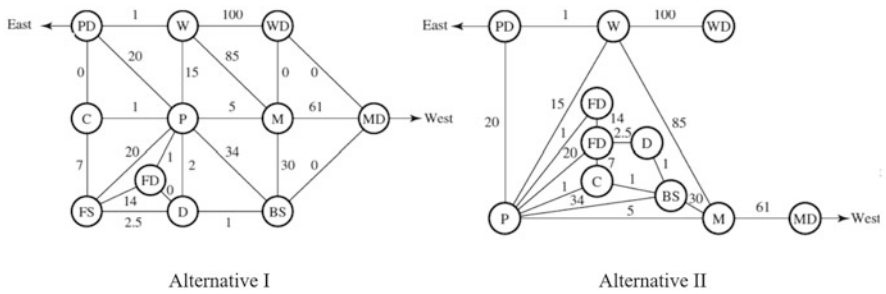


Fig. 8.9 Alternative planar network layouts

- Printing (P) 3000 sq ft
- Printing dock (PD) 625 sq ft
- Finished goods storage (FS) 5000 sq ft
- Finished goods dock (FD) 625 sq ft
- Coating (C) 1250 sq ft
- Drive-in dock (D) 625 sq ft
- Warehouse (W) 7500 sq ft
- Warehouse dock (WD) 2500 sq ft

Figure 8.10 shows the evolutionary generation of the final layout, using MAFLAD (Chap. 4), from the grid to the block plan along with the circulation network obtained by the SMTG algorithm.

While not all of the details are shown, one should understand the basic concepts from the illustrations presented. Notice how the final circulation network is a simple polygon interconnecting all the activities and the exterior of the facility. The MHS

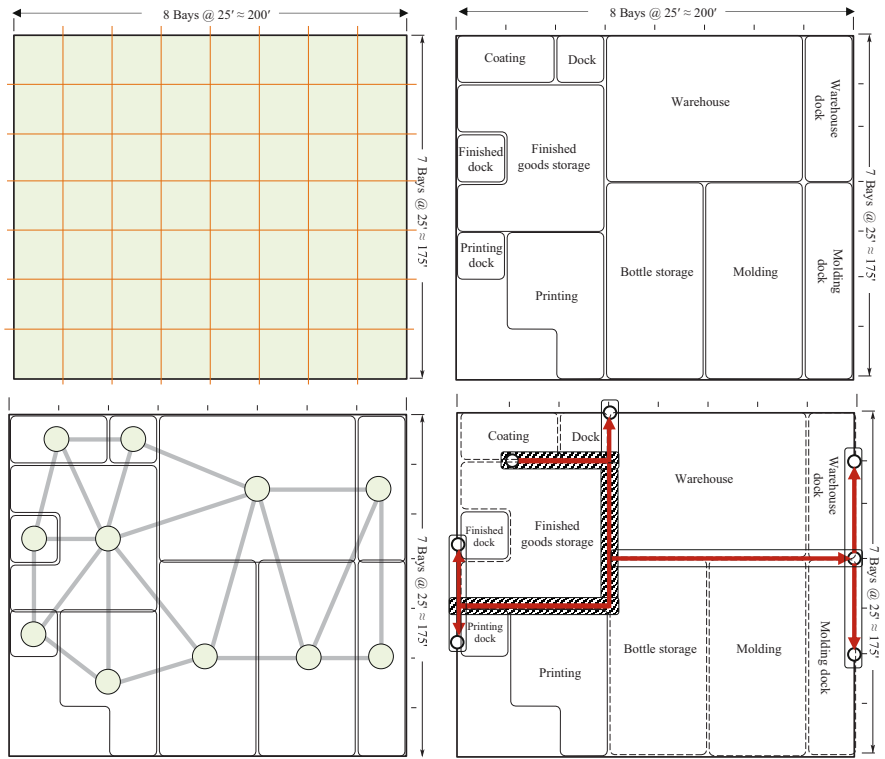


Fig. 8.10 Bottle-making plant layout and MHS Steiner network

network generated represents a rectilinear SMT solution. It is therefore suitable to go to the next step, the actual physical realization, which is illustrated in the lower part of Fig. 8.10. Most factory problems have rectilinear SMT or circuit solutions. Figure 8.11 illustrates a 3-D model for the MHS of the bottle-making plant.

8.2.3 Addenda to Section III of Project

The requirements for Section III of the factory project are described in Sect. 7.8. In order to illustrate the generation of the MHS network design, let us illustrate one example factory project carried out at the University of Massachusetts [13]. The product is a small unit heater and the area requirements for three planning departments and offices are shown in Table 8.2. For many factory projects, 30,000 the MHS network (or part of it) can be included in the flow analysis of the factory project. The 3-D realization of the project is illustrated in Fig. 8.12. Notice how the

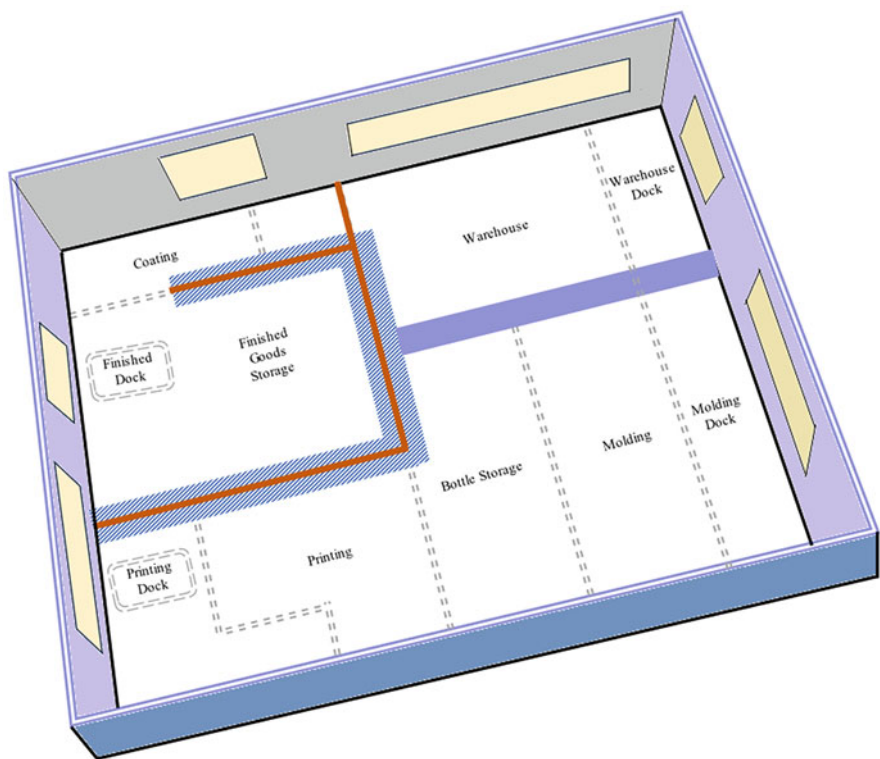


Fig. 8.11 3-D realization of bottle-making plant

Table 8.2 Area requirements

Department area	sq ft
Manufacturing	15,753.5
Warehouse (shipping and receiving)	13,478.0
Assembly area (main and sub.)	7722.0
Offices	5447.5
Total plant area	43,512.5

MHS product flow network is tangential to the activity areas. Once the circulation MHS topology is defined, the analysis of the traffic flow on the network can proceed.

In the factory project, it is recommended to deterministically identify the MHS network with flow diagrams and, if possible, augment the deterministic diagrams with a quantitative analysis of the flows. This will not always be possible for the entire facility, but may be possible for a small segment or subsystem of the facility, such as the assembly area. The student teams can develop a simulation model of the assembly area of the plant since it combines the use of conveyors and the location of workstations and personnel in the facility. Another good study would be to model

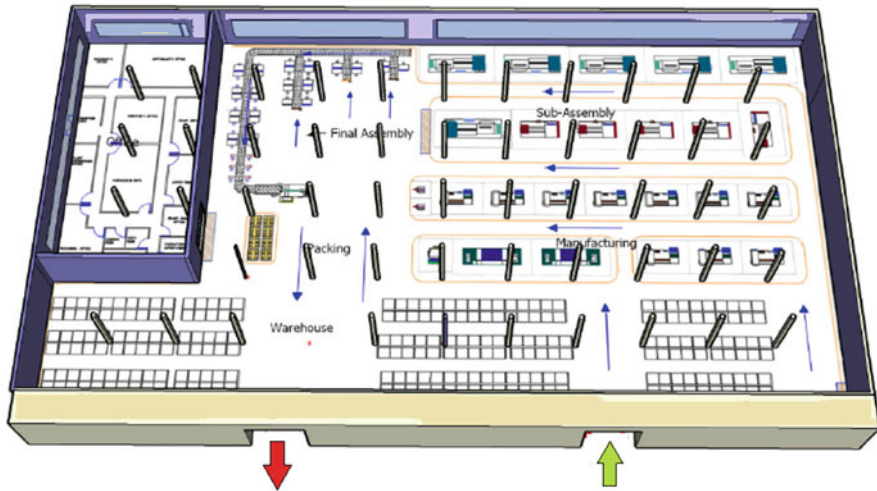


Fig. 8.12 Example factory project layout and MHS network

the packaging area, since it tends to be a smaller queuing network and would lend itself to some interesting flow and space estimation problems.

The open queuing network methodology will be illustrated first since it can be used to model the entire facility or even a subarea of the factory.

8.3 Open Network System Design Tool

This section describes an analytical queuing network procedure for examining the initial design of an MHS. The generalized queuing network (**GQnet**) is a FORTRAN-77 program, which runs on PC systems and it is available on the website. **GQnet** can be used to design open finite queuing networks with various product classes and various sources. It is assumed that the students have some background in queuing theory. Many manufacturing systems utilize queuing theory in their initial as well as detailed design phases, which is why we incorporate this advanced material in this book. Simulation is seen as a detailed tool for refining the MHS system with more specialized assumptions, and it is discussed in more detail in the last two sections of this chapter.

8.3.1 *GQnet Basic Assumptions*

Basic assumptions in modeling facilities with open finite queuing network models are introduced in this subsection.

Complex Mixing of Arrival and Departure Processes In general, there is a set $\{1, 2, \dots, J\}$ of multiple customer classes or product types belonging to a set $\{1, 2, \dots, K\}$ of infinite population sources. A source of arrivals can be either a warehouse or a vendor supplying parts to the manufacturing facility. The average arrival rate per unit time of type j product from source k is λ_{jk} . It is further assumed that the arrival process from each source is a renewal process.

In some facilities, such as airports, there are batch arrivals, yet for the most part, products/customers arrive individually, independently, and at random. Furthermore, products/customers tend to follow deterministic rather than random routes through a facility because of their unique origins and destinations.

Deterministic Routing Vector Type jk products are routed through the facility using a deterministic routing vector, sometimes referred to as a “customer chain” or as a “production plan.” Thus, in the factory project, the process plan defined in Chap. 3 is essentially the same as the routing vector. Also, it is noted that the normal *Sequences* command in program Arena is equivalent to specifying the routing vector.

The routing vector has elements $r_{jkl} (\ell = 1, 2, \dots, L_{jk})$, where the ℓ th element of the routing vector marks the destination to which the product is directed after visiting the previous activity on its route. Thus, type jk products enter a facility of queues $\ell = 1, 2, \dots, L_{jk}$ in independent Poisson stream at rate λ_{jk} and pass through a sequence of queues before leaving the facility.

$$[Q(j, k, 1), Q(j, k, 2), \dots, Q(j, k, L_{jk})]$$

$G(Z, E)$ Is a Dual Graph Every floor plan of a facility can be represented as a planar graph $G'(Z', E')$, as depicted in Fig. 8.13. The *dual graph representation* can be determined mathematically in the following manner from the planar graph of the floor plan:

1. Place a node Z within each face f^0 of the floor plan graph G^0 .
2. Corresponding to each edge e in G^0 , there is an edge e of G . Nodes v_i and v_j are joined by edge e in G if and only if their corresponding faces f^0 and g^0 are separated by an edge e^0 in G^0 .

As can be seen from the transformations in Fig. 8.13, the queuing network is essentially the dual graph of G' . $G(Z, E)$ can be embedded in the plane R^2 with a corresponding distance metric (Euclidean or rectilinear), since the flow of products and goods through the nodes requires a distance movement. Thus, the location of each $v_i \in \mathbf{V}$ is in R^2 , with Cartesian coordinates (x_i, y_i) . In the queuing network, the location of the nodes should arguably be the centroid of the spatial entity it models. Although a facility can be modeled without the network embedding, the transition time between activity nodes needs to be characterized, and this requires a distance movement.

Dichotomous Nodal Types Facilities have two spatial entities, which require a distinction within the queuing network model: the activity network and the circulation network. Thus, the nodes of Z are partitioned into two sets $\mathbf{V} = \{\mathbf{A}, \mathbf{S}\}$:

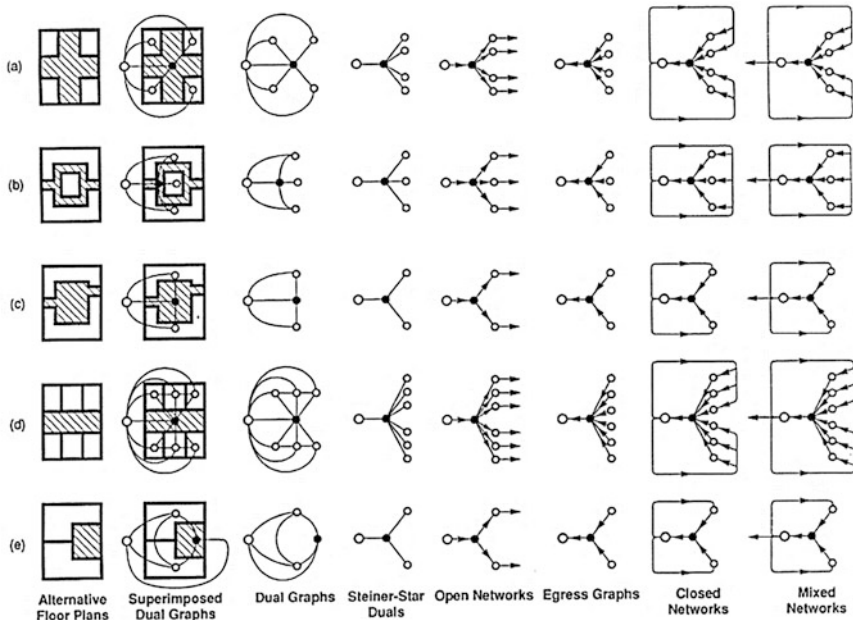


Fig. 8.13 Planar and dual graph transformation and queuing networks

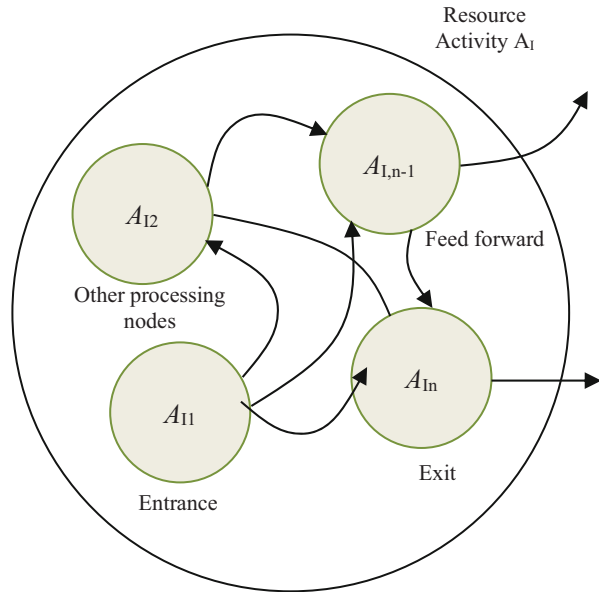
- A set of activity nodes $\mathbf{A} = \{A_1, A_2, \dots, A_n\}$ representing the rooms, departments, or activity areas.
- A set of circulation MHS nodes $\mathbf{S} = \{S_1, S_2, \dots, S_m\}$ representing the hallways, corridors, stairwells, elevators, conveyors, lift trucks, and other movement pathways.

Each facility can be best described as a hierarchical queuing network of nodes and arcs. For our purposes, the hierarchical queuing network has two levels. At the upper level, we have the resource activities $Z_1 = (1, 2, \dots, I)$, where $I = n + m$. At the lower level, we have the subnetwork of activities within each resource activity, $v_{it} = (1, 2, \dots, T)$.

The incidence function regulating the flow of products among the nodes of the subnetwork is a probability transition matrix formulated as shown below.

$$\mathbf{P}_{ijt} = \begin{pmatrix} (p_{11})_{ijt} & (p_{12})_{ijt} & \cdots & (p_{1t})_{ijt} \\ (p_{21})_{ijt} & (p_{22})_{ijt} & \cdots & (p_{2t})_{ijt} \\ \vdots & \vdots & \vdots & \vdots \\ (p_{t1})_{ijt} & (p_{t2})_{ijt} & \cdots & (p_{tt})_{ijt} \end{pmatrix}$$

Fig. 8.14 Resource activity representation



For each resource activity, there needs to be an entrance node, a feed forward node, and an exit node. Therefore, a minimum of three nodes are required. All other nodes added are necessary to fill out the processing requirements (see Fig. 8.14).

Transitions within resource activities are normally accounted for by the amount of time spent at each subactivity v_{it} by a product following this route through $G(Z, E)$. Arcs between resource activities A_i and A_j represent travel time over the circulation network S of the facility.

Non-instantaneous Transitions A unique feature of facility modeling is that transitions within the network are not instantaneous, as they are in computer and communication networks—thus the need for the set S . Vertices from the set S represent additional nodes within a facility designed to handle the intermediate flow of products from origin source nodes A_i to A_k without interrupting service. Often the cardinality and configuration of the nodes in S are determined by the intended building use, building codes, and zoning ordinances for certain building types, taking account of emergency egress conditions or other public access requirements.

We like to refer to these nodes as Steiner nodes, after the renowned Steiner network problem, since there is a similarity between the nodes from the set S within the queuing network modeling of facilities and their use in minimizing overall network costs in the Steiner network problem. Figure 8.13, columns 4–8, illustrates the use of Steiner nodes in capturing the flow of products through the circulation system. In the analysis stage of the model, Steiner nodes become the key modeling

node through which all product traffic flows, while the Steiner-star topology becomes the underlying topology for representing all product traffic flow in facilities.

8.3.2 GQnet Algorithm

In the following algorithmic description, there are four basic steps. **Step 1.0** is concerned with generating the representation of the queuing network, arrival and service rates, routing vector components, and transition matrices. **Step 2.0** computes the traffic loads on the resource activities, which are a function of the transition matrices and routing vector components. **Step 3.0** solves the queuing network performance measures for each of the decomposed queue types, finite and infinite in $G^\ell(Z, E)$. Finally, **Step 4.0** summarizes the overall performance of the network in terms of the sojourn time and processing costs for the various product classes circulating through $G^\ell(Z, E)$.

The most intensive computational parts of the algorithm occur in **Steps 2.2, 3.2, and 3.3**, where matrix inversions and solutions to sets of nonlinear equations are required. **Step 2.2**'s complexity is directly affected by the size of the subnetwork transition matrices which must be inverted in order to compute the traffic on the subnetwork. **Steps 3.2 and 3.3** concern the *exponential* and *generalized* versions of the expansion method.

Step 1. Generate $G^\ell(Z, E)$

- 1.1 Identify $\mathbf{V} = (\mathbf{A}, \mathbf{S})$
- 1.2 Identify $(i, j) \in E$ for all feasible pairs in Z along with the transition matrices $\mathbf{P}_{ijt}$ associated with each subnetwork in G .
- 1.3 Identify $\lambda_{jk}, \bar{\mu}_A, \bar{\mu}_S, r_{jkt}; \forall j, k, (\ell = 1, 2, \dots, L_{jk})$.

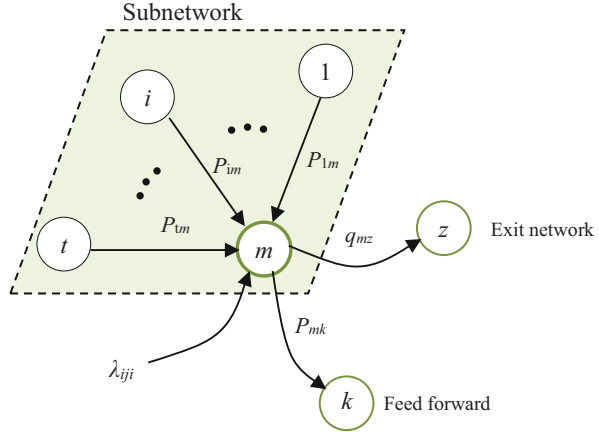
Step 2. Traffic equations

- 2.1 Compute $\lambda_{ij\ell} = \sum_{k=1}^K \lambda_{ijk\ell}$
- 2.2 Compute $\Lambda_{ij\ell} = (\mathbf{I} - \mathbf{P}'_{ij\ell})^{-1} \lambda_{ij\ell}$ (see illustration in Fig. 8.15).

Step 3. Queuing performance measures

- 3.1 Compute the performance characteristics of $M/M/C$, $M/G/\infty$ and $M/M/c/c$ queues using the standard equations.
- 3.2 For the $M/M/1/K$ and $M/G/c/K$ use standard and approximation formulas to solve for the performance measures. Solve these simultaneous equations:

Fig. 8.15 Illustration of Λ_{ijt}^m subnetwork



$$\lambda = \lambda_j - \lambda_h (1 - P'_N) \quad (8.1)$$

$$\lambda_j = \tilde{\lambda}_i (1 - P_N) \quad (8.2)$$

$$\lambda_j = \tilde{\lambda}_i - \lambda_h \quad (8.3)$$

$$P'_N = \left[\frac{\mu_j + \mu_h}{\mu_h} - \frac{\lambda(r_2^N - r_1^N) - (r_2^{N-1} - r_1^{N-1})}{\mu_h(r_2^{N+1} - r_1^{N+1}) - (r_2^N - r_1^N)} \right]^{-1} \quad (8.4)$$

$$z = (\lambda + 2\mu_h)^2 - 4\lambda\mu_h \quad (8.5)$$

$$r_1 = \frac{[(\lambda + 2\mu_h) - z^{\frac{1}{2}}]}{2\mu_h} \quad (8.6)$$

$$r_2 = \frac{[(\lambda + 2\mu_h) + z^{\frac{1}{2}}]}{2\mu_h} \quad (8.7)$$

$$P_N = \frac{(1 - \tilde{\lambda}_i/\mu_h)(\tilde{\lambda}_i/\mu_h)^N}{1 - (\tilde{\lambda}_i/\mu_h)^{N+1}} \quad (8.8)$$

3.3 For the $M/G/1/N$ queues solve these simultaneous equations:

$$\lambda = \lambda_j - \lambda_h (1 - P'_N) \quad (8.9)$$

$$\lambda_j = \tilde{\lambda}_i (1 - P_N) \quad (8.10)$$

$$\lambda_j = \tilde{\lambda}_i - \lambda_h \quad (8.11)$$

$$P'_N = \left[\frac{\mu_j + \mu_h}{\mu_h} - \frac{\lambda(r_2^N - r_1^N) - (r_2^{N-1} - r_1^{N-1})}{\mu_h(r_2^{N+1} - r_1^{N+1}) - (r_2^N - r_1^N)} \right]^{-1} \quad (8.12)$$

$$z = (\lambda + 2\mu_h)^2 - 4\lambda\mu_h \quad (8.13)$$

$$r_1 = \frac{\left[(\lambda + 2\mu_h) - z^{\frac{1}{2}} \right]}{2\mu_h} \quad (8.14)$$

$$r_2 = \frac{\left[(\lambda + 2\mu_h) + z^{\frac{1}{2}} \right]}{2\mu_h} \quad (8.15)$$

$$C_j^2 = y_j \sum_{i=1}^n \left[\lambda_{ij} / \sum_{i=1}^n \lambda_{ij} \right] C_{ij}^2 + 1 - y_j \quad (8.16)$$

$$\hat{\rho}_i = \exp \left\{ -2 \frac{1 - \tilde{\rho}_i}{\left(\tilde{\rho}_i C_j^2 + c_{v2}^2 \right)} \right\} \quad (8.17)$$

$$P_N = \frac{\tilde{\rho}_i(1 - \tilde{\rho}_i)}{\hat{\rho}_i^{(1-M_i)} - \tilde{\rho}_i^2} \quad (8.18)$$

$$C_{ij}^2 = (1 - P_N)C_{di}^2 + P_N \quad (8.19)$$

$$C_{ih}^2 = P_N C_{di}^2 + 1 - P_N \quad (8.20)$$

Step 4. Overall System Performance Measures

4.1 Compute the average sojourn time (cycle time) across all product classes:

$$W = \sum_{j=1}^J \sum_{k=1}^K \lambda_{jk} w_{jk} / \Lambda$$

4.2 Compute the average processing costs across all product classes:

$$W = \sum_{j=1}^J \sum_{k=1}^K \lambda_{jk} c_{jk} / \Lambda$$

4.3 Compute the average total product traffic entering the facility:

$$\Lambda = \sum_{j=1}^J \sum_{k=1}^K \lambda_{jk}$$

For the finite exponential and the generalized service distribution cases, the first seven equations are similar. Equations (8.1) through (8.4) deal with arrivals and the feedback problem associated with the holding node h . Equations (8.5) through (8.7) are associated with solving eq. (8.4) with z being a dummy parameter utilized for simplifying the solution. Additionally, r_1 and r_2 are the roots of eq. (8.5). Finally, Eq. (8.8) is an approximation to the blocking probability derived from the exact formula for the $M/M/1/N$ case. Equations (8.16) through (8.20) in the generalized case are concerned with the squared coefficients of variation of the arrival and service processes in the expanded network together with the formula in Eq. 8.20 for all product classes for computing the blocking probability in the generalized network. Refer to Albin and Whitt for their derivation [1, 2, 21–23]. Equations (8.17) and (8.19) are based on the work of Labetoulle and Pujolle [12]. Refer to [8] for further details on the integration and development of these equations and how they are used in the generalized expansion method.

8.3.3 GQnet Computational Results

In order to demonstrate the effectiveness of the **GQnet**, two examples will be used.

8.3.3.1 Medical Clinic Example

A medical clinic facility consists of three departments (resource activities) with subareas as individual activities. There are three classes of patients: (a) normal adult patients, (b) children, and (c) elderly patients.

Resource activity A_1 represents reception and waiting, resource activity A_2 represents patient examination, and resource activity A_3 represents special testing and X-ray equipment rooms. Figure 8.16 shows the plan of the clinic and the open queuing network.

The arrival rates of the patients during peak hours of the operation of the clinic are $\lambda_a = 10/\text{hour}$, $\lambda_b = 5/\text{hour}$, $\lambda_c = 3/\text{hour}$. The routing vector of the patients is normally $r_a = \{A_1, A_2\}$, $r_b = \{A, A_2, A_3\}$, $r_c = \{A_1, A_2, A_3, A_2\}$. We want to estimate the cycle time or sojourn time of the patients through the clinic, as well as identify any bottlenecks of the clinic.

The detailed parameters for the activity nodes within the resource activities A_2 and A_3 appear in Fig. 8.17. Resource activity A_1 basically has three nodes: an entrance reception area with node 1 having a service rate $\mu = 3$ minutes/patient, an $M/G/\infty$ waiting area represented by node 2 with $\mu = 1/2$ hour wait, and exit node 3 with rate $\mu = 250/\text{hour}$. This node ensures that if a patient leaves the clinic, there is an exit node along the route.

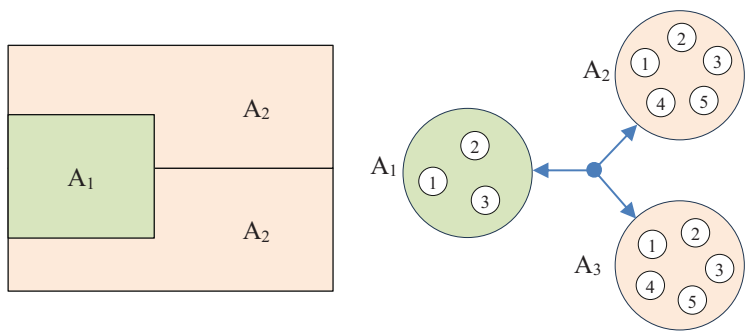


Fig. 8.16 Plan of clinic and open queuing network

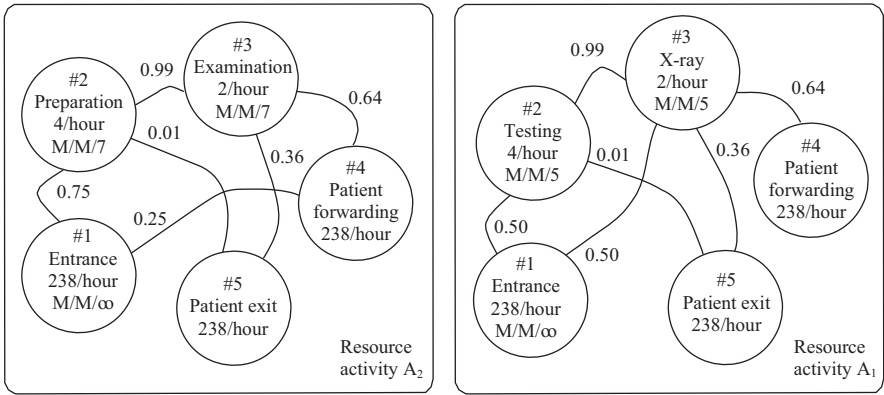


Fig. 8.17 Resource activity parameters

Some partial results of the computer output are shown below. More examples and a user manual can be found on the website.

GENERAL PROCESSING STATISTICS				
GENERATING SOURCE 1				
SOJOURN TIME CLASS	1	A	=	1.4692 HOURS
SOJOURN TIME CLASS	2	B	=	2.2886 HOURS
SOJOURN TIME CLASS	3	C	=	2.7078 HOURS
RESOURCE ACTIVITY 1 1				
NODE: 1 NUMBER OF SERVERS = 1				
ARRIVAL RATE =	18.0000	SERVICE RATE =	20.0000	UTILIZATION = 0.9000
QUEUE LENGTH =	9.0000	STD DEVIATION =	9.4868	QUEUE SIZE AT MOST ≤ 20.7233
WAIT IN QUEUE =	0.5000	STD DEVIATION =	0.5000	PATIENTS WAIT AT MOST ≤ 1.1513 HOURS
TOTAL LENGTH =	9.9000	STD DEVIATION =	9.0449	TOT. SIZE AT MOST ≤ 21.6583
TOTAL WAIT =	0.5500	STD DEVIATION =	0.5025	TOT. WAIT AT MOST ≤ 1.2032 HOURS

RESOURCE ACTIVITY		1	1				
NODE:		2	NUMBER OF SERVERS =		7		
ARRIVAL RATE		= 14.5082		SERVICE RATE		= 4.0000	
				UTILIZATION		= 0.5182	
QUEUE LENGTH		=	0.8776	STD DEVIATION		=	1.4124
WAIT IN QUEUE		=	0.0605	STD DEVIATION		=	0.0729
TOTAL LENGTH		=	4.5047	STD DEVIATION		=	3.7779
TOTAL WAIT		=	0.3105	STD DEVIATION		=	0.2604
QUEUE SIZE AT MOST		≤	2.2576	PATIENTS WAIT AT MOST		≤	0.1556
TOT. SIZE AT MOST		≤	9.4160	TOT. WAIT AT MOST		≤	0.6490
						HOURS	

RESOURCE ACTIVITY		3	3				
NODE :		3	NUMBER OF SERVERS =		5		
ARRIVAL RATE		=	5.7668	SERVICE RATE		=	2.0000
QUEUE LENGTH		=	1.0429	STD DEVIATION		=	1.6723
WAIT IN QUEUE		=	0.1808	STD DEVIATION		=	0.2296
TOTAL LENGTH		=	3.9263	STD DEVIATION		=	3.1730
TOTAL WAIT		=	0.6808	STD DEVIATION		=	0.5502
QUEUE SIZE AT MOST		≤	2.7728	PATIENTS WAIT AT MOST		≤	0.4808
TOT. SIZE AT MOST		≤	8.0512	TOT. WAIT AT MOST		≤	1.3961
						HOURS	

We have illustrated the three nodes with the highest utilization rates. These output statistics as well as others are very revealing of the capacity planning of the clinic to accommodate the expected patient traffic and point to areas where more capacity (space or personnel) might be allocated. Notice that **GQnet** gives an estimate of the maximum size of the queue and total number in the system.

8.3.3.2 Manufacturing Facility Example

This example involves the renovation plan of a manufacturing facility for the assembly of computer products. Some 60 nodes are required to represent the material handling and assembly process requirements of the manufacturing facility for transporting ten products (product classes) through the various work centers. The facility itself is a multistory, multibuilding complex typical of buildings being renovated and restored in modern industry. A mixture of finite and infinite capacity queue types are required, and service times within the network are allowed to be drawn from general service distributions, such as constant, exponential, and Erlang-2. Along with the analytical model, a **Q-GERT** simulation model [15] is generated to act as a baseline comparison tool. In comparing sojourn times of the ten product classes along with other performance measures, **GQnet** is shown to be a very accurate and effective tool.

Network Topology Fig. 8.18 is an isometric view of the large-scale multistory, multi-building complex, and Fig. 8.19 shows the associated queuing network $G(Z,E)$ of a computer company based on [19]. The nodes as they appear in the topology of the network represent the resource activities of the queuing network.

The network is essentially composed of two basic nodal types: **A**, **S**. Type **A** accounts for the activities, such as production floors, workstations, shipping

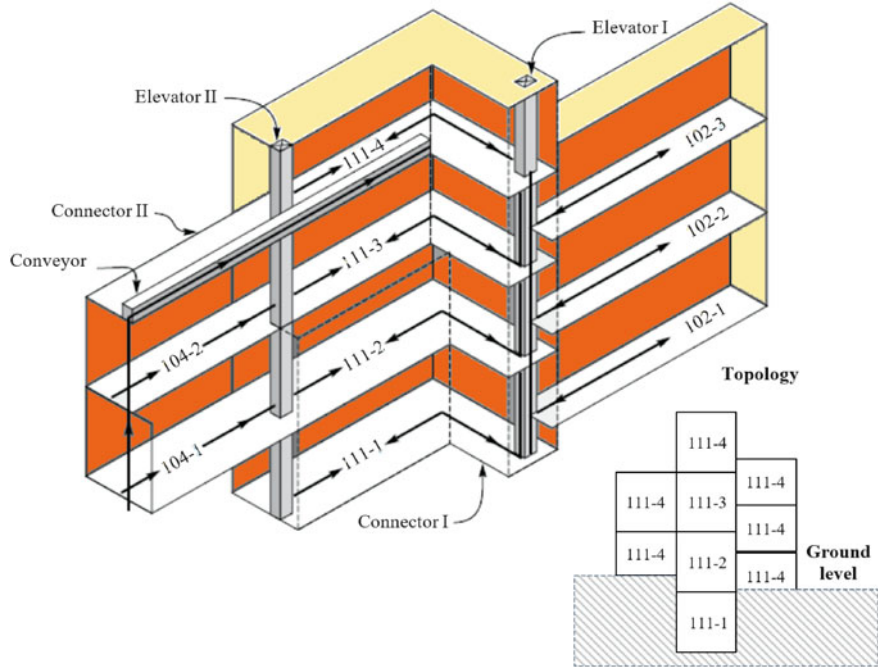


Fig. 8.18 Isometric representation of facility

docks, and other production activities, while the circulation network S accounts for the noninstantaneous transitions for the products (pallets of parts, assemblies, and finished goods) using the resources of the activity network.

Resource activities $A_5, A_6, A_7, A_8, A_{12}, A_{13},$ and A_{14} represent production floor levels of the manufacturing facility. Resource activities S_3 and S_{11} represent the elevators servicing the different floor levels of the production facility, while $A_4, A_9, A_{10},$ and A_{15} represent the staging and buffer areas outside the elevators. The elevators are the critical *finite* queues in the manufacturing facility representation. Resource activities S_1 and S_2 represent different transportation systems used in the movement of different product types, while resource K is the single generating source.

These two networks are integrated into a hierarchical network that allows the modeling of the site plan. Table 8.3 displays the queuing characteristics of all nodes such as arrival and service-time distributions, number of servers, and queuing disciplines (all assumed to be FCFS).

The network is traversed by different product or product classes. Because products are developed at different locations, the routes of flow are different, thus generating different product classes. Table 8.4 displays the ten different product

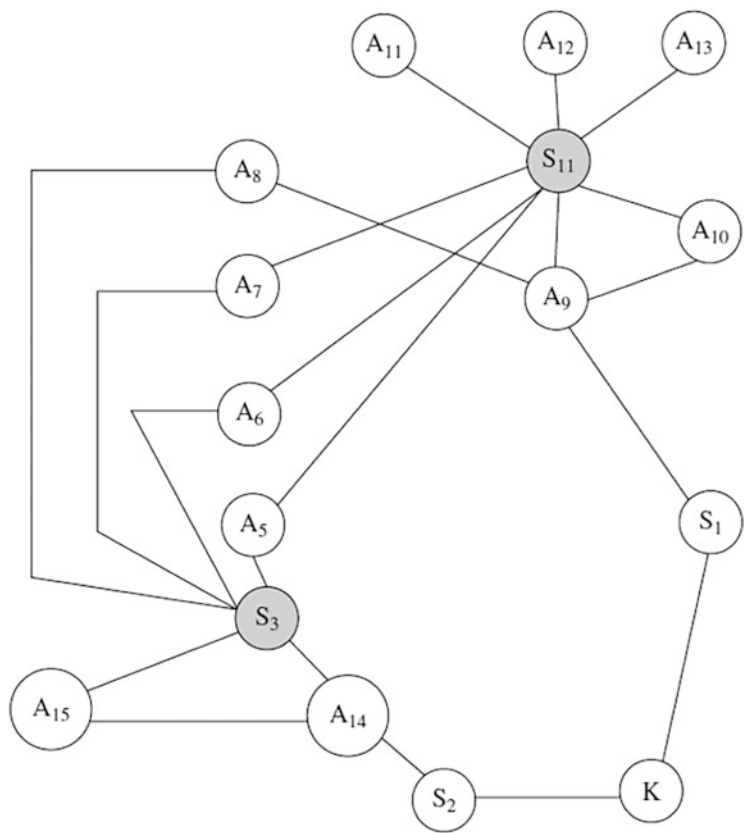


Fig. 8.19 $G(Z, E)$ queuing network representation

classes routed on the ten different routes that are used in this example. A complete analysis of this network is presented in the next section.

Figure 8.18 displays the building complex site plan and internal structure of the elevator resource activities (S_3 , and S_{11}), including the subnetwork of activities, their transition probabilities, and their queue parameters such as arrival and service rates, number of servers, queuing discipline, and queue capacities. The elevators are the critical *finite* queues in this manufacturing facility representation.

GQnet Network Results The network data are prepared in five different files which serve as inputs to the main program. Figure 8.20 represents the process for gathering the data and transforming them into the arrival and service information needed to form the basis of the queuing network.

A simulation of ten problems (products) for the same network was performed using **Q-GERT** [15]. Material movement through the facility was modeled with a constant service time over the various links of the material handling system. Ten

Table 8.3 Resource activities and their characteristics

Subnodes	Queue 1	Queue 2	Queue 3	Queue 4	Queue 5
Activities					
S_1	$M/G/\infty$	$M/G/\infty$	$M/G/\infty$		
S_2	$M/G/\infty$	$M/G/\infty$	$M/G/\infty$		
S_3	$M/G/\infty$	$M/M/4$	$M/M/4/4$	$M/M/2$	$M/G/\infty$
A_4	$M/M/5$	$M/G/\infty$	$M/G/\infty$		
A_5	$M/M/2$	$M/G/\infty$	$M/G/\infty$		
A_6	$M/M/2$	$M/G/\infty$	$M/G/\infty$		
A_7	$M/M/2$	$M/G/\infty$	$M/G/\infty$		
A_8	$M/M/2$	$M/G/\infty$	$M/G/\infty$		
A_9	$M/M/5$	$M/G/\infty$	$M/G/\infty$		
A_{10}	$M/G/\infty$	$M/M/10$	$M/M/10$		
S_{11}	$M/G/\infty$	$M/M/6$	$M/M/4/4$	$M/M/2$	$M/G/\infty$
A_{12}	$M/M/2$	$M/G/\infty$	$M/G/\infty$		
A_{13}	$M/M/2$	$M/G/\infty$	$M/G/\infty$		
A_{14}	$M/M/2$	$M/G/\infty$	$M/G/\infty$		
A_{15}	$M/M/\infty$	$M/M/10$	$M/G/\infty$		

Table 8.4 Customer routes

PN_i	Sink	Route pattern
PN_1	A_{14}	$(S_1 \rightarrow A_9 \rightarrow S_{11} \rightarrow A_{14})$
PN_2	A_7	(A_7)
PN_3	A_8	$(A_7 \rightarrow S_3 \rightarrow A_4 \rightarrow A_8)$
PN_4	A_8	$(S_1 \rightarrow A_9 \rightarrow A_8)$
PN_5	A_{13}	$(S_1 \rightarrow A_9 \rightarrow A_{10} \rightarrow S_{11} \rightarrow S_{11} \rightarrow S_{11} \rightarrow A_{13})$
PN_6	A_{12}	$(S_1 \rightarrow A_9 \rightarrow A_{10} \rightarrow S_{11} \rightarrow S_{11} \rightarrow S_{11} \rightarrow S_{11} \rightarrow S_{11} \rightarrow A_{12})$
PN_7	A_6	(A_6)
PN_8	A_6	$S_2 \rightarrow A_4 \rightarrow A_{15} \rightarrow S_3 \rightarrow A_6)$
PN_9	A_5	(A_5)
PN_{10}	A_5	$(S_2 \rightarrow A_4 \rightarrow A_{15} \rightarrow S_3 \rightarrow A_5)$

replications of the simulation model were made for each problem. Ten runs were found to be adequate to provide a reasonable estimate of the standard deviation of the processes and allow the computation of confidence intervals (C. I.) for the mean sojourn time of the ten different products. Each simulation run ended with either 5000 transactions or 150,000 time-units maximum. Table 8.5 summarizes the comparison between **GQnet** and **Q-GERT**, for two scenarios. In the first one, all service times are assumed to be exponential, and in the second one, they are assumed to be Erlang.

Finite Queues with Exponential Service Times The approximation approach gives results in Table 8.5 within 3% of those produced by the simulation model, which is perhaps surprisingly accurate given the complexity of the network, the routing

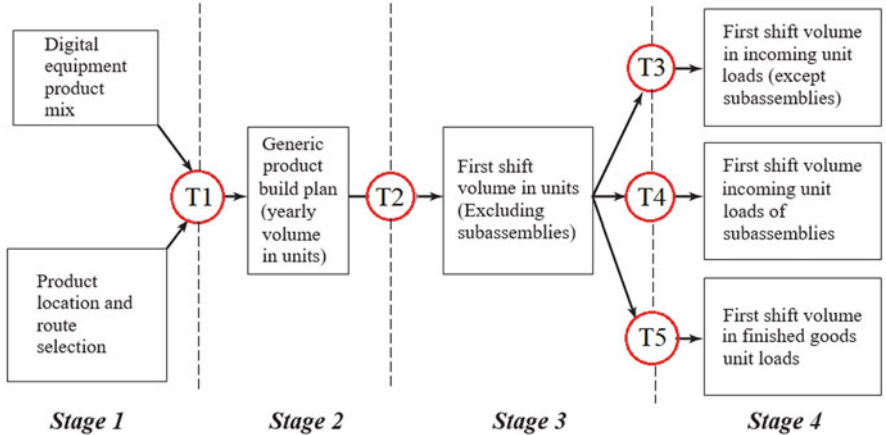


Fig. 8.20 Process for material handling volume calculations

Table 8.5 Analytical vs. simulation results

Problem number	Finite exponential				Finite erlang			
	GQnet	Q-GERT	95% C.I.	% Error	GQnet	Q-GERT	95% C.I.	% Error
1	1.6990	1.7603	(1.7520, 1.7606)	3.2625	1.6990	1.7615	(1.7571, 1.7659)	3.5481
2	0.7830	0.7836	(0.7810, 0.7842)	0.0511	0.7830	0.7823	(0.7791, 0.7855)	0.0895
3	1.6997	1.6937	(1.7073, 1.7197)	0.8054	1.6883	1.6992	(1.6933, 1.7051)	0.6415
4	0.9241	0.9247	(0.9176, 0.9320)	0.0757	0.9241	0.9243	(0.9202, 0.9284)	0.0216
5	3.2998	3.3201	(3.3165, 3.3335)	0.7579	3.2998	3.3269	(3.3194, 3.3344)	0.8146
6	1.3498	1.3921	(1.3874, 1.3922)	2.8781	1.3498	1.3891	(1.3865, 1.3917)	2.8292
7	3.0340	3.0340	(3.0330, 3.0338)	0.0198	3.0340	3.0334	(3.0326, 3.0342)	0.0198
8	3.2306	3.2269	(3.2426, 3.2454)	0.4131	3.2192	3.2316	(3.2287, 3.2345)	0.3837
9	6.0340	6.0348	(6.0329, 6.0349)	0.0017	6.0340	6.0338	(6.0329, 6.0347)	0.0033
10	6.2306	6.2263	(6.2358, 6.2532)	0.2226	6.2192	6.2320	(6.2294, 6.2346)	0.2054

through the finite queues, and the generalized service times. Moreover, only the expected average sojourn time of products 1 and 6 gives relative errors of over 1%. Additional results on a queue-by-queue basis comparison appear in Table 8.6. In this table, the analytical results are shown *above* and the simulation results are *below*

Table 8.6 Detailed node analysis

			Exponential Service Times					Erlang Service Times				
λ_i and μ_i	Resource Activity	Node	L	LQ	W	WQ	ρ	L	LQ	W	WQ	ρ
$\lambda_i = 8.5922$ $\mu_i = 250.00$ $\lambda_i = 2.7610$ $\mu_i = 125.00$	S_3	2	0.0344 0.0343	0.0000 0.0000	0.0040 0.0040	0.0000 0.0000	0.0086 0.0086	0.0344 0.0344	0.0000 0.0000	0.0040 0.0040	0.0000 0.0000	0.0086 0.0086
		3	0.0225 0.0260	0.0004 0.0035	0.0084 0.0094	0.0002 0.0014	0.0221 0.0567	0.0221 0.0248	0.0004 0.0026	0.0080 0.0090	0.0000 0.0010	0.0221 0.0587
$\lambda_i = 11.1080$ $\mu_i = 12.0482$	A_4	1	0.9226 0.9226	0.0006 0.0004	0.0831 0.0830	0.0001 0.0000	0.1844 0.1823	0.9226 0.9226	0.0006 0.0006	0.0831 0.0831	0.0001 0.0001	0.1844 0.1794
		1	0.3464 0.3460	0.0098 0.0094	0.0340 0.0339	0.0010 0.0009	0.1683 0.1691	0.3464 0.3447	0.0098 0.0092	0.0340 0.0338	0.0010 0.0008	0.1683 0.1629
$\lambda_i = 10.1995$ $\mu_i = 30.3030$	A_5	1	0.3464 0.3460	0.0098 0.0096	0.0340 0.0339	0.0010 0.0009	0.1683 0.1662	0.3464 0.3458	0.0098 0.0082	0.0340 0.0339	0.0010 0.0009	0.1683 0.1616
		1	0.3464 0.3460	0.0098 0.0096	0.0340 0.0339	0.0010 0.0009	0.1683 0.1662	0.3464 0.3458	0.0098 0.0082	0.0340 0.0339	0.0010 0.0009	0.1683 0.1616
$\lambda_i = 1.8000$ $\mu_i = 30.3030$	A_7	1	0.0595 0.0596	0.0001 0.0001	0.0330 0.0331	0.0000 0.0001	0.0297 0.0292	0.0595 0.0594	0.0001 0.0000	0.0330 0.0330	0.0000 0.0000	0.0297 0.0298
		1	0.0593 0.0593	0.0001 0.0001	0.0330 0.0330	0.0000 0.0000	0.0296 0.0284	0.0593 0.0593	0.0001 0.0001	0.0330 0.0330	0.0000 0.0001	0.0296 0.0283
$\lambda_i = 7.8022$ $\mu_i = 12.0482$	A_9	1	0.6477 0.6477	0.0001 0.0000	0.0830 0.0830	0.0000 0.0000	0.1295 0.1268	0.6477 0.6477	0.0001 0.0001	0.0830 0.0830	0.0000 0.0000	0.1295 0.1276
		2	0.2996 0.2996	0.0000 0.0000	0.0500 0.0500	0.0000 0.0000	0.0300 0.0300	0.2996 0.2996	0.0000 0.0000	0.0500 0.0500	0.0000 0.0000	0.0300 0.0300
$\lambda_i = 21.7564$ $\mu_i = 370.370$	S_{11}	2	0.0587 0.0585	0.0000 0.0000	0.0027 0.0027	0.0000 0.0000	0.0098 0.0098	0.0587 0.0587	0.0000 0.0000	0.0027 0.0027	0.0000 0.0000	0.0098 0.0098
		3	0.0635 0.0851	0.0057 0.0275	0.0089 0.0122	0.0005 0.0042	0.0578 0.1469	0.0578 0.0809	0.0000 0.0210	0.0080 0.0112	0.0000 0.0032	0.0578 0.1475
$\lambda_i = 5.0686$ $\mu_i = 30.3030$	A_{12}	1	0.1684 0.1683	0.0012 0.0009	0.0332 0.0332	0.0002 0.0002	0.0836 0.0764	0.1684 0.1683	0.0012 0.0011	0.0332 0.0331	0.0002 0.0002	0.0836 0.0774
		1	0.0295 0.0295	0.0000 0.0000	0.0330 0.0330	0.0000 0.0000	0.0148 0.0145	0.0295 0.0295	0.0000 0.0000	0.0330 0.0330	0.0000 0.0000	0.0148 0.0137
$\lambda_i = 0.8973$ $\mu_i = 30.3030$	A_{14}	1	0.0296 0.0296	0.0000 0.0000	0.0330 0.0330	0.0000 0.0000	0.0148 0.0143	0.0296 0.0296	0.0000 0.0000	0.0330 0.0330	0.0000 0.0000	0.0148 0.0141
		2	0.5095 0.5095	0.0000 0.0000	0.0500 0.0500	0.0000 0.0000	0.0509 0.0509	0.5095 0.5095	0.0000 0.0000	0.0500 0.0500	0.0000 0.0000	0.0509 0.0509

each entry. These results include such performance measures as the expected waiting time in the queue, the expected waiting time at the node (including service), the expected queue length, and the utilization of each server.

Finite Queues with Erlang Service Times The service time distributions of the finite queues are assumed to be Erlang with two phases ($k = 2$). Thus, the finite nodes are assumed to be $GI/E_2/1/N$ queues, where N is equal to 4. A summary of results comparing the approximation and the simulation appears in Table 8.5, which illustrates the average sojourn times for the different product types flowing through

the network. As expected from distributions with lower variability, the average sojourn times are slightly lower than those computed from exponential distributions. Actually, all the results are within 1%, except for product classes 1 and 6, which are 3.55% and 2.83%, respectively. Table 8.6 displays additional results on a queue-by-queue basis, comparing the approximate and simulated results. Here, too, the approximate results are very close in value to those given by the simulation.

8.4 Closed-Loop Conveyor Systems

In this section, we consider first a deterministic model for a closed-loop conveyor (such as towline or trolley conveyor), and a closed queuing network model afterward. Conveyors are crucial material handling devices for transferring material between workstations. The design, configuration, and layout of workstations and conveyors are a challenging problem. While there are numerous issues that one could examine, such as the speed of the conveyor, and waiting space for loading and unloading stations, we will focus first on the required capacity of the carriers of a closed-loop system.

8.4.1 Deterministic Conveyor Model

The loading or unloading *stations* are numbered in order *opposite* to the direction in which the conveyor moves. The *carriers* around the conveyor are equally spaced. When the conveyor reaches the steady-state condition the total amount of material loaded is equal to the total amount of material unloaded. Kwo [10, 11] developed the following principles for the analysis of this closed irreversible conveyor:

- Uniformity principle (materials uniformly distributed over conveyor)
- Capacity principle (carrying capacity at least equal to throughput requirement)
- Speed principle (carriers per unit time within allowable range)

The following notation is used in our analysis:

- s number of stations
- k number of carriers
- $\{t_n\}$ sequence of points in time at which carrier n passes station 1 (*reference station*)
- $f_i(n)$ amount of material (flow) *loaded* (+) or *unloaded* (−) on carrier n at station i
- $H_i(n)$ steady-state amount of material in carrier n immediately after passing station i

It is assumed that the conveyor is used continuously over an extended period of time and that the sequences $\{f_i(n)\}$ are *periodic*. The period is represented by p and it is defined as the number of carriers in the sequence. The loading and unloading stations are numbered in order opposite to the direction in which the conveyor moves. The k carriers are equally spaced around the conveyor. When the conveyor

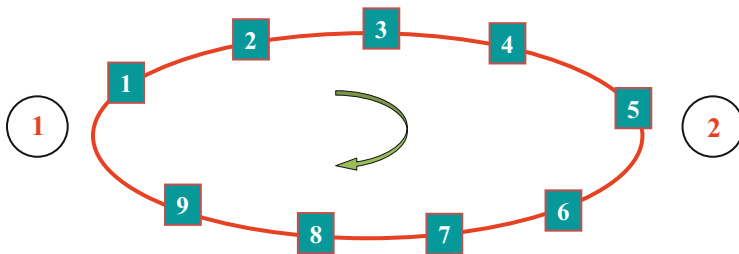


Fig. 8.21 Sample closed-loop conveyor model

reaches the steady state, the total amount of material loaded is equal to the total amount of material unloaded.

Figure 8.21 shows a conveyor with $s = 2$ stations and $k = 9$ carriers. This illustration is based on an example designed by Tompkins and White [21]. Station 1 is a loading station with flow sequence $\{f_1(n)\} = \{1, 1, 2, 2, 2, 1, 1\}$. Station 2 is an unloading station with sequence $\{f_2(n)\} = \{0, 0, 0, 0, 0, -5, -5\}$. Note that the period of the sequences is $p = 7$. It is noted that $(1 + 1 + 2 + 2 + 2 + 1 + 1) - (0 + 0 + 0 + 0 + 0 + 5 + 5) = 0$.

According to the given data, carrier $n = 1$ receives 1 unit at Station 1. Similarly, carriers $n = 2, 3, 4, 5, 6$, and 7 receive 1, 2, 2, 2, 1, and 1, respectively, at Station 1. For carrier $n = 8$, we start repeating the values in the sequence, $\{f_1(n)\} = \{1, 1, 2, 2, 2, 1, 1\}$. Thus, carrier $n = 8$ receives 1 unit and carrier $n = 9$ receives 1 unit, as well. Note that there are five more values in the sequence not used yet. Now all carriers have passed by Station 1 for the first time. As the conveyor continues rotating, carrier 1 reaches Station 1 for the second time. At this time, we relabel the carrier as $n = k + 1 = 10$. In the same manner, carriers 2, 3, ..., 9 are relabeled as carriers $n = 11, 12, \dots, 18$ the second time they reach station 1. Recall that we have used already the first two values of $\{f_1(n)\} = \{1, 1, 2, 2, 2, 1, 1\}$. Thus, carriers $n = 10, 11, 12, 13, 14$ are loaded with quantities (units) equal to 2, 2, 2, 1, 1, respectively, the second time they reach Station 2. At this time, a third cycle is started and the carriers are relabeled as carriers $n = 19, 20, 21, 22, 23, 24, 25, 26, 27$.

8.4.1.1 Muth's Basic Results [15]

- (a) k/p cannot be an integer for steady-state results.
- (b) r/p must be a proper fraction, where $r = k \bmod p$.
- (c) It is desirable for p to be a prime number.
- (d) Material balance equation

$$H_1(n) = H_1(n - r) + F_1(n), \text{ where } F_1(n) = \sum_{i=1}^s f_i(n) \quad (8.21)$$

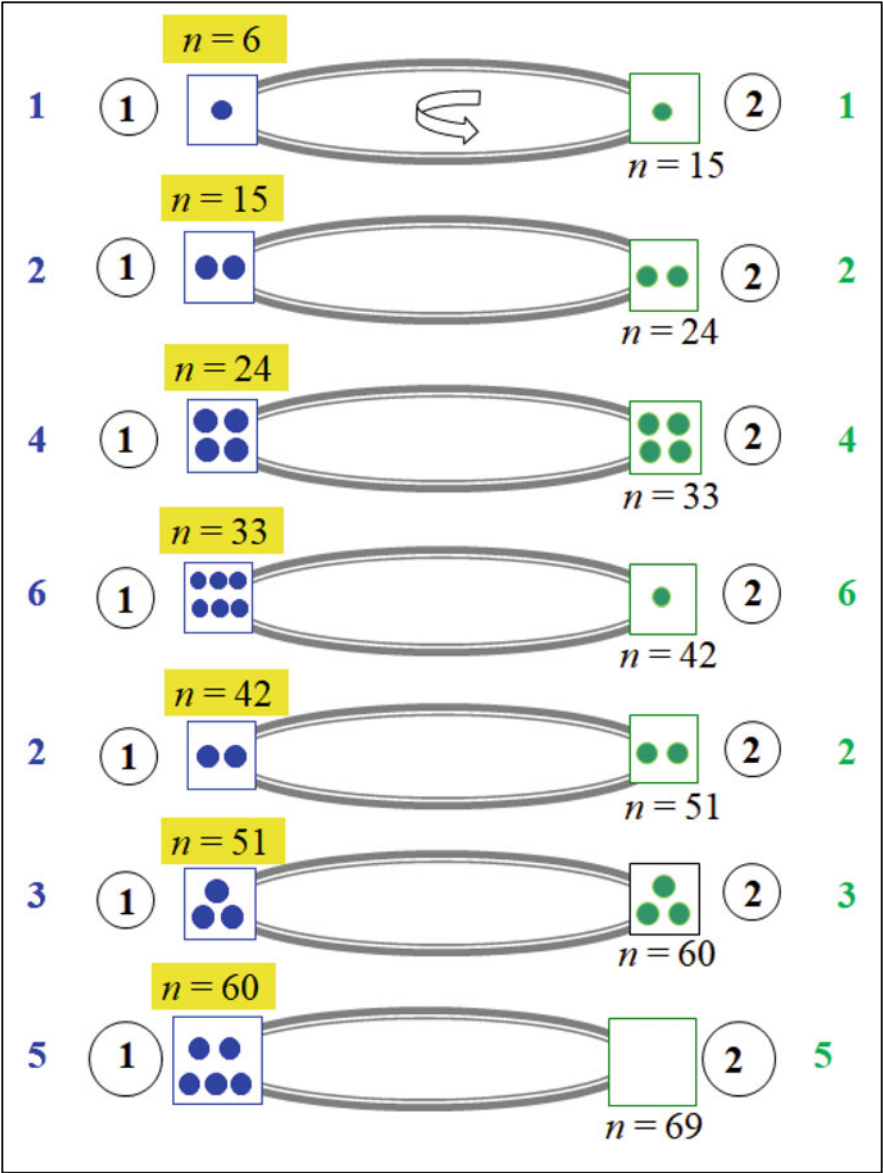


Fig. 8.23 Content of Carrier 6 after Stations 1 and 2

After the illustration of the procedure using carrier 6, we will formulate a general algorithm for conducting the analysis in a more systematic and efficient way. It is clear that as the number of stations and carriers increases so does the amount of computational work. To overcome this limitation, this algorithm has been programmed in Visual Basic.

8.4.1.3 Procedure for Finding the Capacity of the Carriers

Step 1. Initial Sequences. First, we set $H_1^*(1) = 0$. Subsequently, we complete the *initial* sequence for Station 1 using the relationship

$$H_1^*(n) = H_1^*(n-r) + F_1(n), \quad n = 1+r, 1+2r, \dots, p, p+r; r, 2r, \dots, p-1 \quad (8.22)$$

Once we obtain the initial sequence for carrier 1, we can obtain the initial sequence for each other carriers, using the general recursive relationship

$$H_{i+1}^*(n) = H_i^*(n) - f_i(n), \quad i = 1, 2, \dots, s-1 \quad (8.23)$$

Step 2. Steady-State Content of Carriers. The sequence of steady-state content for carriers is found from the initial sequences, using the relationship

$$H_i(n) = H_i^*(n) - c, \quad \text{where } c = \min_{i,n} \{H_i^*(n)\} \quad (8.24)$$

Step 3. Capacity of Carriers. The required minimum capacity for each carrier is:

$$B = \min_{i,n} \{H_i(n)\} \quad (8.25)$$

8.4.1.4 Conveyor Example

We consider again the sample conveyor shown in Fig. 8.21. For this conveyor, $s = 2$, $k = 9$, $p = 7$, $r = 9 \bmod 7 = 2$. Also, $\{f_1(n)\} = \{1, 1, 2, 2, 2, 1, 1\}$ and $\{f_2(n)\} = \{0, 0, 0, 0, 0, -5, -5\}$. Thus, using Eq. (8.21), $\{F_1(n)\} = \{1, 1, 2, 2, 2, -4, -4\}$.

Step 1. Initial Sequences. First, we set $H_1^*(1) = 0$. Equation (8.22) is now used to complete the initial sequence, with $n = 3, 5, 7, 9; 2, 4, 6$.

$$\begin{aligned} H_1^*(3) &= H_1^*(1) + F_1(3) = F_1(3) = 2 \\ H_1^*(5) &= H_1^*(3) + F_1(5) = 4 \\ H_1^*(7) &= H_1^*(5) + F_1(7) = 0 \\ H_1^*(9) &= H_1^*(7) + F_1(9) = 1 \\ H_1^*(2) &= H_1^*(9) = 1 \\ H_1^*(4) &= H_1^*(2) + F_1(4) = 3 \end{aligned}$$

$$H_1^*(6) = H_1^*(4) + F_1(6) = -1$$

Therefore, $\{H_1^*(n)\} = \{0, 1, 2, 3, 4, -1, 0\}$.

Step 2. Steady-State Content of Carriers. From Eq. (8.23), given $s = 2$, we obtain:

$$\begin{aligned}\{H_2^*(n)\} &= \{H_1^*(n) - f_1(n)\} = \{0, 1, 2, 3, 4, -1, 0\} - \{1, 1, 2, 2, 2, 1, 1\} \\ &= \{-1, 0, 0, 1, 2, -2, -1\}\end{aligned}$$

First, we find $c = -2$ as the minimum value among the entries of the following sequences:

$$\begin{aligned}\{H_1^*(n)\} &= \{0, 1, 2, 3, 4, -1, 0\} \\ \{H_2^*(n)\} &= \{-1, 0, 0, 1, 2, -2, -1\}\end{aligned}$$

Now, from Eq. (8.24), the steady-state quantities are given below:

$$\begin{aligned}\{H_1(n)\} &= \{2, 3, 4, 5, 6, 1, 2\} \\ \{H_2(n)\} &= \{1, 2, 2, 3, 4, 0, 1\}\end{aligned}$$

From the value 0 for carrier 6 in $H_2(n)$ we conclude that the analysis of this carrier starts with the carrier being empty before reaching Station 1 for the first time.

Step 3. Capacity of Carriers. Using eq. (8.25), $\mathbf{B} = 6$.

As a result of the analysis summarized above, the conveyor needs to have carriers with a minimum capacity of 6 units of product. The amount of material on the carriers and the carrier capacity in turn obviously depend on the number of carriers, k .

8.4.2 Conveyor Analysis Program

The conveyor analysis program (Conveyor.Vbp) was developed by Praveen K Chapa [4] in 2003, as a partial requirement for his MS degree. The VB program performs the conveyor analysis for a deterministic closed-loop irreversible conveyor. This program is available on the website. The executable file is named Conveyor.exe. To run the program, the user needs to input the password in the password box of the first screenshot, as indicated below.

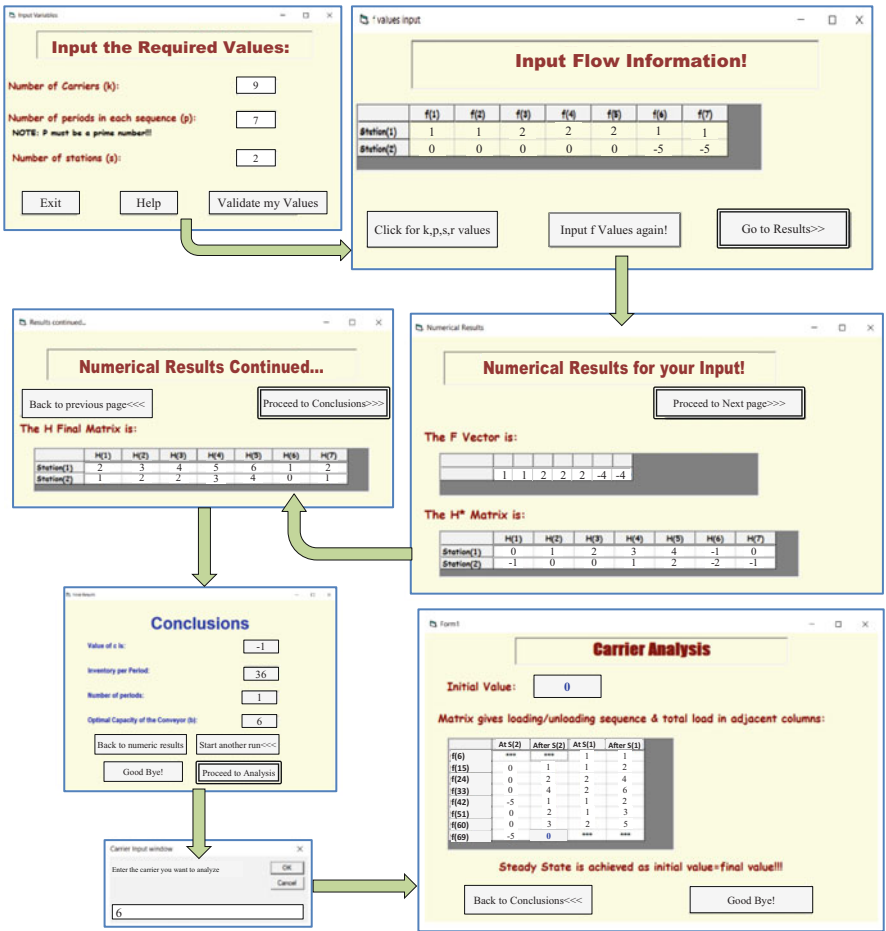


Fig. 8.24 Computer solution for sample closed-loop conveyor problem



Figure 8.24 shows the computer solution to this problem. The figure includes seven screenshots with input and results:

1. Input required values.
2. Input flow information.
3. Initial sequences for carriers.
4. Steady-state sequences.
5. Conveyor capacity and inventory analysis.
6. Label of carrier for which the carrier analysis is done.
7. Carrier analysis for selected carrier.

The capacity of the carrier is shown on the next-to-the-last screenshot. The inventory per period (cycle) is equal to the sum of the steady-state quantities for all carriers at all stations. It is equal to $\sum_{i=1}^s \sum_{k=1}^p H_i(n) = 36$. Furthermore, the number of complete periods (cycles) is equal to the integer part of $k/p = [9/7] = 1$.

8.4.3 Stochastic Analytical Approaches

This section describes another type of closed system with a different type of capacity, where the capacity is a material handling buffer between stations in the layout. Since there will be an interconnected set of finite resources in the layout design, an approach based upon analytical queuing network models will be utilized to determine this inter-line buffer capacity. Because the resources of the workstations and the material handling system are discrete in number, a finite queuing network model with a fixed population of products or unit loads flowing through the system will be described. Also, since the population of carriers or unit loads is finite and one needs to control this variable, a closed network model will be chosen so that the products or products move between the resources of the system and recirculate, as in the example network in Fig. 8.25.

Closed Queuing Network Models The N units flowing through the system can represent products, pallets, vehicles, or totes moving between the workstations or the departments of the system.

The topology of the queuing network will include not only tandem or series systems, but split and merging topologies as well. This topology flexibility allows us to model many different layout types and compare them to help us choose the best layout.

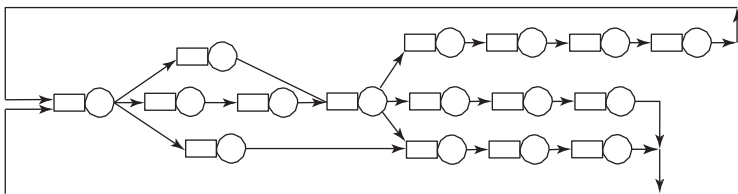


Fig. 8.25 Closed tandem queuing network example

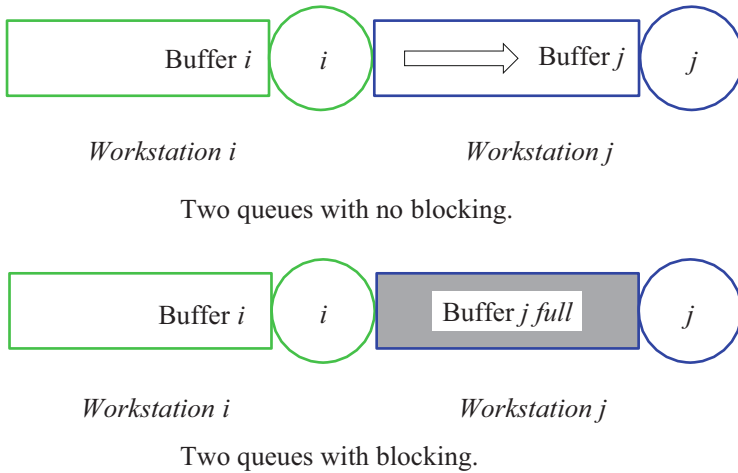


Fig. 8.26 Blocking in two workstation queues

Another important assumption here is that the queue in front of each workstation is finite in size, so that if the “buffer” in front of a workstation is full, it will block the flow of products/customers to the workstation (see Fig. 8.26).

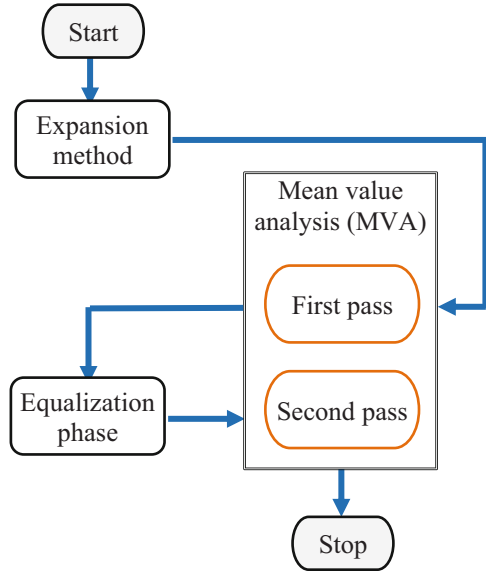
In Fig. 8.26, products/customers from workstation i are blocked from entering workstation j when the buffer in front of workstation j is full. They have to wait until enough space is available to move into the buffer or queue for workstation j . An example of such a buffer would be an in-line conveyor connecting workstation i with j .

In addition, we assume that we know the service rates m_i at each workstation and that these service rates follow an exponential distribution. Assuming an exponential distribution will provide a worst-case design scenario—i.e., an upper bound on the buffer space and the performance measures. This is felt to be important in the initial design stages of a layout. For more general service time distributions, simulation is recommended.

There are a number of algorithms one could use for closed queuing network models. The one that has been most useful has been the mean value analysis (MVA) algorithm, developed by Reiser and Lavenberg [17, 18]. It is largely based on the application of Little’s law to decomposable queuing networks.

We will consider the standard single server model $M/M/1$, the infinite server model $M/G/\infty$, or else the $M/M/C/C$ state-dependent model with *first-come, first-served (FCFS)* or *processor-sharing (PS)* queuing disciplines and traffic utilization $\rho < 1$ for all nodes.

Fig. 8.27 Algorithmic decomposition procedure



8.4.3.1 Algorithmic Decomposition Procedure

The basic procedure for solving the performance modeling and optimization problem involves the performance modeling tool of the expansion method along with an equalization phase and the mean value analysis (MVA) for computing the performance measures in closed queuing networks. Figure 8.27 shows a conceptual view of the algorithm described in Reference [5],

Mean Value Analysis The mean value analysis (MVA) algorithm is based upon the arrival theorem [17, 18] and the application of Little’s law to the entire network. Basically, the arrival theorem states [17, 18]:

Theorem: In a closed queuing network, the steady-state probabilities at product arrival epochs are identical to those of the same network in long-term equilibrium with one product removed.

In other words, at the moment of arrival of a product to a node with L products in the system, it is certain that this arriving product is not in the queue, then there are at most $L - 1$ products ahead in the queue. The number of products at the node is simply the number when there are $L - 1$ products in the system.

The fundamental equation of MVA is based upon the arrival theorem and relates the mean response time of a product at the i th node and the mean number of products at that node with one less product in the network:

$$W_i(N) = \frac{1}{\mu_i} (1 + L_i(N - 1))$$

The other important relationships used by MVA are Little's law, which for the particular node is

$$L_i = \theta_i W_i$$

and its application for the entire closed network:

$$N = \theta_i W$$

where $N = \sum_i L_i$.

In our approach using the MVA, we are assuming that the arrival theorem applies, when in fact, because our network is not product-form, this assumption is only a conjecture. Thus, when the holding nodes' service rate is affected by the squared coefficient of variation in the service time, that change is reflected in the MVA. So, no real change is made to the MVA itself other than what the expansion method passes to it.

Thus, we have an approximate MVA (AMVA) type of approach. What is particularly appealing about this approach is that, since we do not really change the MVA algorithm other than what is passed to the algorithm, we have a very flexible and general approach, which can be extended to multichain and multiclass closed queuing network models with multiple servers. Various other types of AMVA algorithms are discussed by Buitenhek [3]. For more details regarding the MVA algorithm, see [17].

Powell's Algorithm The heart of the optimization procedure is Powell's unconstrained derivative-free optimization method. As presented by Himmelblau [7], the method finds the minimum of a nonlinear function by successive application of unidimensional searches starting at a given point, along a set of conjugate directions. These are generated within the method itself.

Figure 8.28 illustrates the steps of the optimization algorithm to simultaneously find the number of optimal buffers N^* , which is based on an iterative application of Powell's method. Obviously, the algorithm illustrated in Fig. 8.28 is very complex. Only a brief description will follow; for further details, see Reference [5].

In the first phase of the algorithm, the initial buffer vector is either estimated from the service rates and the given N via the MVA algorithm or else provided as input. The starting buffer vector is crucial to the performance of the optimal search. Interestingly enough, the initial starting solution generated through the MVA algorithm seems to be very reliable. Once the initial buffer vector is established, Powell's method searches for the optimal value, while utilizing the expansion method to compute the blocking probabilities and the revised service rates, which are then passed to the multi-pass equalization phase version of the MVA, to compute

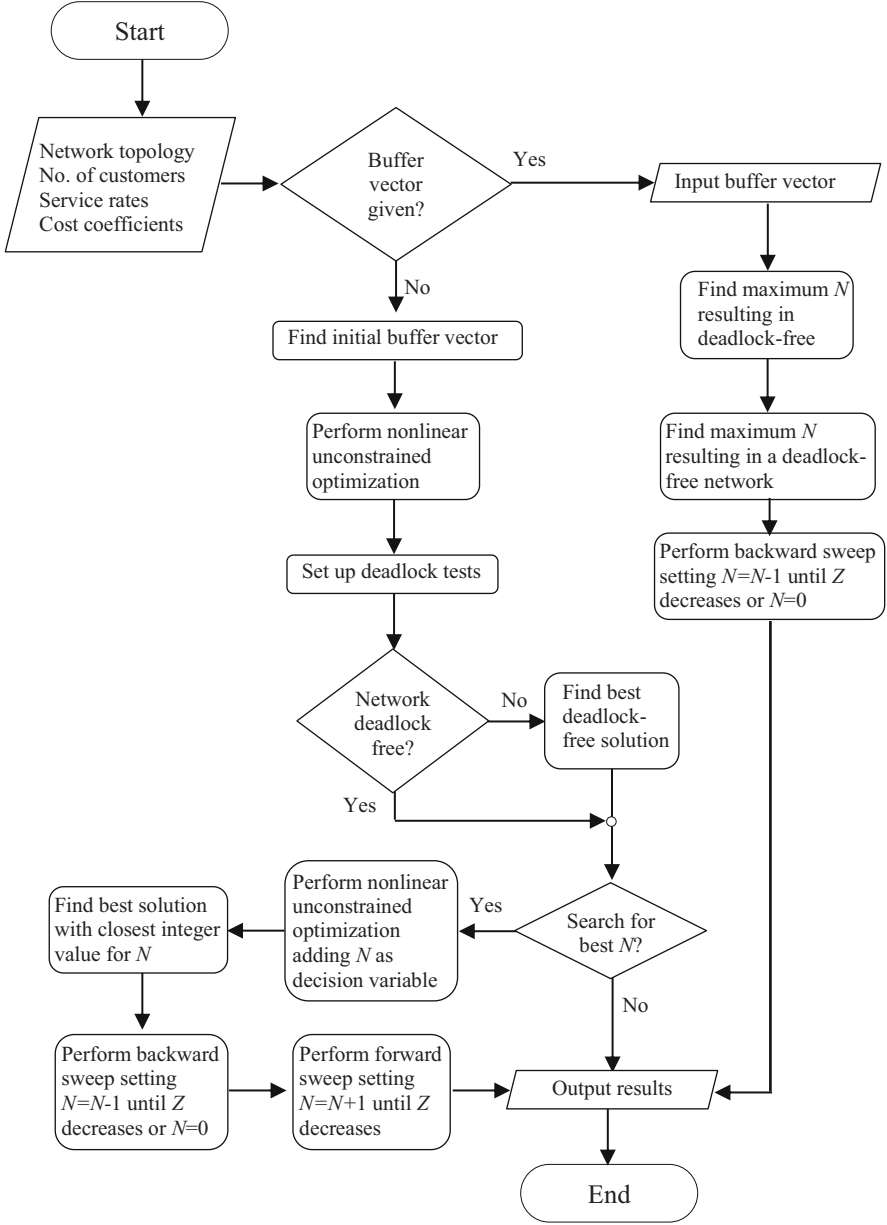


Fig. 8.28 General algorithm flowchart

the performance measures. Deadlock-free tests are carried out. Once they are passed, if requested, the algorithm searches for the best N^* value by performing backward and forward sweeps with Powell's algorithm.

8.4.3.2 Computer Experiments

In this subsection, we will demonstrate the software tool provided on the website for the layout and design of material handling systems and workstations with the aforementioned tools of the expansion method and Powell's optimization procedure.

We will examine closed network topologies, very similar to the conveyor examples, and we will assume that the products are moved from one workstation to another through some discrete material handling system, but we will restrict the number of products or products that can move between workstations. We will consider a modified model for a classical formulation, namely:

$$\begin{aligned} \text{Maximize} \quad & Z = w_\theta \Theta - w_W \bar{W} - w_B \sum_i x_i \\ \text{subject to} \quad & x_i \leq 1, \quad i = 2, 3, \dots, M \end{aligned}$$

where w_θ is a profit coefficient equal to \$35 per unit, w_W is a cost coefficient for the cycle time in the system set at \$10 per time unit, and w_B is a cost coefficient on the cost of each buffer in the network set at \$1 per buffer. Throughput and cycle time are very important performance measures in manufacturing and service systems. These parameters can be varied by the user in the computer program.

Five Node Tandem Network This is the classical tandem network topology (Fig. 8.29). Here, we will vary the service rates at the queues to see how the buffers would be allocated as a function of the service rates.

The output from the computer algorithm is included below. As you can see by the results, the optimal buffer sizes are optimally distributed according to the service rates in order to maximize throughput and minimize cycle time.

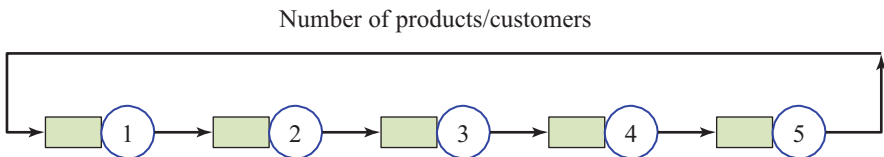


Fig. 8.29 Closed tandem queuing network model

```

#####
Resource Allocation Problem: Finite Closed Queuing Networks
#####
Input
%%%%%%%%
    Number of nodes/stations: 5
    Number of customers in the network:      5
    The service rates are:
        1.0000    2.0000    3.0000    4.0000    5.0000
RESULTS
%%%%%%%%
    The upper bound for throughput is    0.9484422
    The lower bound for cycle time is    5.271803
=====
Resource Allocation Problem: Summary of Results
=====
    * Buffer allocation for a network with    5 customers:
        Function value, F(X) =          31.836267
        Throughput = 0.859103      Cycle time = 5.820027
    Variable/buffer values:
    3.000050      2.000050      1.000000      1.000000      1.000000

    Number of buffer spaces in the minimum chain:      8.00

//////////
Summary of performance measures for final solution
=====

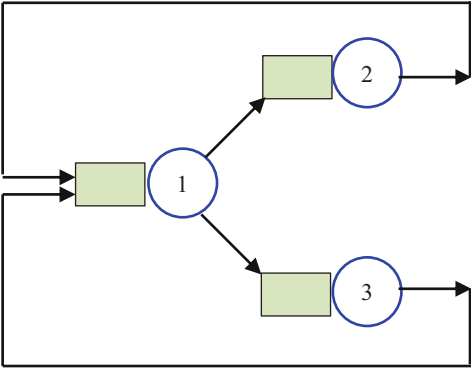
Throughput of network    0.8591025
Cycle time for network    5.820027

           W1           W2           W3           W4           W5
Waiting time:  3.180981  0.9072412  0.4838730  0.3266338      0.9212978
Queuing Time:  2.128641  0.3641728  0.1311366  6.6313565E-02  0.3729516
Avg # at node:  2.732789  0.7794132  0.4156965  0.2806119      0.7914893
Avg # in queue: 1.828721  0.3128617  0.1126598  5.6970153E-02  0.3204037
Utilization:   0.904068  0.4665515  0.3030367  0.2236417      0.4710856
=====

```

Three Node Split Network In this topology, a split situation is examined, as illustrated in Fig. 8.30. Split topologies as opposed to tandem topologies are sometimes very useful in better managing the flows in the network, especially if one has multiple part types flowing through the system. Again, we wish to optimize the buffer allocation by maximizing throughput and minimizing cycle time.

Fig. 8.30 Split queuing network model



The computer input data and output results for the three-node split-topology network with varying service rates are shown below.

```
##### Resource
Allocation Problem: Finite Closed Queuing Networks
#####
```

Input

```
%%%%%%%%
Number of nodes/stations :      3
Number of customers in the network :  10
Coefficient of variation in the network :    1.00
The service rates are :
      5.0000      3.0000 3.0000
```

RESULTS

```
%%%%%%%%
The upper bound for throughput is      4.601167
The lower bound for cycle time is      2.173362
```

```
=====
Resource Allocation Problem:  Summary of Results
=====
```

```
* Buffer allocation for a network with 10 customers:
Function value, F(X) =    -107.963371
Throughput = 4.219017    Cycle time =    2.370221
Variable/buffer values:
      6.000000      5.000000      5.000000
Number of buffer spaces in the minimum chain:      11.00
```

////////////////////////////////////

Summary of performance measures for final solution

Throughput of network	4.219017		
Cycle time for network	2.370221		
	W1	W2	W3
Waiting time, W_i :	1.213372	1.156849	1.156849
Waiting time in queue, W_{qi} :	0.9918701	0.8020995	0.8020995
Average number in node, L_i :	5.119235	2.440383	2.440383
Average # in queue, L_{qi} :	4.184716	1.692036	1.692036
Utilization ratio, P_i :	0.9345181	0.7483472	0.7483472

Layout Comparison This final example compares two layout alternatives involving 11 different workstations. The example is adapted from one given in Reference [14]. We want to compare the performance of the two layouts based on the dynamic performance measures. Four different products are manufactured on a set of 11 workstations. The products, hourly demands, and operation sequences are given in Table 8.7. We are using 25 different MHS carriers to transfer the products through each of the two layout alternatives.

Tandem Network In the first example, we consider the arrangement of workstations as a single tandem network. Figure 8.31 shows the network consisting of 11 workstations. This arrangement is very effective for minimizing the movement

Table 8.7 Product routing information

Product	Hourly demand	Operations sequence
A	20	1-2-3-4-5-6-7-8
B	10	2-3-4-5-7-8
C	15	2-3-4-9-10-11
D	10	1-2-3-4-9-10-11

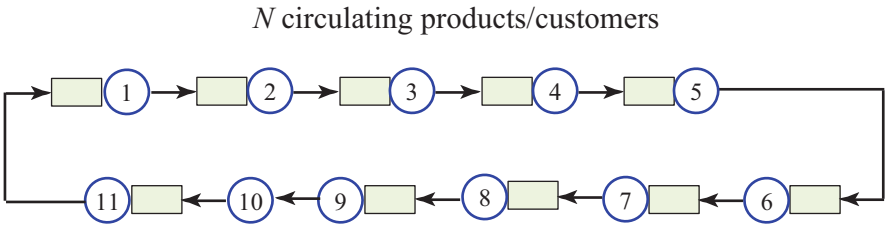


Fig. 8.31 Eleven-node tandem network

complexity in the material handling system, but it has some consequences for the system performance.

The computer results for this 11-node tandem network example are shown below.

```

                                11-Node Tandem Network
Number of nodes/stations:      11
Number of customers in the network:  25
Coefficient of variation in the network:  1.00
The service rates are:
    7.0000    3.0000    3.0000    3.0000    3.0000
    3.0000    3.0000    3.0000    3.0000    3.0000
    3.0000

RESULTS
%%%%%%%%
    The upper bound for throughput is      2.194660
    The lower bound for cycle time is      11.39128

2.508218      2.508218      2.508218      2.508218      2.508218
2.508218      2.508218      1.821958
Average #in queue, Lqi:      0.2248493      1.771606      1.771606
1.771606      1.771606      1.771606      1.771606      1.771606
1.771606      1.771606      1.162171
Utilization ratio, Pi:      0.3792265      0.7366123
0.7366123      0.7366123      0.7366123      0.7366123      0.7366123
0.7366123      0.7366123      0.6597877

=====
Resource Allocation Problem:  Summary of Results
=====
* Buffer allocation for a network with 25 customers:
  Function value, F(X) =  98.573090
  Throughput =  1.876276      Cycle time = 13.324268
Variable/buffer values:
  1.000000      3.000005      3.000005      3.000005      3.000005
  3.000005      3.000005      3.000005      3.000005      3.000005
  3.000005

  Number of buffer spaces in the minimum chain: 31.00
  //////////////////////////////////////
Summary of performance measures for final solution

Throughput of network      1.876276
Cycle time for network      13.32427
Waiting time, Wi:          0.3219547      1.336807      1.336807
  1.336807      1.336807      1.336807      1.336807      1.336807
  1.336807      1.336807      0.9710504
Waiting time In queue, Wqi: 0.1198381      0.9442141      0.9442141
  0.9442141      0.944214      0.9442141      0.9442141      0.9442141
  0.9442141      0.944214      0.6194029
Average number in node, Li:  0.6040758      2.508218      2.508218
```

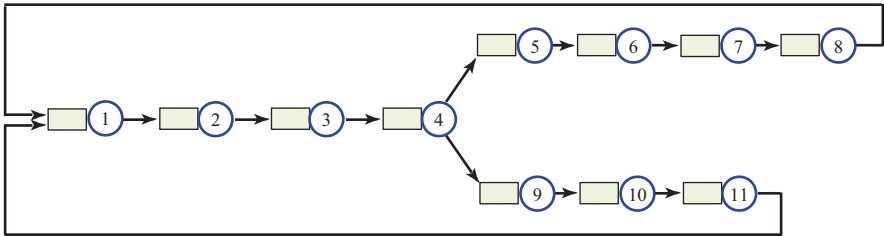



Fig. 8.32 Splitting topology layout

From the computer results, we can see that the throughput of the tandem system is 1.876 units per minute and the cycle time is 13.32 minutes. We are maximizing the throughput and minimizing the cycle time. This results in an objective-function value of \$98.57.

Splitting Network In this layout topology the workstations are organized with regard to the operations on the products, and certain advantages will result in the layout topologies by splitting the flows and redistributing the load on the workstations. Figure 8.32 shows the network for this example. This kind of topology comparison is very valuable in the initial design stages of a layout. Computer results are shown below.

11 Node Split Topology

Number of nodes/stations : 11
Number of customers in the network : 25
Coefficient of variation in the network : 1.00
The service rates are :
7.0000 3.0000 3.0000 3.0000 3.0000
3.0000 3.0000 3.0000 3.0000 3.0000
3.0000

RESULTS

%%%%%%%%%
The upper bound for throughput is 2.701316
The lower bound for cycle time is 9.254749

Resource Allocation Problem: Summary of Results

* Buffer allocation for a network with 25 customers:
Function value, F(X) = 49.086716
Throughput = 2.375790 Cycle time = 10.522814
Variable/buffer values:
1.000000 5.000004 6.011223 6.000004 2.000005
1.000000 1.000000 1.000000 2.000005 1.000000
1.000000
Number of buffer spaces in the minimum chain: 33.00

////////////////////////////////////

Summary of performance measures for final solution

Throughput of network	2.375790			
Cycle time for network	10.52281			
Waiting time, Wi:	0.3930955	2.689033	2.689033	
2.128065	0.8001214	0.8001214	0.8001214	0.6232853
0.8001214	0.8001214	0.6232853		
Waiting time in queue, Wqi:	0.1885984	2.307369	2.307369	
1.763034	0.3873638	0.3873638	0.3873638	0.2634661
0.3873638	0.3873638	0.2634661		
Average number in node, Li:	0.9339124	6.388577	6.388577	
5.055836	0.9504603	0.9504603	0.9504603	0.7403976
0.9504603	0.9504603	0.7403976		
Average # in queue, Lqi:	0.4480702	5.481824	5.481824	
4.188599	0.4601476	0.4601476	0.4601476	0.3129701
0.4601476	0.4601476	0.3129701		
Utilization ratio, _Pi:	0.4858422	0.9067533	0.9067533	
0.8672373	0.4903128	0.4903128	0.4903128	0.4274275
0.4903128	0.4903128	0.4274275		

According to the computer output, in the splitting topology, the throughput is 2.376 units per minute and cycle time is 10.522 minutes. The throughput is 27% higher than in the tandem system, and the cycle time is 21% smaller. Furthermore, the objective-function value of the splitting system is one-half that of the tandem system, $\approx$ \$49.09. Of course, in the splitting system, the number of buffers is larger, reflecting a trade-off between the number of buffers and throughput and cycle time. The trade-off is justified for the given cost coefficients. While some complications may happen, the advantages of the layout and its performance are noteworthy.

Thus, utilizing the closed queuing network model was very revealing in determining the performance measures of the different layout topologies in the manufacturing system. This type of analysis is crucial to layout evaluation. The software used in the previous examples is available on the website.

8.5 Simulation Models

Simulation modeling, especially discrete-event digital simulation modeling, is a powerful and valuable tool for analyzing layouts and material handling systems. In this section, we present a detailed case study of its application to the design of the layout and the material handling system of a cellular manufacturing system. In most cases, a material handling system manages the flow of raw material and components to and from the cell of a cellular layout. Figures 8.33 and 8.34 show examples of layouts integrated with the operational routings in an MHS. In Section 8.6, we focus on the simulation model for a warehouse system.

Fig. 8.33 Example of multiple cells with a common MHS

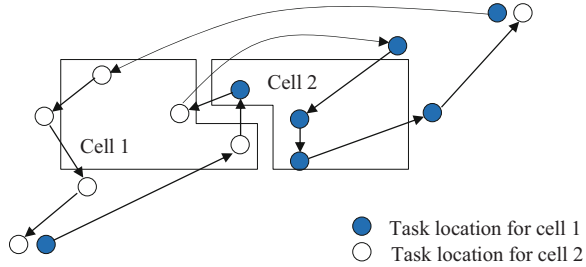
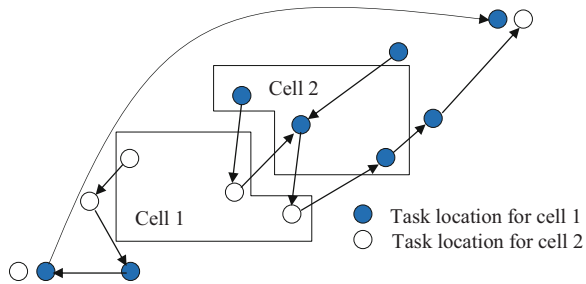


Fig. 8.34 Additional alternative layout relative cell layout



8.5.1 Cellular Methodology

The design process for a plant layout with cellular manufacturing must consist of the following two elements:

1. Layout of the individual cells, wherein the arrangement of machines, process equipment, and assembly stations is decided to facilitate production and to utilize the resources most efficiently.
2. Layout of cells in relation to each other to facilitate material handling and performance of other peripheral activities, without violating the external shop constraints (such as space limitations).

Both issues will be examined. The only object common to the individual cells is the material handling system (MHS). It will be assumed that one can generate different layouts which will satisfy all external constraints. Once different layouts are generated, the proposed methodology can be used to select those layouts that optimize the MHS utilization, while determining the appropriate number of MHSs and suggesting the optimal task schedule for each MHS within the selected layouts.

8.5.2 *Simulation Section Outline*

This simulation section has three parts: (1) Development and evaluation of single-cell layouts; (2) generation and evaluation of cell group layouts; (3) optimization of the material handling system interconnecting the cell groups and selection of final layout. The achievement of these objectives is documented in three subsections:

- (a) Background of case study
- (b) Individual cell simulation model
- (c) Cell network study

8.5.3 *Background of Case Study*

The XYZ Corporation manufactures, as one of its major product lines, a range of high-quality tools, some of which are sold under a well-known brand name. The strength of these products lies in their quality, as borne out by the lifetime warranty provided by XYZ.

To expand its market base, the corporation has decided to manufacture products aimed at the low-cost end of the market. To achieve a high level of productivity at the desired quality standards and low manufacturing costs, the company will use manufacturing cells consisting of three automated turret lathes, one stamping machine, and two assembly stations. An operator runs the cell, while a material handler performs other tasks to support the cell (see Fig. 8.34.).

The first part of the project involved conducting simulation studies of the new manufacturing cells and evaluating layouts for the individual cells. This was extremely valuable to select an appropriate layout for the configuration of each cell and justify the feasibility of this new manufacturing operation.

Table 8.8 shows the estimates in seconds of the loading time required on each machine and the assembly times required, under the column *Man*. When examining Table 8.8, one should refer to the layout in Fig. 8.35 which illustrates that the tasks occur in a counter-clock-wise fashion starting with the ACT-20 machine. Column *Auto* shows the time that the automatic machines require to process the part once the loading has been done. Column *Walk* shows the time required for the operator to move from the present station to the next. It is assumed that a part is always available for the operator to load onto the next machine, or assemble, as the case may be. After the stamping process, handles are collected in a pan, and when the total number of accumulated handles reaches 3600, the batch is sent off for heat treatment. After the heat treatment, which is a three-day process, the handles return to Station 6, where they are required for final assembly. After the stamping process, the operator picks up a body (which is routed here after heat treatment) and assembles it at Station 5. He then moves with the body to Station 6, where he also picks up a heat-treated handle. At this point, the final assembly is made, which is a series of steps as listed in the table. After the final assembly, the operator moves to Machine 1 to load a new

Table 8.8 Standard work combination chart

		Time in seconds				
No	Operation	Stn	Man	Auto	Walk	Part routing after operation
1	P. up forging, load ACT-20	1	5	37	2	Part ejected by ACT-20
2	P. up, load TC-2	2	4	34	2	Part ejected by TC-2
3	P. up, load ACT-20	3	4	43	1	Part ejected by ACT-20
4	P. up, stamp part	4	2	—	1	Handle to heat treatment
5	P. up and assemble body	5	4	—	1	Body taken to next station
6	Assemble body—hang card	6	4	—	—	Heat-treated handles available for assembly
7	Assemble body in handle	6	3	—	—	
8	Assemble spring and pwl	6	4	—	—	
9	Assy—body, hndl, spr, pwl	6	4	—	—	
10	Add grease in pwl pocket	6	2	—	—	
11	Assemble cap	6	4	—	—	
12	Auto torque screw	6	5	—	—	
13	Quality check	6	4	—	—	
14	Box ratchet	6	2	—		Finished part
						Operator moves to Station 1

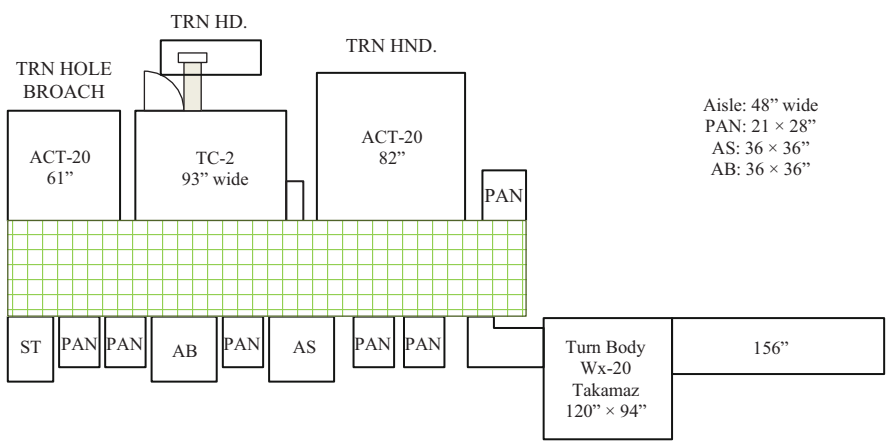


Fig. 8.35 Cell layout 1

Table 8.9 Water spider duties

Activity	Description	Minutes	Frequency	Freq/shift	Min/shift
A	Forgings in from storage	5	1/Shift	1.00	5.00
B	Load steel bars	30	1/Day	0.33	9.99
C	Handle out to heat treat	10	1/Day	0.33	3.33
D	Body out to heat treat	10	1/Day	0.33	3.33
E	Handle in from plate	5	1/Day	0.33	1.67
F	Body in from black oxide	5	1/Day	0.33	1.67
G	Finished ratchet shipment	7	1/Day	0.33	2.33
H	Organize pan, basket, skids	2	Hourly	7.00	14.00
I	Assemble boxes and label	3	Hourly	7.00	21.00
J	Chips out from cell	20	1/Day	0.33	6.67
K	General cell cleaning	30	1/Shift	1.00	30.00
L	Coolant refill	10	1/Shift	1.00	10.00
M	QC audit hnd before HT	10	1/Day	0.33	3.33
N	QC audit bds before HT	10	1/Day	0.33	3.33
O	QC audit bds at mach/hr	2	Hourly	7.00	14.00
P	Run cell through breaks	30	1/Shift	1.00	30.00
Q	Assist in cell tool chng	60	1/Shift	1.00	60.00
R	Run cell through breaks	30	1/Shift	1.00	30.00

forging and repeats the cycle. XYZ estimates that the cycle time will be 59 seconds, and in a shift of 8 hours (1 hour for breaks) the expected throughput should be 400 units.

A material handling person known as a “water spider” performs several duties to support the cell, as shown in Table 8.9. Although the water spider is external to the cell, his performance is critical to the operation of the cell. The times allocated for each task are also shown in Table 8.9. It is desired to increase the productivity of the cell to its full potential to achieve the aim of low-cost production. Our objective in this study was to model the layout and location of machines and workstations, assessing the flow processes and attempting to optimize these processes as best as possible.

We were also interested in developing an animated digital simulation model of the cell, which would allow for the modeling of the material flow and assembly processes. With the help of the simulation model, we can track the different operations, movements of the operator and the water spider, utilizations of the machines and the operator, and flow of different parts within and external to the cell, and to quantify the overall performance measures of the system. Simulation also helped to quantify the benefits resulting from any changes in layouts and locations, as well as any changes in the design of the process itself.

We describe in brief the simulation model and then discuss the different layouts considered in the first part of the analysis. We will then proceed to present the simulation results obtained with each of these layouts and describe some changes in system design.

8.5.4 Individual Cell Simulation Model

An exact simulation model of the cell was built in **Arena IV**, with animation provided by **Cinema IV** used to animate the model [9]. Simulation modeling was chosen as the tool to model the cells as opposed to analytical queuing network modeling techniques due to the complex interdependencies between the operator, the machine processing centers, and the material handling system.

The simulation program basically consists of two frames, the model and experiment frames. The model frame comprises the logic behind the process and the flow of the entities. The experiment frame consists of all experimental parameters to be input into the program for a given cell scenario.

In the Arena IV program, the three automatic machines, the stamping machines, and the two assembly workstations are described as *Resources* and are basically stationary. The delay time of each resource is shown in Table 8.8. The operator is modeled as a *transporter*, who moves from station to station and can be delayed at any station if required. The handles and bodies are the entities in the system. In addition to the time estimates shown in Table 8.8, which can be specified in the experiment frame of the program, one can also specify the distances between stations, the velocity of the operator, the number of transporters and resources, the possible routes that the entities can take, and other such details of the cell. It is easily seen that this system provides the modeler with an extremely powerful tool to quantify the performance of any system and process changes.

The water spider is also modeled as a transporter. The water spider is assumed to move freely between his scheduled duty stations, which are shown in Table 8.9. As seen in the table, tasks H, I, and O are performed every hour, while the other tasks may require up to one visit to the duty station per shift. Therefore, the simulation model creates a request for the water spider at every duty station depending on the frequency of the task. The water spider then travels at his walking speed from the present station to the station requesting his service. Some tasks are transportation tasks from one station to another (A, C, D, E, F, G, and J), while the other tasks are to be performed at a particular station. The Arena IV model therefore creates either a transportation delay or a stationary delay for the water spider, depending on the task. The transportation delay is computed based on the distances between the respective stations, which define the travel of the water spider. The hourly tasks are assigned higher priority over the other tasks.

The Arena program is capable of handling variations in all time estimates. The time estimates of assembly, loading, and automatic processing are assumed to be normally distributed with a mean μ and standard deviation σ . If one estimates no variation in the process at all, it can simply be controlled by setting $\sigma = 0$ in the experiment frame. The walking velocities are described as uniform distributions with a lower and upper limit μ_L and μ_U , respectively. Again, if one expects no variation in the walking speeds, this can be controlled by setting $\mu_L = \mu_U$. The time required to walk from one station to another is calculated by Arena based on the specified distance and the walking speed for every movement of the operator.

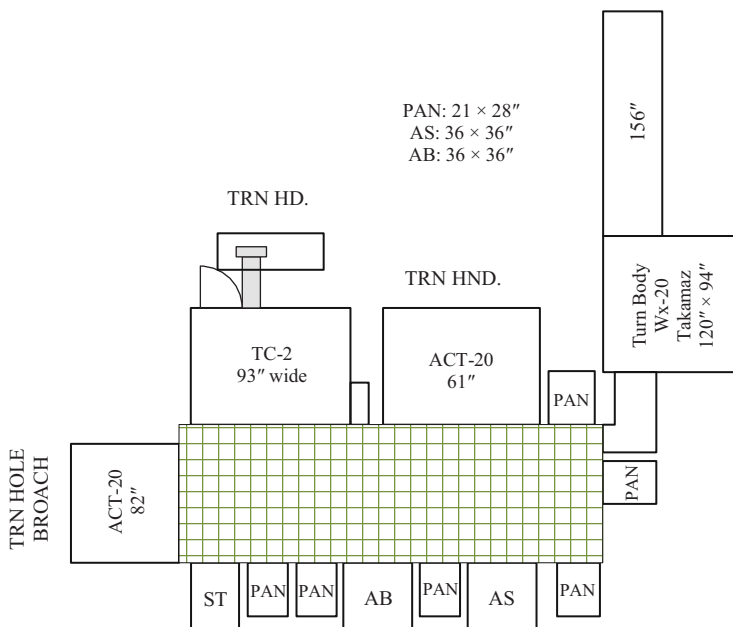


Fig. 8.36 Cell layout 2

Typically, a simulation is run for one shift, i.e., 25,200 seconds, and an additional 1000 seconds in the beginning to reach steady-state conditions. Thus, all results reported are over one shift.

The Arena IV program provides an output file that contains details about all resource utilizations, operator utilizations, cycle times, time spent in system by each part, walking times, throughput, water spider activities, and so on, which can be very insightful for making important decisions about the cell design. Most important of all, Arena IV can provide a report within minutes of any possible system changes, before changing the design of the cell, and justify whether or not any change should be made.

Layouts and Locations in the Cells In addition to the original layout shown in Fig. 8.35 as envisaged by XYZ, we developed two more layouts, shown in Figs. 8.36 and 8.37, which would facilitate shorter and smoother movements within the cell for the operator. Also, in these layouts, the walking distances are reduced between certain stations, and these would lead to an improvement in throughput (as shown by the simulation experiments).

Due to the flexibility incorporated in the simulation model, one can easily specify the distances between the stations for each layout and measure the overall effect on the system. Each of these three layouts has also been animated to visually analyze the system.

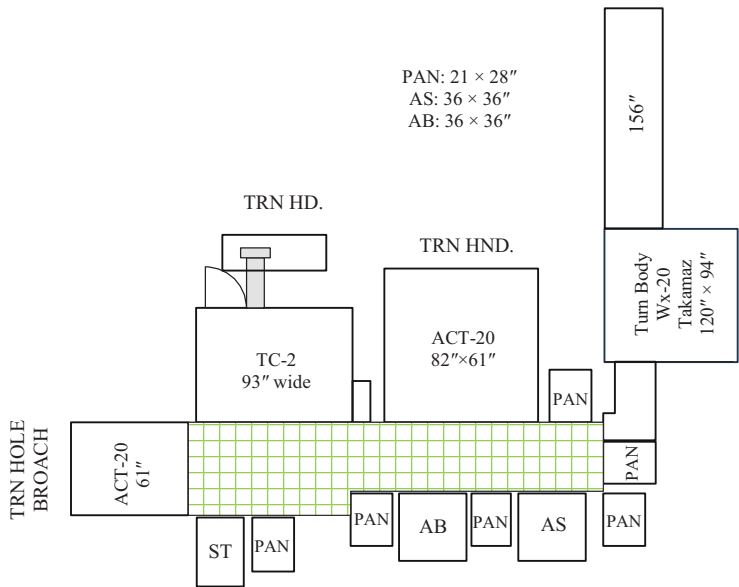


Fig. 8.37 Cell layout 3

In addition to simulating the three layouts with one operator, we considered the cases when two operators would work in the same cell. The reason for the two operators is seen in the last column of Table 8.10, where it is clear that when there is one operator, he is the bottleneck of the cell. As can be seen in Table 8.10, using two operators dropped their utilization to $\approx 62\%$ rather than the 50% that might be expected. Also, having the animation became very valuable with the two operators in the cell because we could see no collisions between them, which was felt might be a possible problem.

We have simulated Layout 1 with another variation where the walking times vary from 0 to 10% to accommodate in-process quality control. In addition, a simulation model was developed for two adjacent cells with two operators, where each operator is responsible for his/her own cell and both cells are arranged according to Layout 1.

Simulation Results Table 8.10 highlights some of the important findings from the simulation experiments. Layouts 2 and 3 yield a higher throughput than Layout 1, while the introduction of two operators yields a still better improvement in throughput. It is interesting to note that the introduction of two operators results in machine 3 becoming the bottleneck instead of the operator. This makes sense; the bottleneck shifts from the single operator to machine 3 because of the intricate system relationships of the work cell. All six variations have also been linked with Cinema to give an animated demonstration of each scenario.

Table 8.10 Results of simulation experiments

No.	Description	Throughput	Cycle time	ACT20 util	Oper util
1	Layout 1, one operator	426	59.76	79.65	98.01
2	Layout 2, one operator	431	58.67	80.48	99.75
3	Layout 3, one operator	432	58.59	80.76	99.72
4	Layout 1, two operators	537	46.70	100.00	62.42
5	Layout 2, two operators	537	46.63	100.00	61.79
6	Layout 3, two operators	537	46.64	100.00	61.57
7	Layout 1, one operator, variation	424	58.93	78.96	99.75
8	Layout 1, two cells, one operator/cell	849	59.25	79.14	99.78

Finally, a model was constructed which combines the activities in the cell and the activities of the water spider. In this case, also Layout 1 was used for the cell. In the model, tasks P and R were excluded, as these are basically similar to the earlier simulations, and the water spider activities were simulated for the remaining 7 hours. Based on the distance matrix generated from the data, it was found that the average spider utilization is 49.95%, while he is busy for 195.98 minutes in one shift (when the remaining hour is added, this would be 255.98 minutes).

8.5.5 Cell Network Study

It was decided to study the impact of operating two cells with two independent operators, and with one water spider performing all the supporting tasks required to maintain the two cells. The two cells would be arranged according to one of the three layouts shown in Figs. 8.38, 8.39, and 8.40. It is important to note the arrangement of machines and work centers within a cell as well as the locations of the two cells relative to each other.

Preliminary simulation results indicated that in most instances the water spider was not able to complete the tasks allocated to him according to those specified in Table 8.9, while supporting two cells. Therefore, the water spider duties were reassigned according to those shown in Table 8.11. The duties shown here are to be performed for every cell that the water spider is designated to support. Thus, the dynamic simulation model was essential in predicting the effect of the task sequence on the cell operations before the actual construction of the cell.

In addition, some maintenance tasks were also allocated to each operator running the cell in order to offload tasks from the water spider. These are shown in Table 8.12.

The three layouts—A, B, and C—were simulated in view of the above changes, and the results are summarized in the next section.

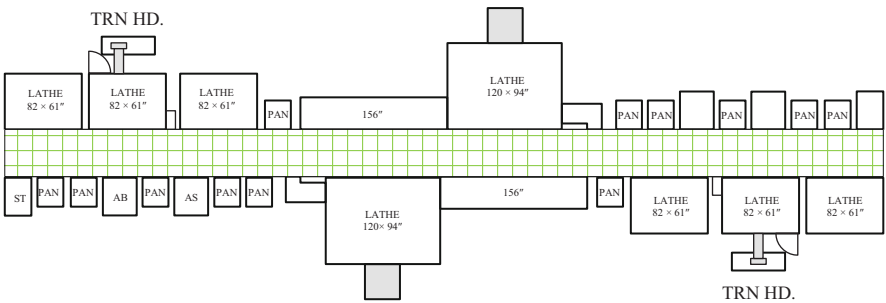


Fig. 8.38 Cell network layout A

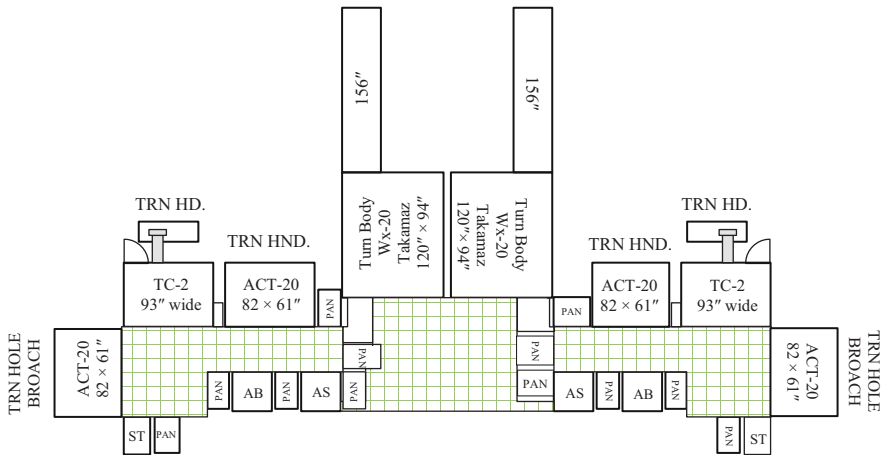


Fig. 8.39 Cell network layout B

Simulation of Cell Network Layouts A, B, and C The simulations of the three layouts were carried out over the period of one day (three shifts). The two operators and the water spider are modeled as transporters, who work in shifts of 8 hours each, with 30 minutes reserved for breaks. While the two operators take staggered breaks, the water spider runs the two cells. Therefore, the two cells will operate for a full 24 hours during a day. However, the water spider will have only 7 hours and 30 minutes per shift to carry out his duties, since his activities are not delegated to anyone else during his break.

While various tasks need to be attended to by the operators and the water spider from time to time, depending upon their frequency and the randomness associated with their creation, it is assumed that the breaks will have the highest priority, followed by maintenance (tool-change) tasks, hourly tasks, per-shift tasks, and

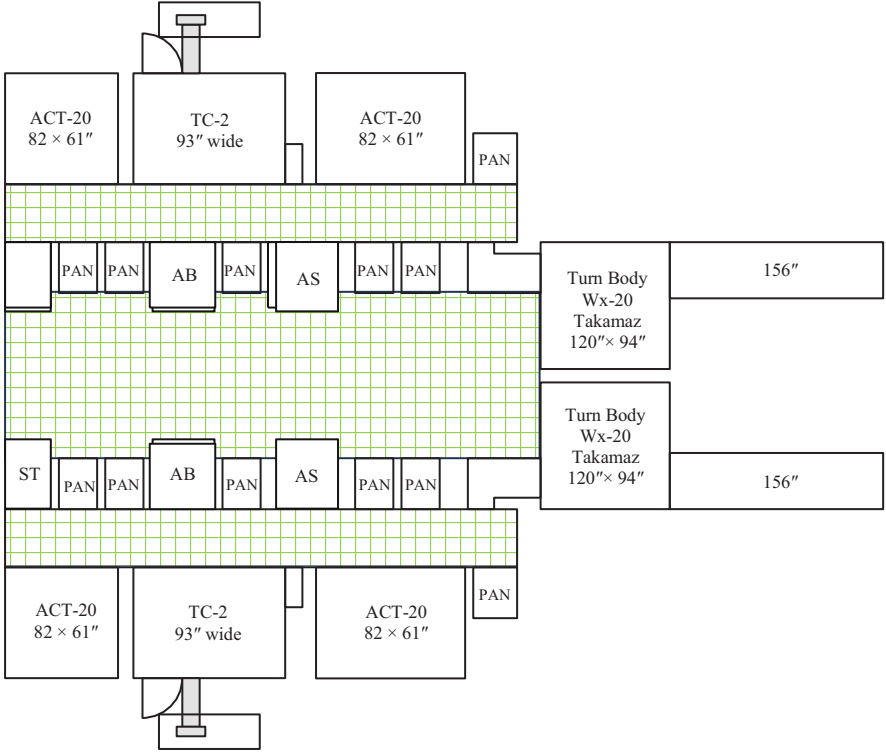


Fig. 8.40 Cell network layout C

Table 8.11 Revised water spider duties

Activity	Description	Minutes	Start location	End location	Type
A	Forgings in from storage	5	Forge room	Cell	L
B	Load steel bars	30	Cell	Cell	S
C	Product out to heat treat	10	Cell	Heat treatment	L
D	Product out to heat treat	10	Cell	Heat treatment	L
E	Product in from plate	5	Heat treatment	Cell	L
F	Product in from black oxide	5	Heat treatment	Cell	L
G	Finished product shipment	7	Cell	Finished goods	L
H	Organize pan, basket, skids	2	Cell	Cell	S
I	Assemble boxes and label	3	Cell	Cell	S
J	Chips out from cell	20	Cell	Chip removal	L
K	General cell cleaning	30	Cell	Cell	S
L	Coolant refill	10	Cell	Cell	S
M	QC audit hnd before HT	10	Cell	Cell	S
N	QC audit bds before HT	10	Cell	Cell	S
O	QC Audit bds at mach/hr	2	Cell	Cell	S
P	Assist in cell tool chng	60	Cell	Cell	S

Table 8.12 Maintenance tasks allocated to operator

No.	Activity	Min.	Freq.
1	ACT20 tool change	10	1/shift
2	TC2 tool change	5	1/shift
3	ACT20 tool change	10	1/shift
4	Body assy. tool change	5	1/shift
5	Washup/cleanup	25	1/shift

Table 8.13 Summary over three independent replications

	Layout A		Layout B		Layout C	
Observation	Average	Maximum	Average	Maximum	Average	Maximum
Cell 1 throughput	1303	1316	1272	1318	1303	1312
Cell 2 throughput	1283	1334	1327	1339	1284	1345
Total throughput	2586	–	2599	–	2587	–
Spider utilization	89.36	97.41	94.24	98.00	89.23	92.07
Spider busy mins	1287	1403	1357	1411	1285	1326

per-day tasks, respectively. The frequency of daily, hourly, and per-shift tasks is controlled in the simulation model by defining the offset time from the beginning of the simulation and the time between the creation of successive tasks. All tasks except the random breakage (tool-change) tasks are assumed to occur with very little variation, and hence the inter-arrival time for such tasks is modeled as a normal distribution with mean m and standard deviation $0.1 m$. The breakage and tool maintenance tasks (as shown in Tables 8.10 and 8.11) are assumed to occur at random, and are modeled with exponential interarrival times to capture the underlying uncertainty. Owing to the large variation here, one needs to run several replications of the simulation experiments and then compare the average results over several runs. Each layout was run over three replications, and relevant average results are presented in Table 8.13.

Simulation Results It should be noted that the variation in the throughputs is due only to the randomness associated with the processes within the cell, such as the random breakdowns that the operator has to attend to and the variation in his walking speed, and not due to the differences in Layouts A, B, and C. It can be seen from the above throughput results that one will (on an average) obtain a throughput of 1295 products per cell per day (which is the mean of all the above throughputs). To measure the effect of Layouts A, B, and C, one has to examine the water spider utilization. It appears that Layout C performs better than Layouts A and B, since the average water spider utilization is lower with Layout C. Even when the worst-case utilization is considered, Layout C performs better than the other two layouts.

To compare the three layouts without the large-variability conditions of random breakdowns, they were simulated under conditions where each of the three layouts was subjected to identical breakdown situations. The summary of these results is given in Table 8.14. In this simulation experiment, each breakdown appears only

Table 8.14 Summary over identical breakdown schedules

Observation	A	B	C
Cell 1 throughput	1289	1276	1281
Cell 2 throughput	1286	1279	1291
Total throughput	2575	2555	2572
Spider utilization (%)	87.91	88.82	87.21
Spider busy mins	1266	1279	1256

once a shift, toward the end of 4 hours into the shift, for each of the three layouts. It is now clear that Layout C performs better than the other two layouts, when the water spider utilization is considered.

8.6 Warehouse Simulation

A key concept in this book is that the factory design process is essentially a dynamic planning problem. Once the deterministic model of the plant is developed, it must operate in an environment where flows of material and people dynamically interact with the planned facility. It is very difficult to generate and model this complex interaction process, estimate its parameters, and quantify its performance without a stochastic or discrete-event simulation model. This section illustrates an analysis of a large-scale storage warehouse and plant layout operation, where a discrete-event simulation model was crucial to the evaluation of the layout and final configuration of the plant design.

8.6.1 Motivation

Part of the reason for including this case study is to link it to the simulation model of the facility on the website of the textbook. Users can view the simulation model and actually see for themselves the material handling system of the storage warehouse interacting with the resources of the plant layout that is described in this section. It is a very interesting and revealing simulation model and plant layout analysis.

8.6.2 Background

This project provides a compelling example of the storage and warehousing concepts to be presented in Chap. 9. It was generally concerned with the facility planning design of a polymer reprocessing plant in western Massachusetts.

8.6.3 Problem Description

The managers of the company are not certain of the capacity of their warehouse, the layout of the manufacturing process, and the interaction of the material handling system with the manufacturing processes and storage and warehouse capacity in responding to increased demands for their product. If input volumes were to increase dramatically over time (10–20%), would the warehouse be suitable to house this increased demand? The plant maintains a dynamic material handling system which operates three shifts 24 hours a day.

The problem as first posed to the factory design team largely revolved around space capacity and equipment needs, since the business was growing and there was some real concern about the ability of the present site to accommodate future growth. The business is largely concerned with manufacturing four different polymer products, PC, PC/ABS, PS, ABS, and their combinations. In fact, the unit load of the plant is 1000-pound gaylords (e.g., 48" × 40" × 36" containers of raw materials and finished goods) filled with various plastic pellets. As will unfold, forecasting the ability of the plant to respond to fluctuations in demand over time became a critical part of the study.

8.6.4 Factory Layout

Figure 8.41 illustrates the initial plant layout that formed the basis of the manufacturing layout and systems model about to be discussed. One can see the 4' × 4' gaylords spread throughout the facility. The gaylords are stored on the floor and stacked two to three gaylord units high and moved about with forklifts from the receiving areas, onto the manufacturing areas, and finally to the finished goods and shipping areas.

As one can see in Fig. 8.41, the plant has little room for expansion, and there is a restricted material handling system where the forklift traffic coming and going must traverse the same aisles. This is actually a dangerous situation.

In the case of the polymer recycling plant, when the facility was first examined, the receiving and shipping areas were collocated in the same area of the plant (see the lower left-hand corner of Fig. 8.41), which resulted in severe material handling conflicts involving forklift truck movements, accidents, and space utilization problems. It was obvious that separate receiving and shipping areas were desirable—thus, the problem was the same as the solution: “Revise the plant layout and separate receiving and shipping.” Some facility planning issues surrounding the problem were:

1. Is the number of accidents and potential conflicts with personnel in the plant at the receiving and shipping areas excessive?
2. How can the number of physical conflicts between plant personnel and forklift trucks be minimized?

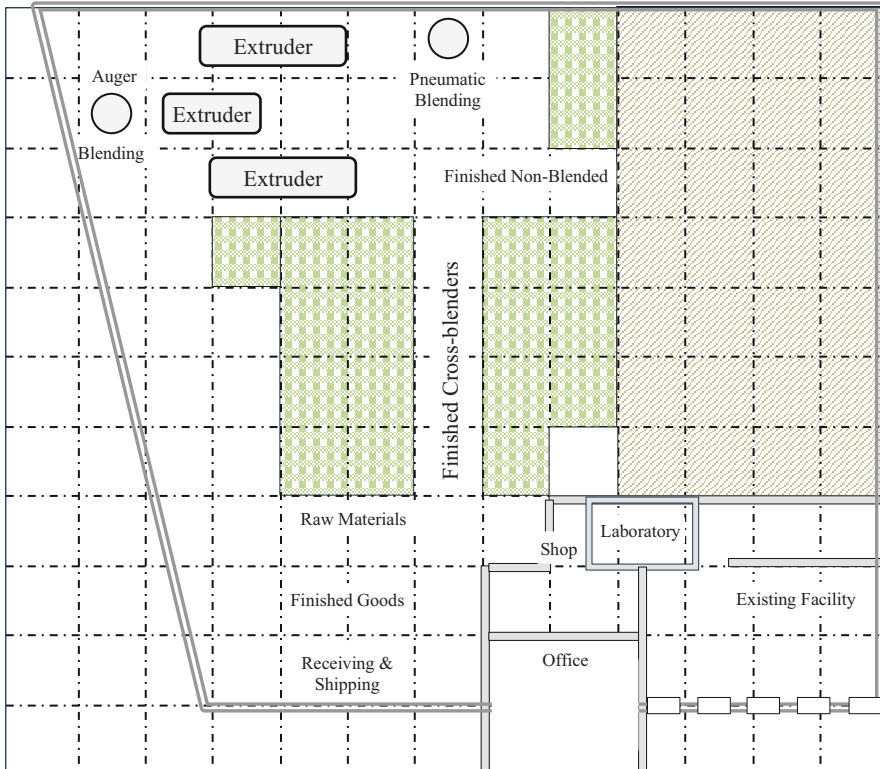


Fig. 8.41 Existing polymer reprocessing plant

3. How should congestion between forklift trucks and plant personnel be avoided at the receiving and shipping area?
4. How can clear separation between the forklift trucks and the plant personnel within the receiving and shipping area be realized?
5. If space is available, how can separate receiving and shipping areas be designed along with the material handling systems in the plant in perhaps a U-shaped layout?
6. If space is unavailable, how can we clearly demarcate, if at all possible, the receiving and shipping areas and the paths of the vehicles and pedestrians?
7. What types of bottlenecks and capacity planning concerns will occur over time as the input demand for the products increases?

The above are planning issues for which evidence must be brought forth to support or refute each of them. Likewise, even the instrumental issues likely need supporting evidence. This can be produced with sophisticated simulation and queuing models to estimate expected (maximum) volume of forklift traffic, number of

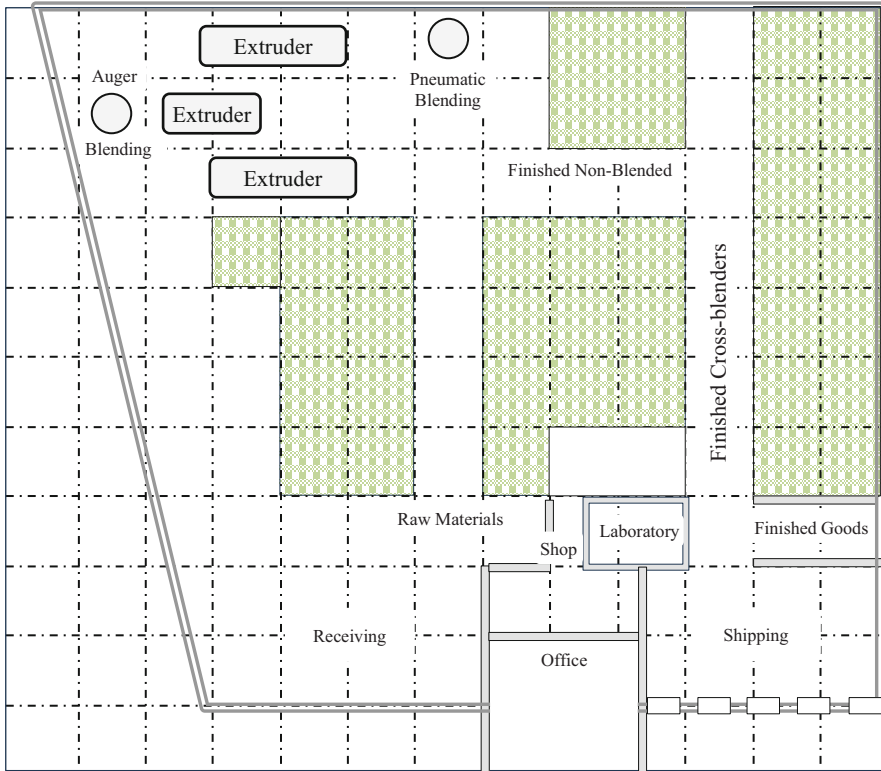


Fig. 8.42 Final plan for polymer reprocessing plant

expected gaylords in the shipping and receiving areas, and so on. The need for a U-shaped layout is certainly arguable.

We constructed a discrete-event digital simulation model of the polymer recycling plant in order to better understand the manufacturing processes and the system as well as the logistics of the product shipments to and from the plant. This was felt to be crucial before simply re-laying out the plant, and it proved to have been an extremely fortunate decision, since the model became a useful forecasting tool for layout changes.

Figure 8.42 illustrates the layout plan arrived at with a U-shaped circulation flow to eliminate the forklift conflicts from the previous scheme (Fig. 8.41). Unfortunately, although this plan design seemed very logical and reasonable, this was not the end of the story. What is crucial here is that the simulation is able to indicate the bottleneck of the system and to show how the bottleneck shifts as more resources are deployed. In order to test the design layout, we ran the simulation model and

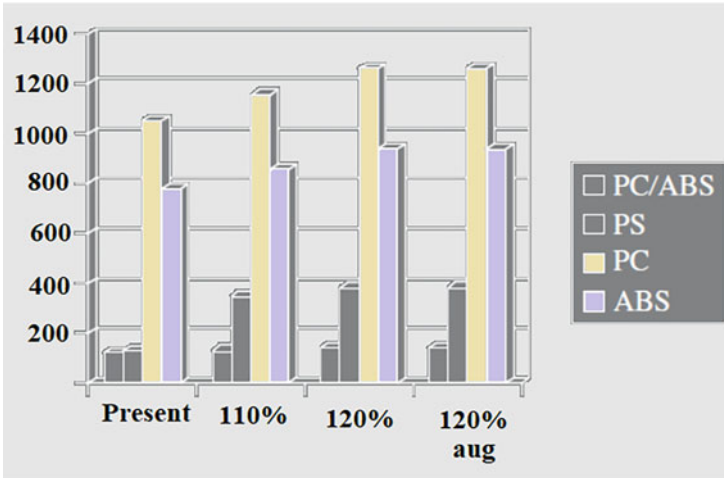


Fig. 8.43 Total number of raw material gaylords

calculated the number of gaylords in the warehouse as a function of variations in the input demand λ_i , for all i , from 0% to 20%. Figure 8.43 illustrates the results of the simulation runs for the total number of raw material gaylords possible on the vertical axis vs. the input demand on the horizontal axis.

The first three columns of Fig. 8.43 illustrate the number of raw material gaylords as a function of input demand. Thus, as one can see, the initial design of the plant was fairly robust.

However, Fig. 8.44 revealed that as the input volume ramped up in the plant to 120% (third column), a serious problem arose with one of the key resources, because the minimum raw material input volume went negative by 670 gaylords. The plant input-processing of raw materials basically shuts down. We needed to find out which resource was causing the bottleneck.

After a detailed analysis of the simulation model outputs, we found the answer in the third column of Fig. 8.45, where it is shown that the auger blender was operating at 100% capacity and could not handle any more input. The auger blender was the bottleneck. Thus, if the input demand was to be greater than 120% of the current demand, it became obvious that a minimum of two auger blenders would be needed.

In subsequent runs of the simulation model, two auger blenders were utilized, so that in viewing the fourth column in Figs. 8.43, 8.44, and 8.45, the output statistics include two auger blenders operating within the plant. Finally, Fig. 8.45b illustrates that with two auger blenders, the total capacity of the plant (number of gaylords including raw materials and finished goods in the revised layout) is acceptable for the given input levels of input demand.

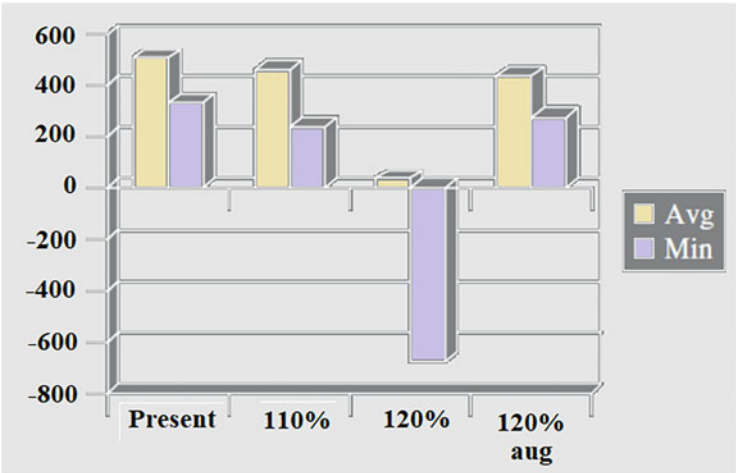


Fig. 8.44 Average and minimum raw material capacity

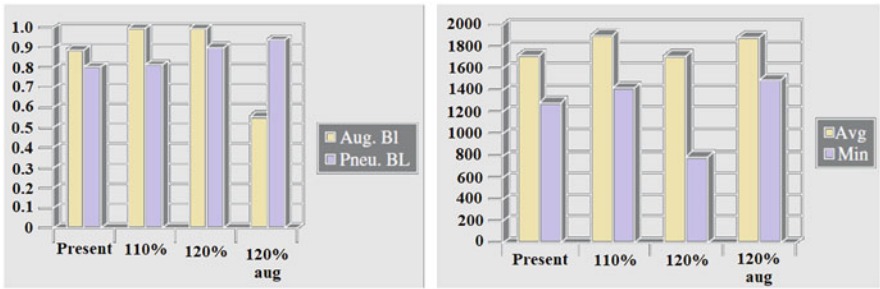


Fig. 8.45 Blender utilization vs. (a) input demand and (b) final warehouse capacity

Additional runs of the simulation model revealed that if future input demand were to increase beyond 20%, four extruders rather than the current three would be needed to handle the demand. Thus, the simulation model became an invaluable tool to identify the shifting bottlenecks and forecast the configuration of resources needed within the plant as demand increased over time.

Even with all the detailed and painstaking use of simulation models to understand the plant, when it came to examining the relocation of the polymer processing plant two years after the study, everything had to be redone, because the site was different, the existing buildings were not the same, the input volume had changed, and so on.

In summary, this section has illustrated a case study where the dynamic interaction of the material handling system and the manufacturing layout was crucial to the overall configuration of the factory design scheme. The simulation model is

available on the website, and it illustrates the power of simulation and its importance to facility layout planning.

Chapter 9 discusses in more detail the design of storage and warehouse systems. One can understand from the case study examined in this section that storage and warehousing play a critical role in the functioning of the overall plant layout.

8.7 Summary and Conclusions

This chapter has discussed the general topic of material handling system analysis. It has provided an overview of some of the types of analytical and simulation models available for facility planning and material handling analysis. Section 8.2 described the fundamental principles underlying the analysis and integration of the layout and material handling system. Extensive examples were included to illustrate the principles. Section 8.3 demonstrated the application of queuing networks to the modeling of large-scale facilities. The approach to the modeling of material handling system design is based on an open queuing network methodology.

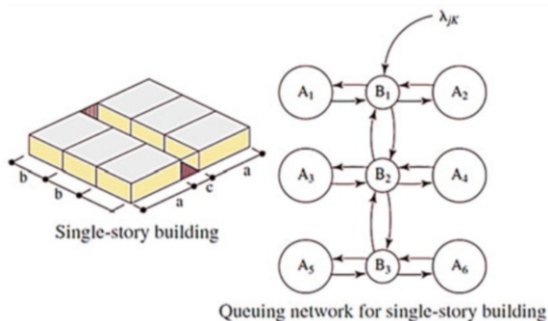
An example of a multistory, multibuilding manufacturing complex was modeled, clearly demonstrating that the approach is both viable and computationally effective for modeling large-scale facilities with multiple classes of customers and very general capacity and service restrictions. The representation, analysis, and synthesis stages defined in this chapter are notoriously difficult, yet the theory, algorithms, and modeling concepts necessary to model large-scale facilities with open finite queuing networks lie within our grasp.

In Sect. 8.4, Kwo's algorithm for determining the capacity of closed-loop conveyors was described and illustrated, along with a computerized procedure for carrying out the analysis of larger systems in terms of number of loading or unloading stations and carriers around the conveyor.

In Sect. 8.5, a case study of a manufacturing cell layout and corresponding material handling systems analysis problem was analyzed in detail to show the scope and limitations of simulation models in the facility layout process. While analytical models depend upon certain modeling assumptions, simulation models are not so restricted. However, it is difficult to build effective simulation models, and their statistical analysis can be complex. Finally, Sect. 8.6 described a simulation analysis of a warehouse material handling system. The symbiotic relationship between the warehouse storage system and the material handling system and the layout was amply illustrated.

8.8 Exercises

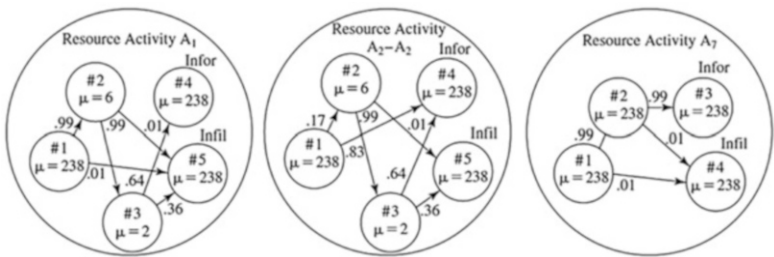
- 8.1 For the receiving area of your factory project, categorize the items for inbound shipments of raw materials. Estimate the time between arrivals of inbound shipments. Estimate the probability distribution most appropriate for these shipments. This is a necessary starting point for building a dynamic model of the plant. Build an analytical model or a simulation model of the receiving area, and correlate your estimate of the buffer and staging (queuing) area square footage of the incoming products with the product types.
- 8.2 For the shipping area of your factory project, estimate how often shipments will be made from the plant. Also, estimate the number of docks needed for the trucks.
- 8.3 For the factory project identify the material handling flow network. Superimpose the network on the facility layout and graphically illustrate the flows throughout the departments of the layout. On this basis, indicate where the queues and bottlenecks may likely occur. Identify the most significant bottleneck, preferably a workstation, and with an analytical model or a simulation model, dynamically study the workstation, as it was done for the XYZ corporation in this chapter.
- 8.4 A single-story facility and its queuing network are represented below. Each activity A_i ($i = 1, 2, \dots, 6$) has about 20 people and 2400 sq ft. The horizontal circulation elements adjoining the activities are represented by B_1 , B_2 , and B_3 . These nodes are M/G^a or $M/G/c/c$ queues. Seven customer classes have routing vectors and resource activities as shown below. The routing vectors are shown below as columns in the matrix on the left, and the number of multi-server nodes within the facility is shown in the table on the right. The service rates of the activities are shown in the nodes of the accompanying diagrams. Refer to the GQnet user's manual on the website for additional details. Use this program and compute all performance measures



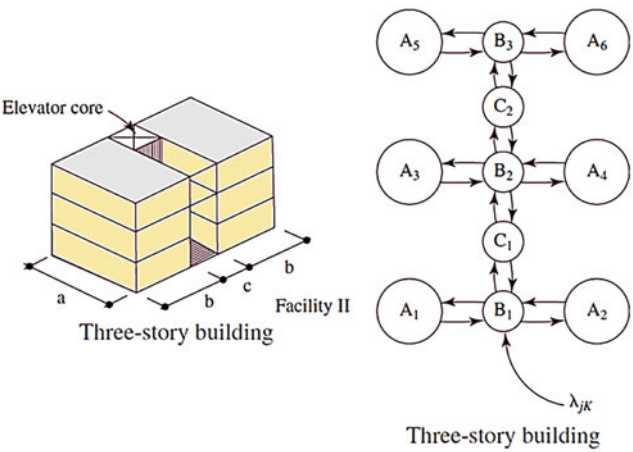
R_1	R_2	R_3	R_4	R_5	R_6	R_7
1	1	1	1	1	1	1
0	7	7	7	7	7	7
0	2	7	4	7	7	2
0	0	3	0	5	6	7
0	0	0	0	7	7	3
0	0	0	0	1	5	7
0	0	0	0	0	0	1

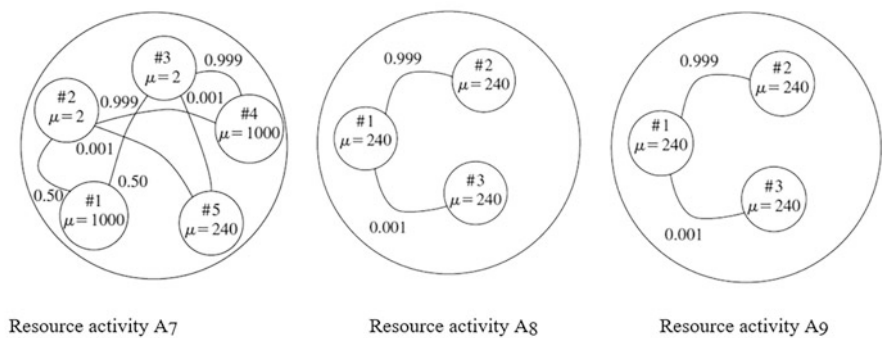
Routing vectors

Resource activities and number of servers		
Activity	Subactivity	Number of servers
1	2	20
1	3	10
2	2	20
2	3	10
3	2	20
3	3	10
4	2	20
4	3	10
5	2	20
5	3	10
6	2	20
6	3	10



8.5 The following figures represent a three-story facility and its corresponding queuing network. The B-nodes represent horizontal circulation travel and the C-nodes represent elevator travel. In this model, we have additional resource activity nodes for the elevator, elevator waiting, and horizontal circulation network. Resource activities A_1 – A_6 are the same as in Exercise 8.4, whereas activities A_7 , A_8 , and A_9 are as shown below. Node A_7 represents the elevator movement. Node A_8 represents the horizontal circulation movement, and node A_9 represents elevator waiting.





Below are the routing vectors and the number of multi-server nodes within the facility. No tice that the elevator waiting A₉ precedes the elevator movement A₇. Two A₇ nodes in succession represent movement between two floors. Use GQnet to analyze the facility and compute all performance measures.

R_1	R_2	R_3	R_4	R_5	R_6	R_7
1	1	1	1	1	1	1
0	8	9	9	9	9	8
0	2	7	7	7	7	2
0	0	3	4	7	7	9
0	0	0	0	5	6	7
0	0	0	0	7	5	9
0	0	0	0	7	0	7
0	0	0	0	1	0	1
0	0	0	0	0	0	0

Routing vector

Resource activities and number of servers		
Activity	Subactivity	Number of Servers
1	2	20
1	3	10
2	2	20
2	3	10
3	2	20
3	3	10
4	2	20
4	3	10
5	2	20
5	3	10
6	2	20
6	3	10
7	2	6
7	3	6

8.6 Consider a conveyor system with one loading station and one unloading station. There are seven carriers equally spaced around the conveyor. The material flow sequences are {2,3,1,0,0} and {0,0,0,-2,-4}. (a) Verify if the given data satisfies Muth's basic results. (b) Find the required capacity per carrier.

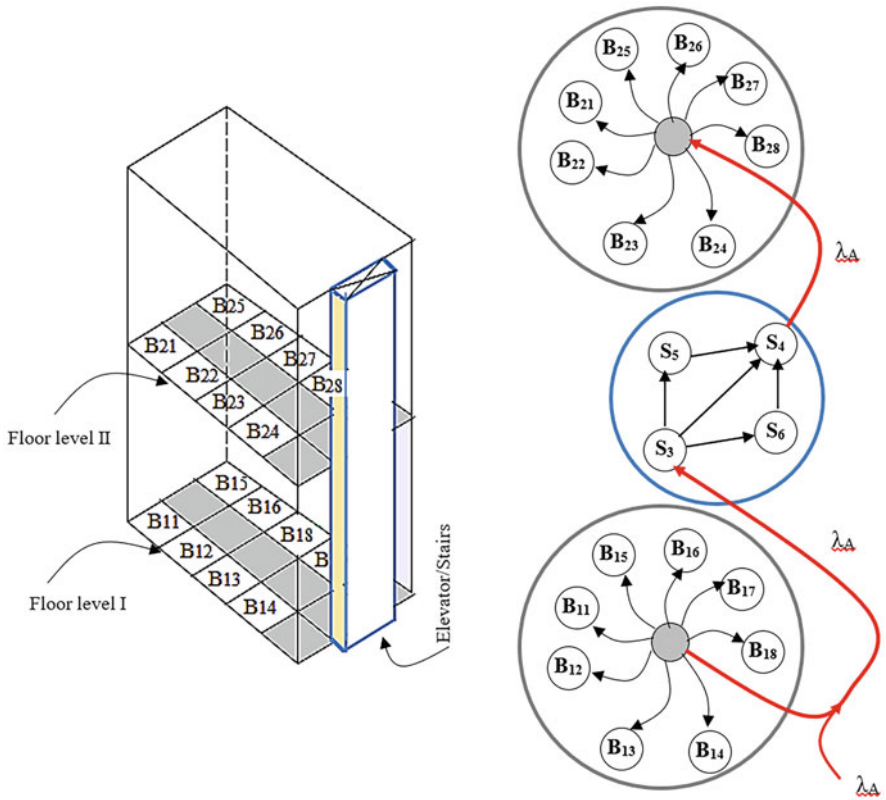
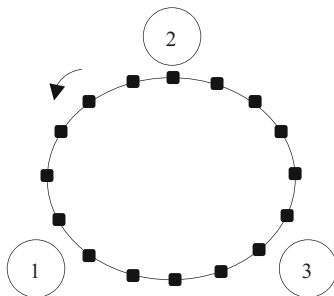


Fig. 8.46 Two-story office facility

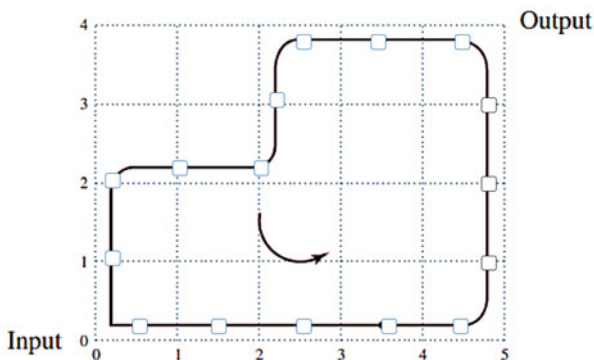
- 8.7 Figure 8.46 is an illustration of another two-story office facility. Estimate the number of customer classes (λ_{jk}) arriving at the facility along, with their length of route and the activities they will be visiting. You can vary the number of generating sources, as well as the number of classes within each generating source. Detail the resource activities B_{ij} on the two floors as necessary. You might start out small with the number of subactivities, then proceed to increase their number. A series of experiments might be in order. Nodes S_1 and S_2 are the corridor circulation areas, S_4 is elevator travel, S_5 is stairwell travel, and S_3 and S_6 are landing areas on the two floors. S_1 and S_2 can be modeled as M/G^d or else as $M/G/c/c$ queues. See the user manual for further details. Run the model GQnet by varying the arrival rate of the customer classes and identify the key bottlenecks of your system as λ_{jk} varies.
- 8.8 A closed-loop conveyor has seven equally spaced carriers and two stations, one for loading with sequence $\{0, 0, 3, 2, 1\}$ and another one for unloading with sequence $\{0, 0, 0, -2, -4\}$. (a) What is the minimum capacity for the carriers? (b) Solve using the conveyor.exe program. For the conveyor shown

(16 carriers), station 1 has the sequence $\{f_1(n)\} = \{0, -2, -2\}$. Station 2 has the sequence $\{f_2(n)\} = \{4, 4, 0\}$. Station 3 has the sequence $\{f_3(n)\} = \{-3, -1, 0\}$. (a) Find the capacity of the conveyor, (b) Find the labels of carrier 2 at station 1 the first, second, and third time the carrier passes the station. (c) If we want to do the analysis for carrier 2, which will be the initial quantity in the carrier before it reaches state 1? (d) Show the results four four *loops* for carrier 2. (e) Run the conveyor.exe program to find the capacity of the conveyor, and the analysis results for carrier 2.

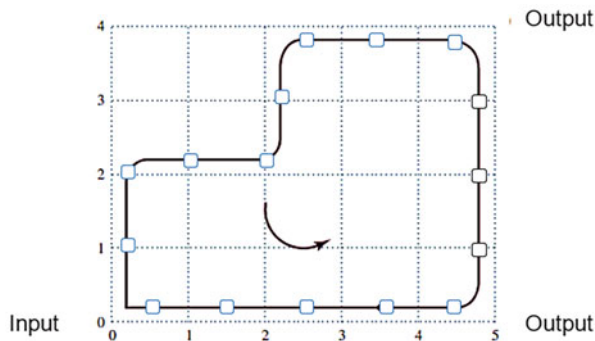
- 8.9 For the conveyor shown (16 carriers), station 1 has the sequence $\{f_1(n)\} = \{0, -2, -2\}$. Station 2 has the sequence $\{f_2(n)\} = \{4, 4, 0\}$. Station 3 has the sequence $\{f_3(n)\} = \{-3, -1, 0\}$. (a) Find the capacity of the conveyor, (b) Find the labels of carrier 2 at station 1 the first, second, and third time the carrier passes the station. (c) If we want to do the analysis for carrier 2, which will be the initial quantity in the carrier before it reaches state 1? (d) Show the results four four *loops* for carrier 2. (e) Run the conveyor.exe program to find the capacity of the conveyor, and the analysis results for carrier 2.



- 8.10 You are designing a layout with an overhead bucket conveyor connecting portions of an assembly area within a plant, as shown in the fig. A total of 16 buckets approximately 10 feet apart are needed. There are two input and output stations with sequences $\{f_1(n)\} = \{1, 1, 2, 4, 2, 1, 1\}$ and $\{f_2(n)\} = \{0, 0, 0, 0, -4, -4, -4\}$. (a) Find the capacity of the buckets. (b) Find the capacity using the conveyor.exe program.



- 8.11 Find the capacity of the buckets for a variation of Exercise 8.10 having three stations with sequences $\{f_1(n)\} = \{7, 7, 0\}$, $\{f_2(n)\} = \{-4, -3, 0\}$ and $\{f_3(n)\} = \{0, -3, -4\}$. You can verify your results by running the program Conveyor.exe,



- 8.12 As another variation on Exercise 8.11, reposition the input station, shifting the loading and unloading patterns, so that $\{f_1(n)\} = \{0, -3, -4\}$, $\{f_2(n)\} = \{7, 7, 0\}$ and $\{f_3(n)\} = \{0, -4, -3\}$. What is the new bucket capacity?

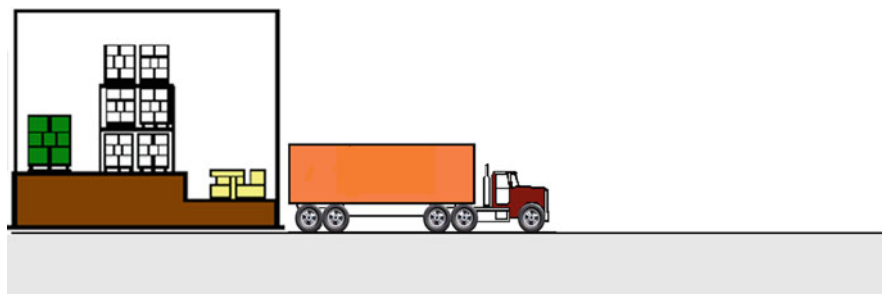
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Chapter 9

Storage and Warehouse Systems



9.1 Introduction

The efficient and effective handling of materials within various departments of a factory or another suitable type of business requires keeping every section of storage space accessible, selecting proper placement of every inventory item, implementing appropriate storage policies, and keeping adequate control of these policies. This chapter represents an effort to address various factors considered to be relevant when designing a storage and warehouse system; it also discusses fundamental principles required for the formulation of practical and efficient storage policies.

A comprehensive storage system includes the building housing the storage facility, the storage medium, the dock areas, the processing areas, the location of inventory (supplies, intermediate materials, and final products), the material handling system, and the workers in charge of storage operations. These components must be effectively integrated in such a way as to significantly reduce all relevant

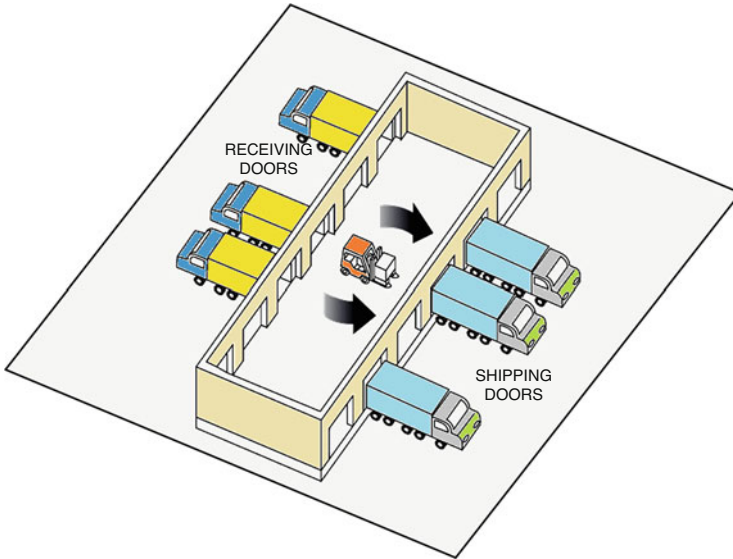


Fig. 9.1 Typical warehouse

storage-related costs. These costs are strongly dependent on the patterns allowed by the storage layout design to move materials out of and into storage facilities.

This chapter consists of eight sections, including this introduction. Section 9.2 focuses on receiving and shipping operations. Section 9.3 describes and compares two popular storage policies, known as dedicated and random storage policies. Section 9.4 introduces models for storage capacity and Sect. 9.5 presents specific procedures for storage capacity determination. Section 9.6 is devoted to dock planning and design. Section 9.7 addresses the important topic of warehouse system design. Section 9.8 provides basic considerations for determining the dimensions of an automated storage and retrieval system. In addition to the bibliographical references directly related to our discussions in this chapter, to those interested in expanding their knowledge on the topic of storage and warehousing, we would like to recommend the work by Bartholdi and Hackman [1], Decker et al. [2], Heragu et al. [4], Hill [5], and Jenkins [6].

9.2 Receiving and Shipping

A warehouse is a buffer between inbound orders arriving from suppliers and outbound orders delivered to customers as illustrated in Fig. 9.1.

The two major traditional activities of a storage process are receiving (inbound operations) and shipping (outbound operations). *Receiving* operations move items from docks where they are unloaded to warehouses. *Shipping* operations move items

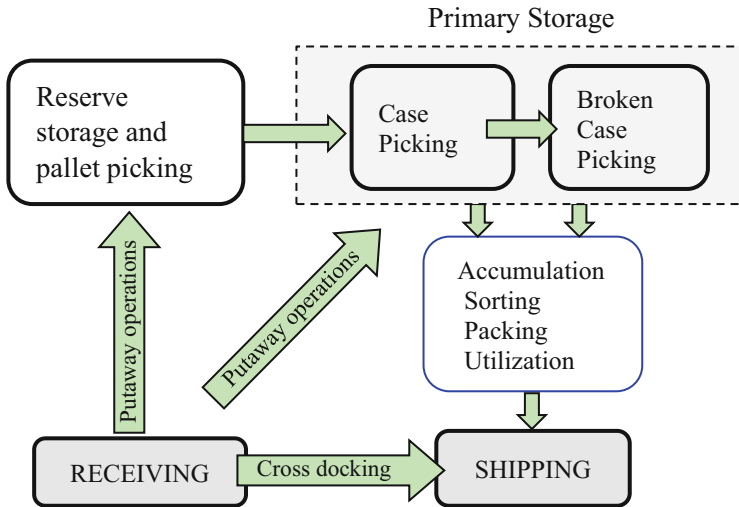


Fig. 9.2 Basic activities of a warehouse

from the warehouses to the area where they will be loaded into the shipping vehicles, usually trucks and railroad cars. Both types of operations are significantly affected by the equipment selected and the movement pattern used to displace the products, either from the receiving docks to warehouses, or vice versa. The choice of means of transportation, the scheduling of transportation activities, and the integration of storage and material handling operations are the objects of a *total-system* storage and warehousing system design.

Inbound processes typically include two operations—*receiving* and *putaway*. Similarly, outbound processes typically include five operations—*processing*, *picking*, *checking*, *packing*, and *shipping*. Figure 9.2 illustrates the interaction existing among these activities. A brief description of these operations is given next.

9.2.1 Receiving and Putaway Operations

Receiving operations include all those performed from the time the order is placed until the products are received at the inbound dock of the warehouse. These operations actually begin with a notification of the arrival of goods. Once the products have arrived, they are unloaded and possibly staged for subsequent putaway operations. Depending on the level of technology, automation, and mechanization used, the products may be scanned to register their arrival, to enable ownership, and to record their availability to fulfill customer demand. The products should be inspected to detect damage, incorrect counts, wrong descriptions, and the like. Products typically arrive in larger units such as pallets, boxes, or other types of containers. Receiving operations can account for about 10% of operating costs.

Putaway operations start with the confirmation of the location, order quantity, and product batch identification codes for the incoming items. The main purpose of these activities is to determine the most effective storage location for incoming products. The overall putaway process usually consists of the following operations:

1. Operations to ensure that the entire product receipt is validated before products are prepared for their distribution. These operations usually require large staging areas and may be significantly time consuming.
2. Operations to allow some putaway to occur prior to receiving every item on the purchase order. These operations usually require the staging of each product by items. These operations require less storage space and tend to consume less time.
3. Operations to place products directly in their final locations when received. These operations focus on speedy movement of the product to warehouse locations, and utilization of smaller staging areas.

9.2.2 *Processing Customer Orders*

Processing starts when a customer order is received. Typical activities include verifying availability of items, generating pick lists to consolidate the order, scheduling order picking and shipping operations, and documenting the entire process. Activities for grouping and releasing orders for picking can be accomplished by a *warehouse management system* (WMS), a large software system that coordinates the activities of the warehouse. A WMS has the capability of tracking and controlling inventory and orders as they move through the warehouse. Furthermore, it can provide workers with more data to perform their jobs and helps firms get better control over the entire distribution network, due to its ability to generate real-time results.

In addition to the previously described activities, a comprehensive, state-of-the-art WMS can consolidate back orders, handle rush orders, trigger replenishment, and perform a number of the functions required to keep orders flowing smoothly and efficiently through the warehouse. Being a dynamic planning tool, a WMS can use demand patterns to adjust picking operations and reconfigure stock locations as necessary. A WMS can also generate data to design an *advance shipping notice*, informing customers of delivery times before the stock physically leaves the dock.

9.2.3 *Order Picking*

In the present context, the term *picking* means *retrieving*. Order picking is the process of selecting and retrieving specified items from a warehouse, in specified quantities, to satisfy a customer order. Depending on the type and size of items to be retrieved, there are five levels of order picking [8]:

1. Pallet picking (full pallets from storage).
2. Layer picking (full layers of cardboard boxes or containers from pallets).
3. Case picking (full cardboard boxes or containers from storage).
4. Split-case picking (packs from containers).
5. Broken-case picking (individual items from storage).

There are four well-known procedures for picking orders [8]. These procedures can be combined in a manner appropriate for each particular storage operation. A common term used as a unique numeric identifier to permit systematic tracking of a specific product or item in inventory is *stock keeping unit (SKU)*. In the description of order picking procedures, it is assumed that a unique SKU is assigned to each product and each of its variants (different colors, models, sizes, and so on). The procedures are defined in terms of three operating parameters: (a) pickers per order, (b) number of orders processed, (c) picking periods per shift. A short description of picking procedures follows.

Discrete Picking This is the most common and simple picking procedure. It is also known as *order picking* because only one worker picks one order of one type of product at any particular time. Orders are retrieved at any time during the specified shift. Discrete picking requires only one picking document to be processed, it minimizes risks of omitting items, it promotes faster service, and it allows clear accountability for the condition and completeness of an order. Its major disadvantage is the likelihood of long travel times needed by the single picker.

Zone Picking In this method, the total picking area is divided into several sections, one for each type of product, and one picker is assigned to each section. The picker assigned to any section retrieves all the requirements for each order calling for items in the section. All the requirements from each zone are moved to a special area, where individual orders are assembled. Each picker works on one order at a time and, as in discrete picking, the picking period is the same as the length of the specified shift. Depending on the order according to which the sections or zones are considered, two classes can be identified for this procedure: (a) in *sequential zone* picking the order progresses from one zone to the next, skipping those without requirements included in the order; (b) in *simultaneous zone* picking items are picked simultaneously from each zone or section and the order is assembled when all requirements have been retrieved.

Group Picking In this procedure, one picker is in charge of retrieving items of one type of product at a time for a group of orders. Once all requirements for a product are retrieved, they are divided among the orders. This operation may take place at the picking place or in a specialized area. As in the previous methods, the picking period is the same as the shift.

Wave Picking In wave picking, as in discrete picking, one picker is assigned to each order, considering the requirements of one type of product at a time. However, the shift is divided into several picking periods, each period being dedicated to a group of orders.

Combined Picking Procedures The above basic procedures can be combined in different ways. Examples of typical combinations are provided below, emphasizing the choices for the three fundamental parameters used to describe the procedures:

- (a) Combine the zone and group picking procedures: multiple pickers, multiple types of product picked at a time, and one picking period per shift.
- (b) Combine the zone and wave picking procedures: multiple pickers, a single type of product picked at a time, and multiple picking periods per shift.
- (c) Combine the zone, group, and wave picking procedures: multiple pickers, multiple types of product picked at a time, and multiple picking periods per shift.

In the first combination, each picker is responsible for retrieving requirements stored in a zone or section for a group of orders. In the second combination, each picker is assigned to a zone as well but picks all requirements for products in the zone, one order at a time. Finally, in the third combination, one picker is assigned to each zone, retrieving all requirements of products included in several orders.

Order picking is the most critical of all distribution operations. Olson [8] provides a very interesting and informative treatment of this topic, including industry trends, principles of order picking, picking procedures, conventional order-picking systems, automated picking systems, selection considerations, and implementation. The reader is encouraged to read Olson's article.

9.2.4 Packing and Shipping

Shipping includes all operations that are performed from the time an order is placed by a customer until the products are finally shipped. Packing is an activity that supports the shipping process by putting items in a protective container, usually a case, package, or a pallet, with the purpose of shipping them to a customer.

Since the packer handles each piece of a customer order, packing is usually labor intensive. During the process of placing the items in the container, it is convenient to verify the completeness and accuracy of each order. Order accuracy is a key measure of the effectiveness of service to the customer. Inaccurate orders not only indicate poor customer service quality but also cause returns, adding to the workload of storage and material handling operators, increasing costs, and lowering the effectiveness of distribution efforts.

An effective packing process requires sound coordination to guarantee that all the items or products included in an order are available for packing at the scheduled time and ready to be delivered to the customer using as few containers as possible. Otherwise, partial shipments will have to be staged, waiting for completion before packing. Only in special circumstances should the packing and shipping of partial orders be allowed.

Shipping practices may have important consequences for an entire organization. The underlying concept stressed here is *customer service quality*. Integrating this concept with those of *product quality* and *economic pricing* may transform an organization into a great one, enjoying

- (a) Increased customer satisfaction.
- (b) Reduced delivery times and errors.
- (c) Increased sales order throughput.

These goals can be advanced through the following shipping practices:

- (a) Streamlining the order configuration process.
- (b) Providing management visibility to the orders in process.
- (c) Avoiding configuration errors and shipment delays.

9.2.5 Cross Docking

Cross docking in the retail and trucking industries refers to the logistics of directly moving finished products from the manufacturing plant to the customer with minimum material handling efforts. It is affected by placing pallets on lanes corresponding to the receiving doors, sorting the pallets into shipping lanes, and loading them into outbound trailers. Cross docking essentially eliminates the inventory-holding function of a warehouse while still allowing it to serve its consolidation and shipping functions. Benefits derived from cross-docking include:

- (a) Reduction of the need for handling and storing inventory.
- (b) Increased emphasis on satisfying demand in a timely manner.
- (c) Streamlining of the supply chain.
- (d) Reduction of operating costs.
- (e) Increased throughput.
- (f) Reduction of product damage and product obsolescence.

To yield these benefits, cross-docking requires an effective information system.

Depending on its purpose, cross-docking takes several forms, including manufacturing cross-docking, distributor cross-docking, transportation cross-docking, and retail cross-docking. Products arriving from the vendor already have a customer assigned, so shipments need only be moved from the inbound to an outbound trailer.

The layout of the warehouse must facilitate the development of the warehouse's activities keeping in mind the fundamental guiding principles of saving time, reducing costs, minimizing inventories, and speeding up service. A sample layout is shown in Fig. 9.3.

9.3 Dedicated and Random Storage

Storage warehousing can be implemented in three ways, depending on the particular storage conditions required. First, space can be rented in a public warehouse on the basis of storage volume for a specified time period, without any capital investment

Fig. 9.3 Sample warehouse layout



for equipment. Second, when there is a long-term storage need, a warehouse can be leased. This decision might require some investment for handling equipment. Third, a company whose main business is other than warehousing can operate a private warehouse as a separate division. Although this option has several advantages over the other two, owning a warehouse and handling equipment may result in substantial fixed and variable costs. This section is adapted from the presentation on this topic by Tompkins and White [11].

The storage capacity of a warehouse is defined as the amount of storage space required to accommodate the materials to be stored in order to meet a desired service level. Storage capacity depends rather significantly on the type of storage policy being used. The two most utilized storage policies are *dedicated storage* and *random storage*.

9.3.1 *Dedicated Storage*

Each product unit load is assigned to a fixed location based on throughput and storage space required. The main advantage of dedicated storage is the data handling efficiency, as each product has a predetermined address. The guiding principle to storing items under this policy is that the products responsible for more of the travel activity between the warehouse and the docks should be assigned to locations closer to docks.

The following notation will be used to formulate a mathematical model that considers a measure of effectiveness defined as the minimization of the total expected distance traveled:

- q number of storage locations
- n number of products
- m number of input/output points (docks)

- S_j number of storage locations required by product j
 T_j number of trips in/out of storage for product j
 p_i percentage of travel in/out of storage to/from point i
 d_{ik} distance or time required to travel from point i to location k
 x_{ik} = 1 or 0 for assigning or not assigning product j to location k

Mathematical Model

$$\text{Minimize } \sum_{j=1}^n \sum_{k=1}^q \frac{T_j}{S_j} \sum_{i=1}^m p_i d_{ik} x_{jk} \quad (9.1)$$

$$\sum_{j=1}^n x_{jk} \leq 1 \quad k = 1, \dots, q \quad (9.2)$$

$$\sum_{k=1}^q x_{jk} = S_j \quad j = 1, \dots, n \quad (9.3)$$

$$x_k = 0, 1 \quad j = 1, \dots, n; \quad k = 1, \dots, q \quad (9.4)$$

Solution Procedure The objective function (9.1) can be rewritten as

$$\text{Minimize } \sum_{j=1}^n \frac{T_j}{S_j} \left(\sum_{k=1}^q \sum_{i=1}^m p_i d_{ik} \right) x_{jk} \quad (9.5)$$

Using $f_k = \sum_{i=1}^m p_i d_{ik}$, the objective function (9.5) can be reformulated as

$$\text{Minimize } \sum_{j=1}^n \frac{T_j}{S_j} (f_1 x_{j1} + f_2 x_{j2} + \dots + f_q x_{jq}) \quad (9.6)$$

Therefore, a heuristic procedure for solving this model can be sketched as follows:

- Order the products according to their decreasing values.
- Find the values of (expected distance traveled between location k and docks).
- Assign the locations in the warehouse to products according to their f -values from lowest to highest.

Example 9.1

The dimensions of a rectangular warehouse are 40×40 ft. The warehouse has one *shipping and receiving* dock located at the northeast corner of the layout. Two products A and B are going to be stored using a dedicated-storage strategy. The total number of pallets per week (input/output activity) for product A is 100, and for product B it is 80. Furthermore, product A requires 10 storage bays, each having

dimensions of 10×10 ft. Product B requires 4 storage bays of the same dimension. Find the optimal warehouse layout, assuming rectangular distances. Provide a sketch of your layout.

Solution

- (a) Product A has $T_A/S_A = 100/10 = 10$ and Product B has $T_B/S_B = 80/4 = 20$. Therefore, the products will be considered in the ordered sequence B, A.
- (b) Find the values of f_k (the expected distance traveled between the center of location k and the dock). These values are shown below:

40	30	20	10
50	40	30	20
60	50	40	30
70	60	50	40

- (c) Assign the locations to products according to their f -values from lowest to highest. First, Product B is assigned the four locations with f -values equal to 10, 20, 20, 30, and 30, respectively. Afterward, Product A is assigned 10 locations with values equal to 30, 30, 40, 40, 40, 40, 50, 50, and 50, respectively. The final layout is shown below:

A	B	B	B
A	A	A	B
A	A	A	A
	A	A	A

Example 9.2

The expected distances from the center of each bay to the two docks are shown below. As an illustration, the bay located at the southwest corner is considered. The distance from the center of the bay to the receiving dock is 70, and the distance to the shipping dock is 20. Since each dock processes 50% of the total activity (i.e., probabilities equal to 0.5), the expected distance is equal to $0.5(70 + 20) = 45$.

35	30	30	30
30	35	30	30
35	35	35	35
45	45	45	45

Assigning bays first to product B and then to product A, using the expected distance as the criterion to be minimized, the following results are obtained. It can be verified that there are alternative optimal solutions.

A	A	B	B	
A	A	B	B	
A	A	A	A	
A	A			

9.3.2 Random Storage

Incoming items are equally likely to be stored among all available storage spaces. In practice, incoming items are stored in the available location that is closest to the input/output point (usually a dock). Under the assumption that the storage locations are highly utilized, indicated by a high rate of product moves into and out of storage locations, most actual warehouse operations can be modeled using a random storage policy. The main advantage of random storage is a better utilization of the available storage space.

9.4 Models for Determining Storage Capacity¹

This section considers two approaches to determine the required capacity of a storage facility. The first approach is based on the desired service level, and the second is on the total storage cost of the facility. These two approaches are discussed by Francis et al. [3].

9.4.1 Service-Level Approach

The amount of storage space is minimized subject to the constraint that a specified probability of space shortage, α is not exceeded. The probability $1 - \alpha$ is known as the *service level*. A space shortage occurs when the available space capacity is insufficient to accommodate a storage space requirement. It is assumed that the shortage is met using leased storage space.

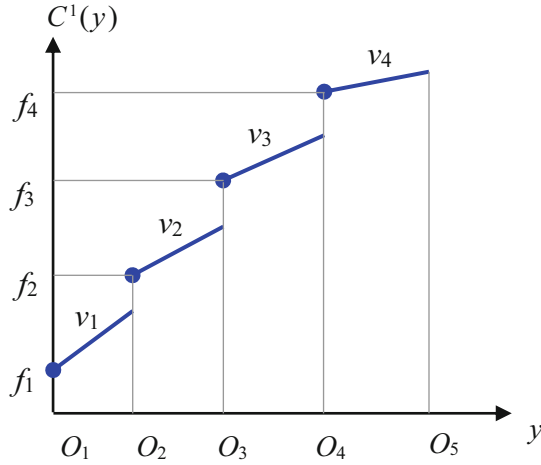
Let X_i be a random variable representing the inventory level of item $i = 1, \dots, n$ and let $X = \sum_i X_i$. It is assumed that X_i follows a uniform distribution, $X_i \sim U(a_i, b_i)$, $i = 1, \dots, n$. Without any loss in generality, it will be assumed that the items are labeled in nonincreasing order of b_i values. The storage capacity at the service level $1 - \alpha$, represented by the symbol $S(\alpha)$, is defined by means of the probabilistic statement $P(X \leq S(\alpha)) \geq 1 - \alpha$.

9.4.2 Cost-Based Approach

According to this approach, the total storage space is found by minimizing the sum of costs associated with owned storage space and contracted storage space for accommodating space shortages regardless of service level. The total storage cost usually includes a fixed and a variable component. The fixed cost is incurred when purchasing material handling equipment. The variable cost is given per storage area unit.

Figure 9.4 shows four intervals of the piecewise linear cost function used in the determination of storage-capacity requirements. It is assumed that the required storage capacity can be satisfied with owned and leased storage area. The following notation is illustrated in Fig. 9.1 for the own storage case:

¹This section can be omitted without significantly affecting the coverage of the material in classes with less emphasis on analytical models.

Fig. 9.4 Piecewise storage cost function

y owned warehouse area.

$C^1(y)$ cost of owned warehouse area associated with y ; it is assumed that the function is piecewise linear, with the j th linear segment being $O_i \leq y \leq O_{i+1}$, $i = 1, \dots, S-1$.

f_i fixed cost for the i th interval of y .

v_i variable cost per unit of owned warehouse area for the i th interval of y .

For the case of leasing storage area, a function similar to that shown in Fig. 9.1 is assumed.

The corresponding notation for this case is shown below:

Y leased warehouse area.

$C^2(Y)$ cost of leased warehouse associated with Y ; it is assumed that the function is piecewise linear, with the j th linear segment being $L_j \leq Y \leq L_{j+1}$, $j = 1, \dots, T-1$.

F_j fixed cost for the j th interval of Y .

V_j variable cost for the j th interval of Y .

In general, both O_1 and L_1 are set to be zero. Relationships (9.7) and (9.8) are formulations for the total cost:

$$C^1(y) = f_i + v_i y \quad O_i \leq y \leq O_{i+1}, \quad i = 1, \dots, S-1 \quad (9.7)$$

$$C^2(Y) = F_j + V_j Y \quad L_j \leq Y \leq L_{j+1}, \quad j = 1, \dots, T-1 \quad (9.8)$$

9.5 Storage-Capacity Determination²

Two policies will be considered: (a) randomized storage and (b) full turnover-based storage. According to the first policy, incoming items are equally likely to be stored in any available location, often the available location that is closest to a dock. According to the second policy, items with larger ratios of activity levels to storage space are allocated to the locations closer to a dock. The storage capacity for both policies will be determined by minimizing the total storage cost while satisfying the desired service level. The following discussion is extracted and adapted from an article on procedures for finding storage capacity by Lee and Elsayed [7], assuming independent replenishment of items.

9.5.1 Randomized Storage Policy

It is assumed that X_i represents the storage area required by item $i = 1, \dots, n$; and all X_i 's are statistically independently and uniformly distributed between a_i and b_i . Thus, the density function for X_i is:

$$h(X_i) = \begin{cases} \frac{1}{b_i - a_i} & a_i \leq X_i \leq b_i \\ 0 & \text{otherwise} \end{cases} \quad (9.9)$$

The required storage capacity is equal to $X = \sum_i X_i$. Now, let $A = \sum_i a_i$ and $B = \sum_i b_i$, and $Z = (X - \mu)/\sigma$, where $\mu = \frac{1}{2}(A + B)$ and $\sigma = (\sum_i (b_i - a_i)^2/12)^{1/2}$. Assuming that n is sufficiently large for the central limit theorem to be applied, Z follows a normal distribution with mean equal to 0 and variance equal to 1:

$$y(z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2} \quad -\infty < z < \infty \quad (9.10)$$

Following Lee and Elsayed [7], for a given probability (assumed to be less than or equal to 0.5) of accommodating the initial incoming items, the storage capacity can be expressed by

$$S(\alpha) = \mu + Z_\alpha \sigma \quad (9.11)$$

where $\alpha \leq \alpha_0$ and $P(z > z_\alpha) = \alpha$.

²This section can be omitted without significantly affecting the coverage of the material in classes with less emphasis on analytical models.

A current trend in the manufacturing industry is to do more leasing of warehouse storage space. In addition to owning storage space, a company may lease storage space from external sources.

For each breakpoint of the piecewise linear cost function introduced before, the value can be determined by solving Eq. (9.12) for the owned-space case, and Eq. (9.13) for the leased-space case. In Eq. (9.12), the storage capacity defined in Eq. (9.11) is set to be equal to the initial point of the i th owned storage-space interval. In Eq. (9.13), the expected amount of space shortage is set equal to the initial point of the j th leased storage-space interval.

$$S(\alpha) = \mu + Z_\alpha \sigma = O_i \quad i = 1, \dots, S \quad (9.12)$$

$$E[S(\alpha)] = \frac{\sigma}{\sqrt{2\pi}} e^{-\frac{1}{2}Z_\alpha^2} - \alpha z_\alpha = L_j \quad j = 1, \dots, T \quad (9.13)$$

Let $\alpha_i^O = i$, $i = 1, \dots, S$ be the solutions for owned storage space; let $\alpha_j^L = j$, $j = 1, \dots, T$ be the solutions for leased storage space. Since the leased storage-space cost function is not defined for $\max \alpha_j^L$ and $\alpha < \alpha_0$, then $\alpha \leq \theta$, where $\theta = \min(\max_j \alpha_j^L; \alpha_0)$. This implies that the values of α_i^O and α_j^L exceeding the value of θ are infeasible.

The feasible values are now arranged in *increasing order* according to their magnitude to form the sequence of points φ_k where $k = 1, \dots, m$; also, $\varphi_m = \theta$. Note that these points form a sequence of mutually exclusive intervals $\varphi_k \leq \alpha < \varphi_{k+1}$, for $k = 1, \dots, m - 1$. The total expected storage cost for the k th interval is found to be [7]:

$$T_k(\alpha) = v_{(k)}(\mu + \sigma z_\alpha) + V_{(k)} \sigma \left(\frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z_\alpha^2} - \alpha z_\alpha \right) + \alpha(F_{(k)} - V_{(k)}L_{(k)}) + f_{(k)} - v_{(k)}O_{(k)} \quad (9.14)$$

The optimal value $\alpha_{(k)}^*$ can be proved to be the solution of the nonlinear Eq. (9.15):

$$\alpha = \frac{v_{(k)}}{V_{(k)}} - \frac{1}{2} \frac{F_{(k)} - V_{(k)}L_{(k)}}{V_{(k)}} \frac{e^{-z_\alpha^2/2}}{\sigma\sqrt{2\pi}} \quad (9.15)$$

if $\varphi_k \leq \alpha < \varphi_{k+1}$. Otherwise,

$$\alpha_{(k)}^* = \varphi_k \quad \text{if } T_k(\varphi_k) \leq T_k(\varphi_{k+1}) \quad (9.16)$$

$$\alpha_{(k)}^* = \varphi_{k+1} \quad \text{if } T_k(\varphi_k) > T_k(\varphi_{k+1}) \quad (9.17)$$

Equation (9.15) can be easily solved using a numerical analysis procedure, such as the well-known *Newton-Raphson (N-R)* method. When the *N-R* method converges,

the nonlinear equation $f(x) = 0$ can be approximately solved by iteratively using the relationship $x_{i+1} = x_i - f(x_i)/f'(x_i)$, $i = 1, 2, \dots$. It is assumed that the initial solution x_0 is available.

9.5.2 Dedicated Storage Policy

This section continues the treatment of storage-capacity analysis based on the work by Lee and Elsayed [7]. Let β_i be the probability of space shortage for item $i = 1, \dots, n$. As in Sect. 9.5, the required storage space for item i is represented by X_i and assumed to be uniformly distributed between a and b ; thus $h(X_i) = 1/(b_i - a_i)$, for $a_i \leq X_i \leq b_i$. If q_i is the storage space dedicated to item i , and X_i is the required storage space, the shortage probability is given by $\beta_i = P(X_i > q_i)$; then

$$q_i = a_i + (1 - \beta_i)(b_i - a_i) \quad (9.18)$$

Assuming statistical independence, the overall service level of the system is defined as $\prod_i (1 - \beta_i)$. The minimum amount of storage space required to provide the desired level of service is obtained by setting the shortage probability to be less than or equal to α_0 . It can be shown that the storage capacity of owned storage space is

$$S(\beta) = \sum_{i=1}^n b_i - \sum_{i=1}^n (b_i - a_i) \quad (9.19)$$

Additionally, the expected shortage area is

$$E(\beta) = \sum_{i=1}^n \beta_i (b_i - a_i) \quad (9.20)$$

The mathematical model to be solved is formulated below, where the indexes take on the values: $s = 1, \dots, S - 1$; $t = 1, \dots, T - 1$. The objective function (9.21) represents the total storage costs (due to owned and leased storage areas). Constraint (9.22) specifies a minimum acceptable shortage probability for the entire system or operation. Constraints (9.23)–(9.26) ensure that the owned space forms a region of specified size. Constraint (9.31) defines a feasible region for each shortage probability. All remaining constraints are formulated to achieve the condition that the leased space will form a region of specified size.

$$\begin{aligned} \text{Minimize } & S(\beta) \sum_s v_s y_s + E(\beta) \sum_t V_t Y_t + \sum_s (f_s - v_s O_s) y_s \\ & + \sum_t (F_t - V_t O_t) Y_t \end{aligned} \quad (9.21)$$

Subject to

$$\prod_i (1 - \beta_i) \geq 1 - \alpha_0 \quad (9.22)$$

$$O_s < S(\beta) y_s + M(1 - y_s) \quad (9.23)$$

$$S(\beta) y_s \leq O_{s+1} \quad (9.24)$$

$$\sum_s y_s = 1 \quad (9.25)$$

$$y_s = 0 \text{ or } 1 \quad (9.26)$$

$$L_t < E(\beta) Y_t + M(1 - Y_t) \quad (9.27)$$

$$E(\beta) Y_t \leq L_{t+1} \quad (9.28)$$

$$\sum_t Y_t = 1 \quad (9.29)$$

$$Y_t = 0 \text{ or } 1 \quad (9.30)$$

$$0 \leq \beta_i \leq U_i \quad (9.31)$$

where U_i is a known upper bound on b_i .

The procedure to find the optimal storage capacity is fully developed in the article by Lee and Elsayed [7]. Here we describe it, dividing it into five steps.

Step 1 Minimize $-E(\beta'') = -\sum_{i=1}^n (b_i - a_i) (1 - e^{-\gamma_i''})$

Subject to
$$\begin{aligned} \sum_{i=1}^n \gamma_i'' &\leq -\ln(1 - \alpha_0) \\ 0 \leq \gamma_i'' &\leq -\ln(1 - U_i) \quad \forall i \end{aligned}$$

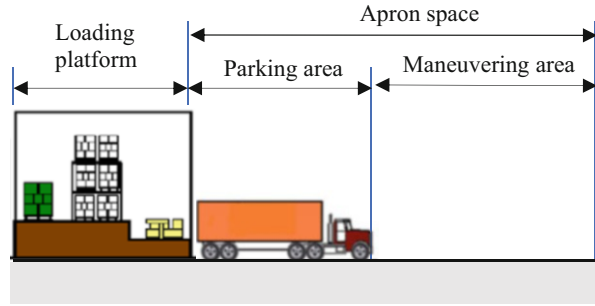
Step 2 Set $s = s'$, $t = 1$, $Z_{\min} = \infty$

Step 3 Minimize $T^{st}(\beta_i^{st}) = (V_t - v_s) \sum_i (b_i - a_i) \beta_i^{st} + v_s \sum_i b_i + f_s - v_s O_s + F_t - V_t L_t$

Subject to
$$\begin{aligned} \prod_{i=1}^n (1 - \beta_i^{st}) &\geq 1 - \alpha_0 \\ 0 \leq \beta_i^{st} &\leq U_i \quad \forall i \\ \sum_{i=1}^n (b_i - a_i) \beta_i &\in \left[\sum_i^n b_i - O_{s+1}, \sum_i^n b_i - O_s \right) \cap (L_t, L_{t+1}) \end{aligned}$$

If the solution is feasible, $\beta_i = \beta_i^{st*}$.

Fig. 9.5 Illustration of dock planning terminology



Step 4 If an infeasible solution was obtained in Step 3, set $T^{st}(\beta_i^{st}) = \infty$. Otherwise, if $Z_{\min} > T^{st}(\beta_i^{st})$ let $Z_{\min} = T^{st}(\beta_i^{st})$.

Step 5 Reset $s = s + 1$, $t = t + 1$. Repeat Steps 3 and 4 for every combination of s and t such that $S' \leq s \leq S$, $1 \leq t \leq T'$. The optimal storage capacity is equal to $Z_{\min}$.

9.6 Dock Planning and Design

Docks are the most utilized facilities in a warehouse system. Material is transferred from storage locations to a dock before shipping activities or from a dock to storage locations after receiving activities. The objective of dock design is to make the transportation of materials between the warehouse and the bed of the carrier safe and efficient. The carrier bed may be elevated by the carrier's wheel and the axle structure. As a result, often the warehouse floor must be brought to the same level to permit material handling equipment to traverse back and forth over a bridge, dock plate, or dock lever connecting the warehouse and the carrier levels. Usually, this is achieved by elevating the warehouse floor, or by gradually lowering the level of carrier.

A substantial portion of the remainder of this chapter is based on the work by A. J. Templar on dock planning and design [10]. The three factors that need to be considered in planning the loading dock are: (a) dock location and design, (b) dock leveler selection, and (c) safety. The main terms used in dock planning are (a) loading platform, (b) parking area, (c) maneuvering area, and (d) apron space. These terms are illustrated in Fig. 9.5.

9.6.1 Dock Location

In general, the facilities planning process includes two major components: design and location. The location of a dock should be chosen with the goal of minimizing

the in-plant traffic and ensuring safe movement of trucks in and out of facility grounds. The following factors can influence the selection of the site for a dock:

- (a) Truck access.
- (b) Waiting areas.
- (c) Loading areas.
- (d) Maneuvering space.

Truck Access Trucks should move around the building in a counterclockwise direction. The following traffic standards should be ensured: (a) Wide-angle mirrors are specified for turning blind corners. (b) Speed limits are posted. (c) Pedestrian and vehicle flows are routed separately. (d) Roadways are separately designed for truck traffic and the flow of employees. (e) Parking is prohibited in areas associated with limited vision.

Waiting Areas There should be a waiting area adjacent to the dock large enough to handle the anticipated number of vehicles. Waiting and parking areas should be properly designed to avoid conflict with the area reserved for maneuvering the vehicles.

Loading Areas These areas are specified for parking the tractor-trailer combinations during loading and unloading. For each dock, its loading area should extend at least 65 feet in front of the dock and 3 feet on each side.

Maneuvering Areas These areas are required to allow changes in the direction and position of large tractor-trailer combinations around the dock. The total maneuvering area of a dock should extend at least 70 feet outward from the loading area. For a counterclockwise traffic flow, the maneuvering area should extend at least 120 feet from the dock, assuming a tractor-trailer combination length of 65 feet.

Types of Dock Locations There are two basic strategies to combine docks:

- (a) Receiving and shipping docks are combined in the same general location at a storage facility. This is mainly done for small plants where relatively small parts need to be handled. The major problem associated with this strategy is the substantial amount of material flow and vehicular traffic resulting from the combined location of shipping and receiving activities.
- (b) Receiving and shipping docks are assigned individual separate locations, usually when the receiving and shipping activities are performed at different sides of the storage facility.

9.6.2 Types of Docks

Five dock configurations are commonly used: enclosed docks, open docks, sawtooth docks, dock piers, and freestanding docks.

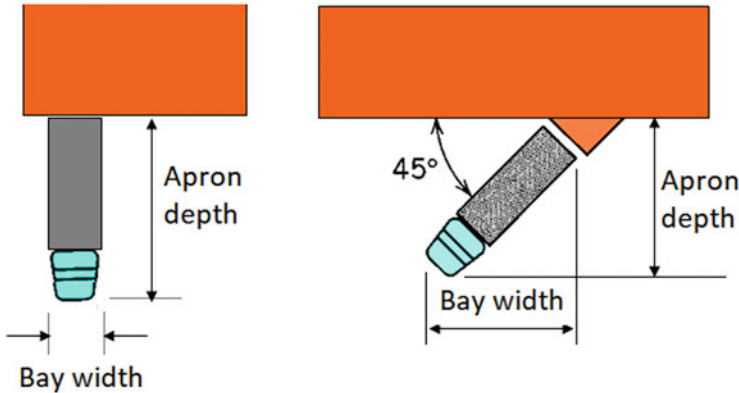


Fig. 9.6 Sawtooth dock type

Enclosed Dock In this type of dock, the loading or unloading tractor-trailer combination is parked in an area delimited by a wall on each side and a roof. Vehicles are parked perpendicularly to the building wall, inside this area, and dock levelers are usually needed for each vehicle as an interface between the vehicle and the loading/unloading platform. Enclosed docks offer optimal protection from the weather and provide security.

Open Dock In this type of dock, the tractor-trailer combination is parked in an area with no walls on the side and no roof. Sufficient space must be available between loading ramps and the building wall to enable forklift maneuvering.

Sawtooth Dock This type of dock (also known, as a *finger dock*) is used when the size of the area for maneuvering the vehicle is limited. The vehicles are positioned at an angle to the building to reduce the apron space required. As can be observed in Fig. 9.6, which shows a dock with a 45° saw tooth angle, this type of dock requires more linear wall space than a perpendicular design (also known as a 90° dock).

Dock Pier Dock piers are usually built when it is not possible to position docks along the perimeter of the building. Dock piers must be large enough to safely handle forklift traffic. A dock pier is shown in Fig. 9.7. Dock piers can have enclosed or open designs.

Freestanding Dock A freestanding structure outside the building can be constructed, as illustrated in Fig. 9.8, when the available space is limited or an obstacle impedes the construction of a loading dock.

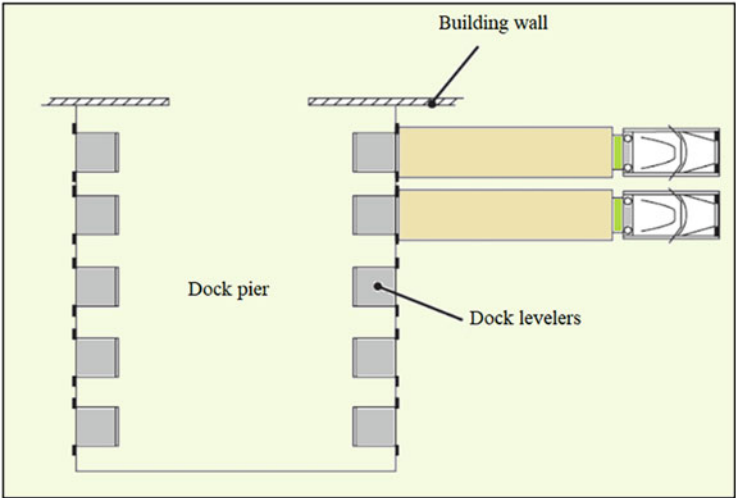


Fig. 9.7 Dock pier

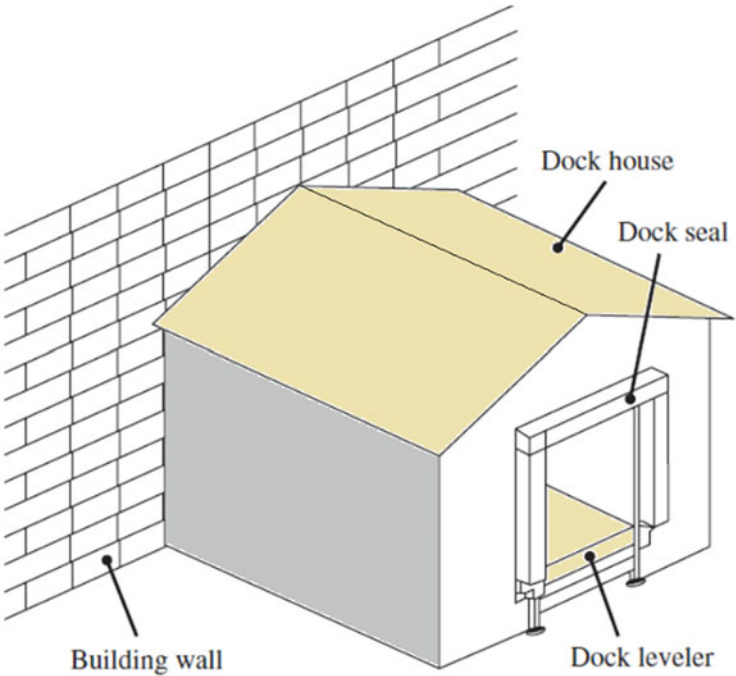


Fig. 9.8 Freestanding dock

9.6.3 Dock Design

The primary objective of dock design is to minimize the difference between the heights of the dock platform and the trailer bed. An effective design allows a diversity of vehicles to be used. In particular, the following truck dimensions need to be considered: truck or trailer bed height, total truck height, total truck width, and rear axle settings.

Table 9.1 shows typical truck dimensions [10]. The trailer and bed heights can vary by as much as 6" from their loaded to unloaded conditions, and sometimes more when air suspension systems are used. The most appropriate dock height can be determined by analyzing the bed heights of the trucks that utilize the dock to determine an average height. Table 9.2 gives suggested dock heights for level docks [10].

9.6.4 Dock Levelers

Dock levelers are platform-like devices used to bridge the gap between the dock and the trailer during loading and unloading by moving up or down to meet the trailer bed. This allows material handling trucks, such as forklifts, to make a smooth, safe

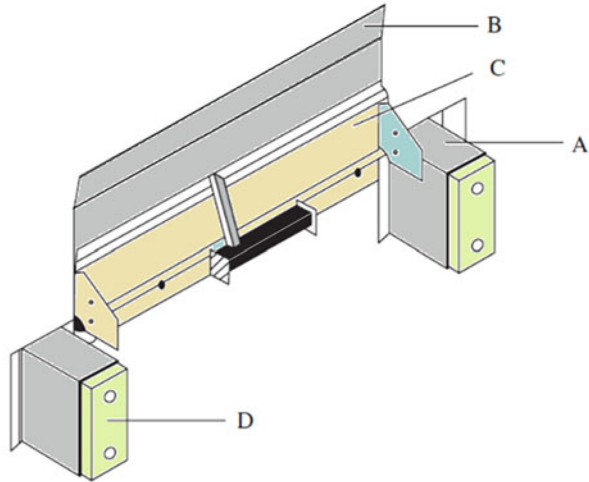
Table 9.1 Typical truck dimensions

Type of vehicle	Overall length (L)	Truck bed height (BH)	Rear axle (RA)	Overall height (H)	Overall width (W)
Flatbed	55"–70"	48"–60"	48"–144"	–	96"–102"
Semitrailer, road	55"–70"	48"–52"	48"–144"	12"–14"	96"–102"
Container	55"–70"	56"–62"	35"–48"	12"–14"	96"
Refrigerated	40"–55"	50"–60"	48"–60"	12"–14"	96"–102"
Semitrailer, city	30"–35"	44"–48"	35"–48"	11"–13"	96"
High cube	55"–70"	36"–42"	48"–144"	13"–14"	102"
Straight truck	15"–35"	36"–48"	27"–144"	11"–12"	96"

Table 9.2 Dock heights

Truck type	Dock height
Flatbed	52"
Semitrailer, road	48"
Container	46"
Refrigerated	55"
Semitrailer, city	52"
High cube	40"
Straight truck	44"

Fig. 9.9 Edge-of-dock leveler



transition into and out of the trailer. Dock levelers can also enhance safety and productivity on the dock through a variety of design features.

There are four major types of dock levelers: edge-of-dock, front-of-dock, vertical storing, and recessed levelers. The most important factors affecting the selection of a particular dock leveler are the specific needs to be satisfied; operators' safety; operational requirements; initial investment and maintenance costs; durability and reliability; and manufacturer's support.

- (a) **Edge-of-Dock Leveler:** This is an economical kind of leveler that attaches permanently to the front of the dock. An illustration is shown in Fig. 9.9, where A is a dock bumper projection, B is an outer lip, C is an inner lip, and D is a bumper pad (one on each side). The leveler has guards that keep feet under a ramp and comes in several designs, including mechanical, electric, and hydraulic designs. The mechanical leveler is operated by hooking a lip that is pulled up and extended to provide a platform or surface that is subsequently lowered to the level of the bed of the loading/unloading vehicle. It serves only a narrow range of truck and trailer heights with a minimum dock height of 48 inches.
- (b) **Front-of-Dock Leveler:** Like the edge-of-dock leveler, this type also has a limited range of height differential between dock and vehicle. Although it is bolted to the concrete wall at the front of the dock, it can be easily relocated. An illustration is shown in Fig. 9.10.
- (c) **Vertical Storing Dock Leveler:** This type of leveler, designed to eliminate obstructions in a pit that is parallel to the building, allows the vehicle to back against the building without opening the trailer doors. The leveler is configured for installation on the top of the dock. Its design allows the leveler to rotate from a raised position to a lowered operating position. An illustration is shown in Fig. 9.11.

Fig. 9.10 Front-of-dock leveler

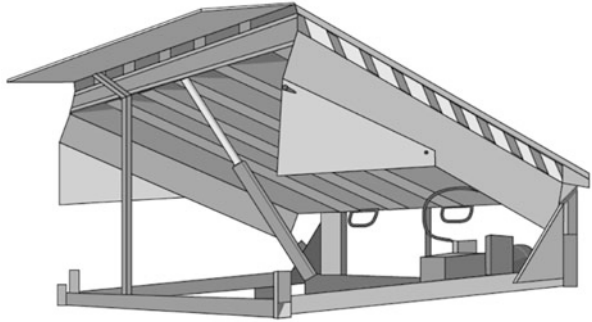
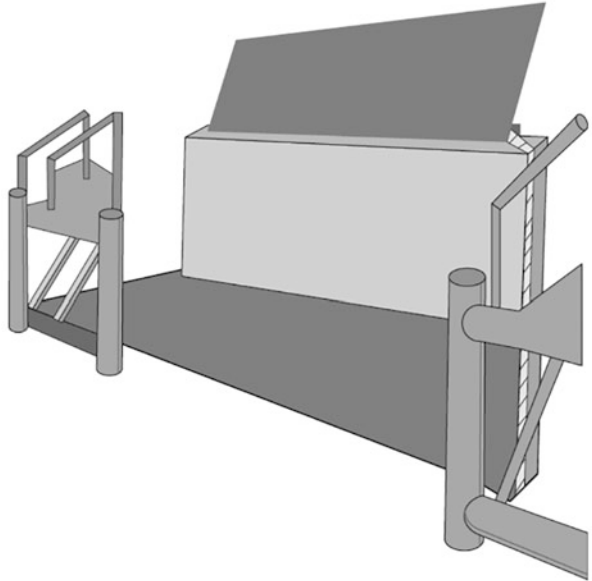


Fig. 9.11 Vertical storing dock leveler

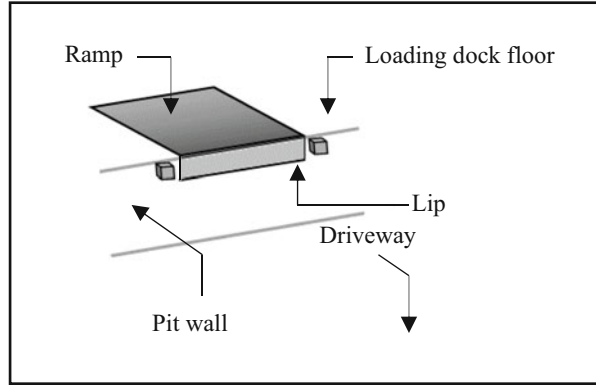


- (d) **Recessed Dock Leveler:** This type is designed to be installed in a pit formed at the dock location. It has a greater operating range above and below the dock level. It can also allow the access of wide trucks and trailers. Additionally, it has the highest load capacity and long service life. An illustration is shown in Fig. 9.12.

9.6.5 Dock Safety

Dock safety is the result of a successful integration of a diversity of factors, with particular emphasis on dock design, effectiveness of truck restraint, information and

Fig. 9.12 Recessed dock leveler



communication, lighting conditions, and training programs. When properly combined, these factors promote the following benefits:

- (a) Significant reduction of cross-traffic interference.
- (b) Proper location of staging and storing areas away from the dock area.
- (c) Adequate lighting conditions.
- (d) A good communication system between dock workers and truck drivers.
- (e) Significant increase in the protection level required for the operation of all material handling equipment.

9.7 Warehouse Systems Design

All warehouses perform at least four basic functions: (a) receive goods, (b) store and protect the goods until they are needed, (c) pick the product according to customer requirements, and (d) prepare the items to be shipped to the customer. An efficient design of a warehouse depends largely on the proper selection and utilization of the warehouse equipment. Ultimately, the design of warehouse is mostly based on the market it is intended to serve.

Although initial costs associated with the acquisition of equipment are usually a very significant investment, continuing costs associated with the operation and maintenance of the equipment can also be a major component of the total cost of the warehouse operation. Several aspects need to be effectively addressed in determining the type of warehouse equipment to be purchased. These will typically include (a) scope of job, (b) safety, (c) suitability of equipment, and (d) purchase and operating costs.

9.7.1 Storage Equipment

The three main types of material handling equipment covered in Chap. 7 are often used in carrying out warehousing operations. The *lift truck* is perhaps the most versatile of these since it can move horizontally and vertically, travel along varying paths, and with appropriate attachments, it can perform a wide range of pick-up, turn, push, and pull operations. *Conveyors* are best used for moving high-volume items in a fairly constant flow along a fixed route. Finally, *cranes* and *hoists* provide an effective and versatile way to perform lifting, loading, and unloading operations associated with overhead locations.

In addition, specialized equipment is often required to conduct the operations of a warehouse. Most of this equipment can be classified as carousels and rack storage systems.

9.7.2 Carousels

The carousel is a most ingenious material handling device. It is reliable, simple, and highly efficient. The density of storage associated with its use is exceptionally high. Furthermore, it can be located in areas where no other utilization seems to be likely, such as overhead locations in dry cleaning stores. Perhaps its biggest advantage is its effectiveness in bringing the inventory to the order picker instead of having the order picker traveling to the inventory location.

Carousels are almost always set up in groups of two or three to facilitate picking operations when conducted by a single picker walking down multiple aisles between carousels. Although picking hourly rates can vary from 80 to 200 operations per person, the *effective* rate may be less because of the need to perform restocking during picking operations. A frequent limitation is the requirement that only one picker can access the carousel at any given time. Depending on the space available, three types of carousels are frequently used: (a) horizontal carousels, (b) vertical carousels, and (c) independent rack carousels.

Horizontal Carousel A horizontal carousel is a linked series of rotating bins of adjustable shelves driven on the top or bottom by a motor. Rotation takes place around an axis perpendicular to the floor at approximately 80 feet per minute. Order pickers, able to control the rotation speed, are located at fixed positions in front of the carousel to remove items from it. Horizontal carousels vary in length from 15 to 100 feet and in height from 6 to 25 feet. Heights over 6 feet require the use of ladders or robot arms on vertical masts to access the items. A horizontal carousel is illustrated in Fig. 9.13.

Carousels can be controlled manually and automatically. Manual control is achieved by means of a keypad and a foot pedal. The keypad indicates to the carousel which bin location is to be rotated forward, and the pedal frees the carousel

Fig. 9.13 Horizontal carousel

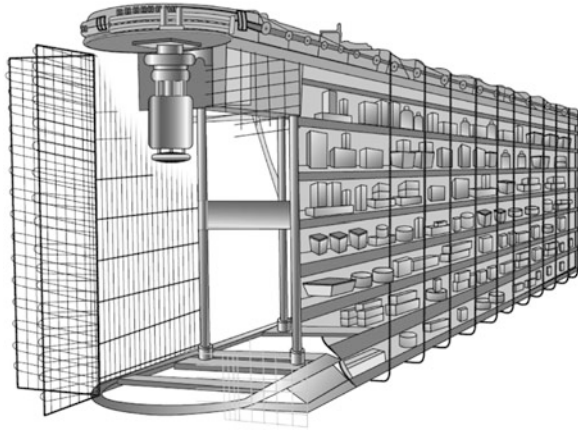
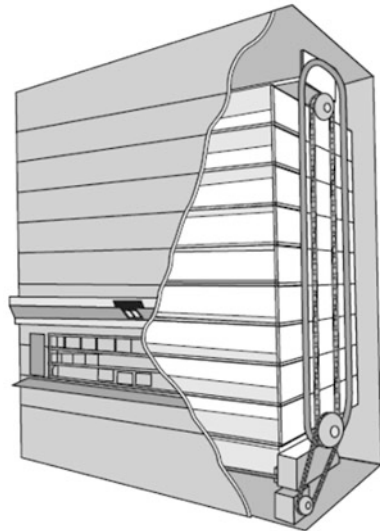


Fig. 9.14 Vertical carousel



to rotate. In the case of automatic control, a sequence of pick locations stored in the memory unit of a computer is retrieved and executed.

Besides enabling a high pick rate, horizontal carousels offer a way to enhance space utilization, since little space is required between adjacent carousels, and the only lost space is that between parallel sections of bins on the carousel unit. An important disadvantage of horizontal carousels is that the shelves and bins are open, and item security and protection can become a problem.

Vertical Carousel This type of carousel is in essence a horizontal carousel turned to a vertical position and placed in a sheet metal open-front enclosure. As in the case of horizontal carousels, an order picker can operate one or more units. The carousel

height typically ranges from 8 to 35 feet. A vertical carousel is illustrated in Fig. 9.14.

Order pick times for vertical carousels are in theory less than those for horizontal carousels because of the elimination of stooping and reaching activities. Additionally, vertical carousels can help to reduce the search time and to promote more precise picking. Benefits resulting from the utilization of vertical carousels include outstanding item protection and effective product security, since only one shelf of product is exposed at a time, and the carousel can be locked up.

Independent Rack Carousel Independent rotating rack carousels are in principle multiple one-level horizontal carousels stacked on top of one another, with each level having a separate power and communication link to be able to rotate independently. The order picker may access several locations at any time, allowing for *continuous* picking.

9.7.3 Rack Storage Systems

The rack storage system is frequently used as a storage facility in warehousing, mainly because it is highly cost effective and promotes an efficient utilization of vertical space. The most widely used storage facilities of this type include walkthrough rack storage devices, push-back rack storage systems, very narrow racks, structural drive-in racks, gravity-flow racks, mobile racks, double-deep racks, rollout shelf racks, reel racks, and cantilever racks.

The *walkthrough rack storage* system permits immediate accessibility to every pallet load in the system and sets a standard for rigidity, strength, and durability. An illustration is shown in Fig. 9.15. This type of storage facility is available in a large range of sizes and capabilities.

The *push-back rack storage* system derives its name from the fact that the pallet loads are literally pushed back into the rack. When a pallet load is retrieved at the aisle, the deeper pallet load automatically advances to the aisle. An illustration is shown in Fig. 9.16.

Specially designed forklift trucks can operate in aisles less than 5 feet wide, creating in turn a demand for *very narrow aisle (VNA) storage racks*. They provide a significant reduction in floor aisle space due to designs with heights of 40–50 feet. The pallets in VNA systems are accessed with turret or side loader lift trucks. Some VNA systems are designed with top and bottom monorails. An illustration of this type of storage facility is shown in Fig. 9.17.

The *structural drive-in rack* is used for large items stored in cartons that can be stacked one over the other, forming high columns of product. An illustration is shown in Fig. 9.18.

Gravity-flow racking is a storage system that relies on gravity flow to load, organize, and retrieve stored cartons or pallets within a warehouse. A gravity-flow

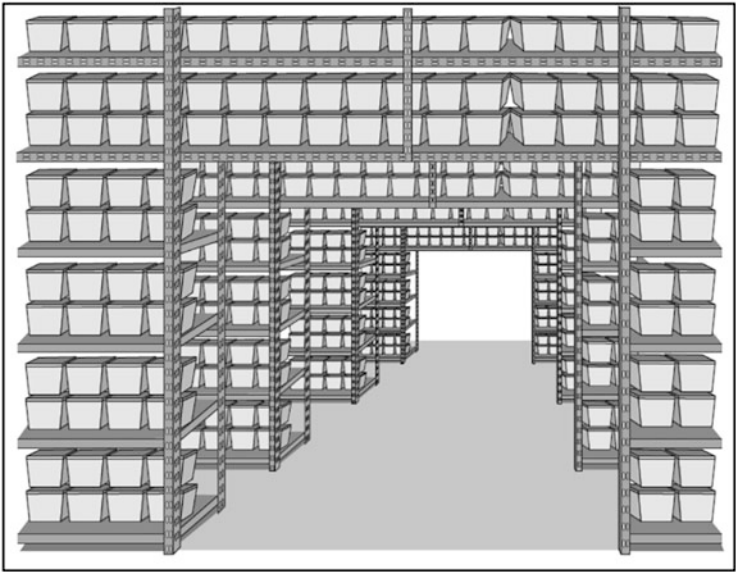


Fig. 9.15 Walk through rack storage system

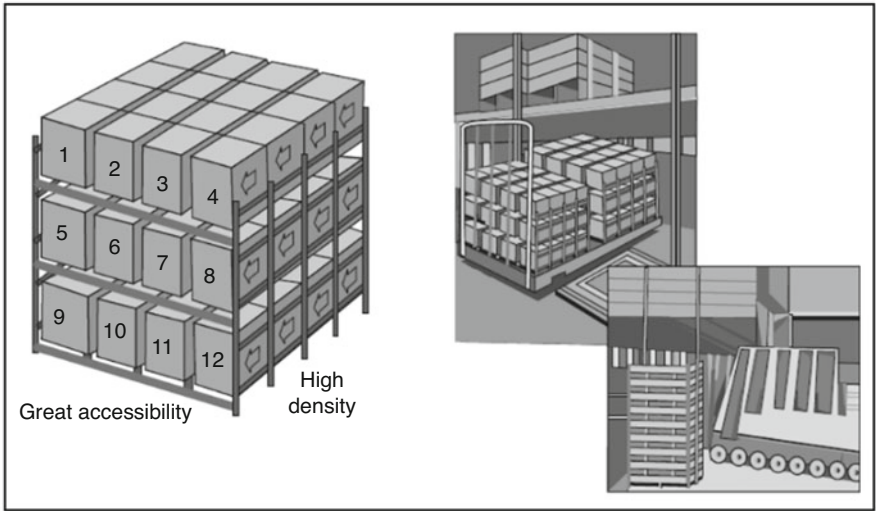


Fig. 9.16 Push-back rack

rack, illustrated in Fig. 9.19, serves principally as a storage device, but also as a means to transfer parts in the rows of the rack itself without much effort.

The *mobile rack* is a very high-density storage system allowing full utilization of pallet positions. The system consists of 100% selective back-to-back pallet racks



Fig. 9.17 VNA rack

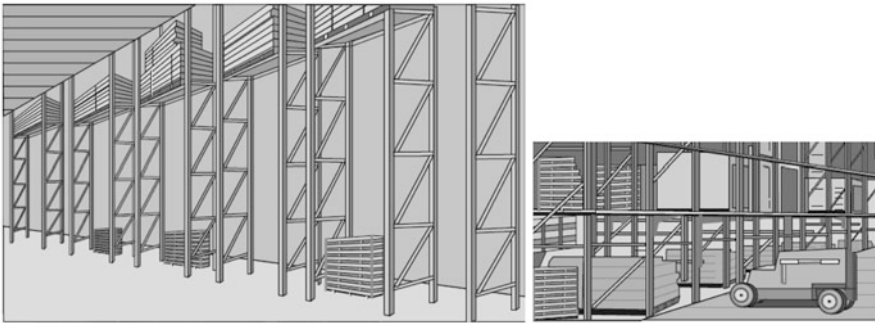


Fig. 9.18 Structural drive-in rack

mounted on mobile bases that travel on racks laid into the floor. The storage carriages are driven by electric motors and can be moved individually or as a section, permitting access to any pallet at any time. Mobile racks are particularly effective where aisle space is at a premium and speed of product movement is not a major concern. An illustration is shown in Fig. 9.20.

The *double-deep storage* rack is a popular choice for high-throughput storage operations. In addition to having low cost, it promotes high levels of productivity and product protection. The rack is designed to allow the placement, by means of a deep-reach lift truck, of a pallet in the back of the storage system followed by the placement of another pallet in front of it. Twice as many pallets are stored for a given

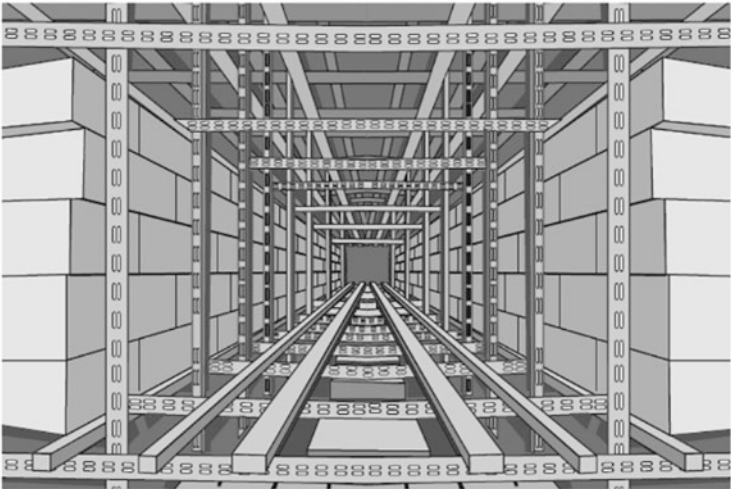


Fig. 9.19 Gravity-flow rack

Fig. 9.20 Mobile rack

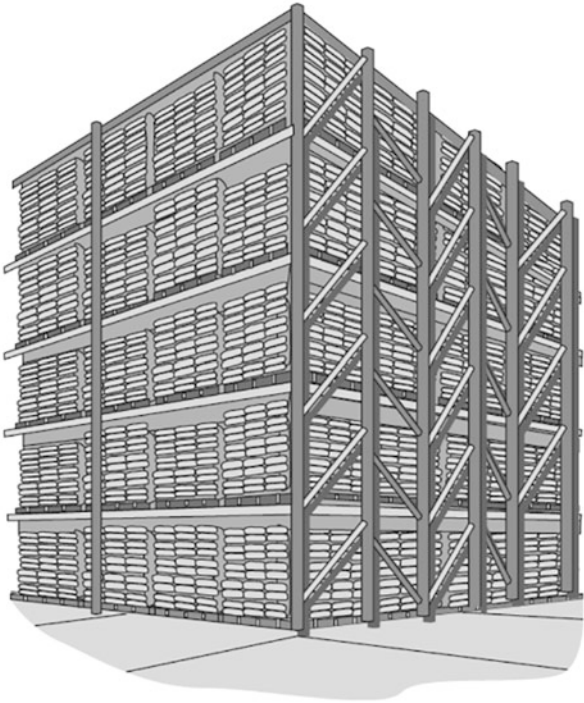




Fig. 9.21 Double-deep rack

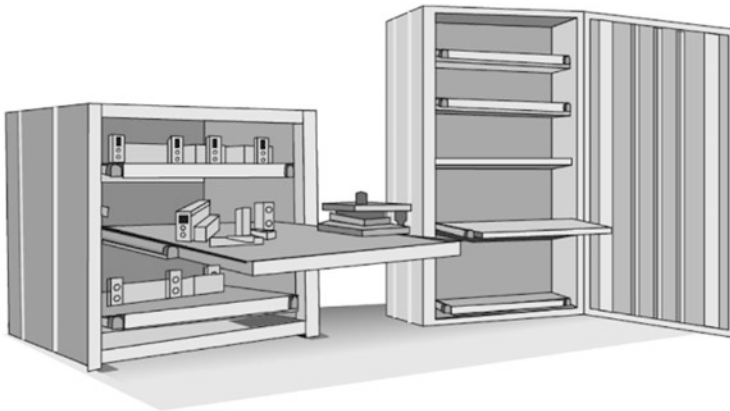


Fig. 9.22 Rollout-shelf rack

number of aisles when compared to the single-rack system. An illustration is shown in Fig. 9.21.

A *rollout shelf rack* is a specialized type of storage device used for relatively smaller parts that must be handled carefully. An illustration is shown in Fig. 9.22.

Reel racks are specifically designed for storing spools of different sizes, weights, and materials. The system has adaptors that can be repositioned on the racking to store different sized spool axes or in some cases sized pipes. An illustration is shown in Fig. 9.23.

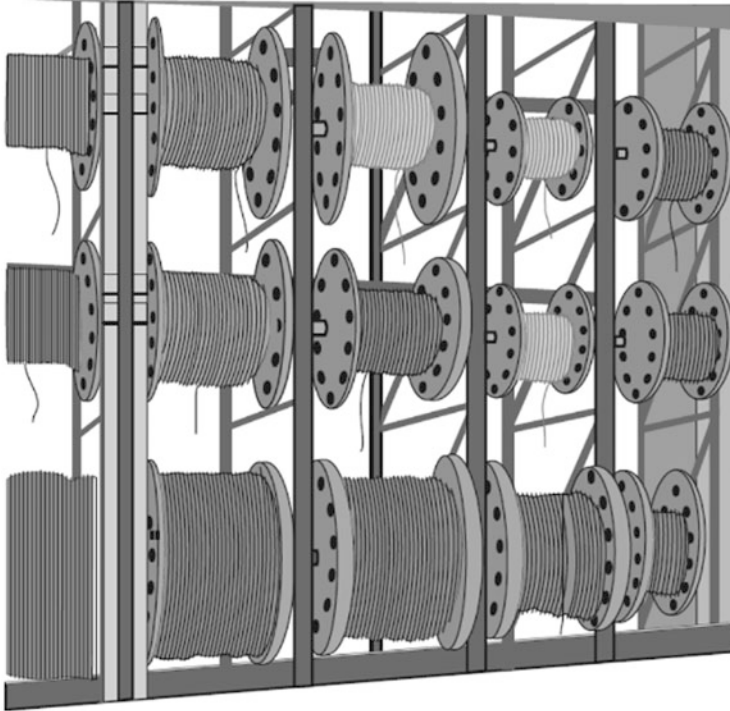


Fig. 9.23 Reel rack

Cantilever racks are used for relatively lightweight parts. Bulky and lightweight product is especially suitable for storage using this type of storage rack design. An illustration is shown in Fig. 9.24.

9.8 Automated Storage and Retrieval Systems (AS/RS)

This section introduces automated systems used for integrated storage and retrieval operations. Some design considerations and an illustrative numerical example are provided in this discussion, which has been adapted from work by Sule [9]. AS/RS have a significant effect on the performance of a storage and warehousing facility when integrated into manufacturing and distribution processes with the aid of a computerized system. Each storage and retrieval (S/R) machine operates in a single aisle and has storage racks on each side of the aisle.

A vertical stack of unit loads forming a column of product from the floor up to the ceiling of the storage facility is known as a *bay*. A group of bays placed side by side forms a *row*. Stacker cranes move along the *aisles* between the rows, serving both sides of the aisle. Basic terminology is illustrated in Fig. 9.25a; an industrial AS/RS

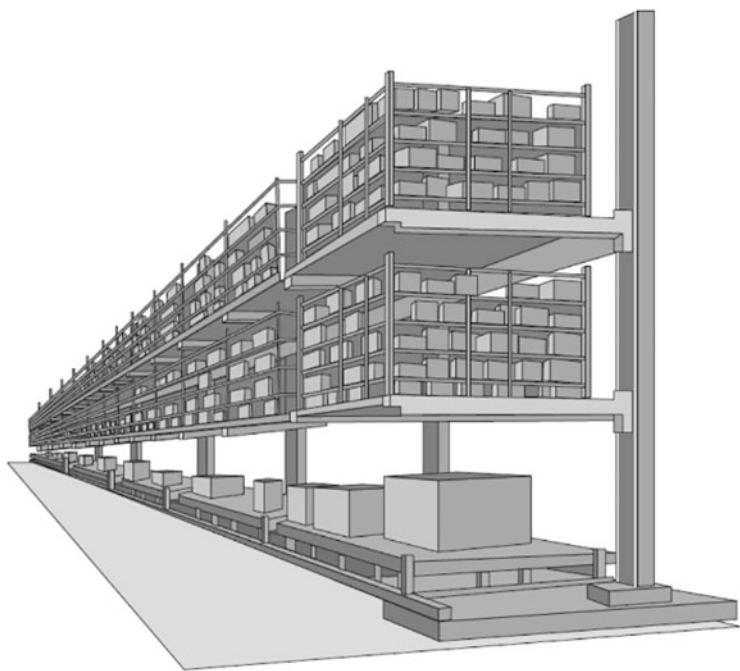


Fig. 9.24 Cantilever rack

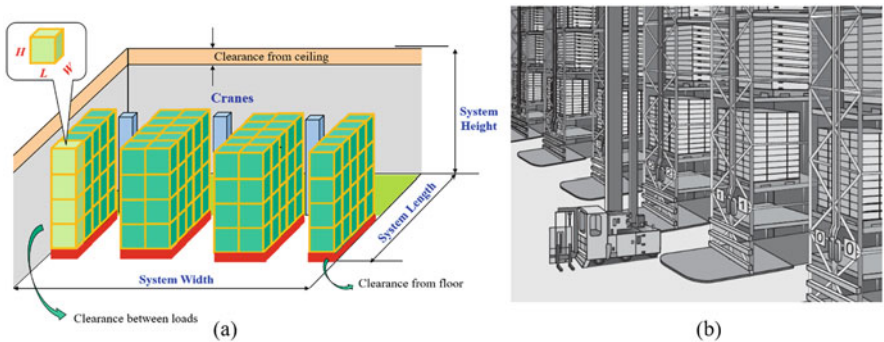


Fig. 9.25 An AS/AR system

system is shown in Fig. 9.25b. Light loads of less than 2500 pounds require a 6-inch clearance for rack support and crane entry. Heavier loads require 9 inches.

The AS/RS illustrated in Fig. 9.25b consists of *storage and retrieval cranes*, *storage structure*, *conveying devices*, and *controls*. The cranes travel on floor-mounted rails and can simultaneously move in the horizontal and vertical directions to reach specified locations. They may be equipped to function in single-command mode (store or retrieve) or double-command mode (store and retrieve) in one trip.

The storage structure (up to 90 feet) has guide rails that allow the cranes to move in and out, stopping at required locations. Specialized devices, such as forklift trucks, conveyors, towlines, and guided vehicles, are auxiliary equipment interfacing with the storage/retrieval cranes and several departments within the plant. The control unit consists mostly of computers and support mechanisms that regulate the functions and performance of the storage/retrieval cranes and auxiliary devices. Typically, a distributed system consists of several small computers communicating with one large computer. The individual computers control separate devices, and the larger computer is in charge of inventory maintenance and other activities such as cost calculation and billing information.

The number of cranes needed is determined by Eq. (9.32), where T is the throughput, C represents the number of cycles per hour, and E is the efficiency of the operation.

$$N = \frac{T}{CE} \quad (9.32)$$

In Eq. (9.32), the throughput is the sum of the maximum number of loads in and loads out carried per hour; the number of cycles is usually 32 for single-cycle cranes and 22 for double-cycle cranes; and the efficiency rate is commonly equal to 0.85.

An important factor affecting the height of the storage system is the number of unit loads vertically stacked in each bay (column of unit loads). If the height of the building H is given, the number V of unit loads vertically stacked can be calculated using Eq. (9.33).

$$V = \frac{H}{h + c} - 1 \quad (9.33)$$

In Eq. (9.33), h represents the load height and c represents the clearance between stacks. The desired value is the integer part of the calculation. The subtraction of 1 is to allow for floor and ceiling clearance. If this clearance is specified in advance, there is no need for the subtraction.

If U is the number of load units to be stored, the number of bays per row is calculated using Eq. (9.34).

$$B = \frac{U}{2NV} \quad (9.34)$$

Note that the number of rows is equal to $2N$.

The *width* of the storage system depends on both the number of cranes (or aisles) and the width of the *aisle unit*, which is defined as an aisle and two neighboring storage racks. Therefore, the width of the aisle unit is equal to twice the storage width (which is the same as the *depth* or *length* of the unit load, here to be represented by ℓ) plus the aisle width (which should accommodate the length of the load) plus

clearance. Thus, the width of the system is equal to (at least) three times the length of the unit load plus 2 feet for clearance, as indicated in Eq. (9.35).

$$W = N(3\ell + 2) \quad (9.35)$$

The length of the storage rack is equal to the combined width of the bay w and clearance b between bays multiplied by the number of bays in a row, plus the crane runout clearance, as indicated in Eq. (9.36).

$$L = B(w + b) + r \quad (9.36)$$

In Eq. (9.36), the crane runout clearance r is usually 25 feet.

Example 9.3

A manufacturing company wishes to store a unit on a $36'' \times 48'' \times 24''$ pallet having a weight of 1400 lb and 75 dual cycles per hour. The total storage is 18,000 unit loads. The height of the building is 80 feet, but clearances of 4.5 feet from the ceiling and 6 inches from the floor for rack support are needed. (a) Determine the number of stacks that can be accommodated with height of the load. (b) Determine the number of dual cranes (22 cycles per hour) needed. (c) Determine the number of bays needed. (d) Determine the storage dimensions. Consider a clearance equal to 6 inches between stacks and an availability factor of 85% for cranes.

Solution

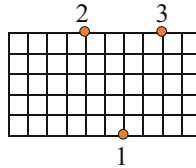
- (a) The number of loads vertically stacked per bay is obtained using formula (9.33) without subtracting 1, since the clearance is specified in advance. After setting $H = 80 - (4.5 + 0.5) = 75$, then $V = 75/(2 + 0.5) = 30$.
- (b) The number of dual cranes is obtained using formula (9.32), $N = 75/(22 \times 0.85) = 4.01 = 5$ cranes. Thus, number of rows is equal to 10.
- (c) Using Eq. (9.34), the number of bays per row is $B = 18,000/(10 \times 30) = 60$.
- (d) The dimensions of the storage system are determined as follows. The width is obtained using Eq. (9.35), $W = 5[3 \times 4 + 2] = 70$ feet. The length is obtained using formula (9.36), $L = (3 + 0.5) \times 60 + 25 = 235$ feet. The height was given 80 feet.

9.9 Exercises

- 9.1 Suppose that a 40-foot by 40-foot warehouse is used to store products P and Q under a dedicated storage policy. The floor can be represented as a grid with 10-foot by 10-foot cells, each cell corresponding to one storage space unit. In this grid, the bottom left corner represents the location of a dock. Pallets of products are moved between a dock and the warehouse, along rectilinear distances. The first product accounts for about 30% of the total travel activity and the second one for the remaining 70%. The first product requires typically

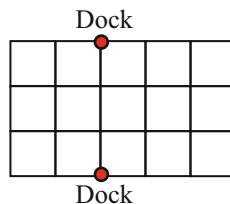
six storage space units per day and the second product nine per day. Find the policy that minimizes total travel distance.

- 9.2 A warehouse 200 feet long and 100 feet wide has three docks located as shown in the figure.



Two products are to be stored. Product A enters the warehouse at dock 1 at a rate of 600 pallet loads per month and is shipped from docks 2 and 3 at rates of 120 and 480 pallet loads per month, respectively. Product B enters the warehouse at dock 1 at a rate of 1000 pallet loads per month and is shipped from docks 2 and 3 at rates of 200 and 800 pallet loads per month, respectively. Storage spaces of 8000 and 12,000 square feet are required for A and B, respectively. The warehouse is arranged into bays 20 feet by 20 feet, and only one type of product can be stored in a given bay. Assume rectilinear travel. (a) Determine the order in which the products should be considered when assigning storage locations. (b) Find the expected distance traveled between storage location 1 (top left cell) and the docks.

- 9.3 Consider a rectangular warehouse layout with 10×10 feet storage bays. The layout consists of four rows and four columns of bays. A single dock is located at the **top left** corner of the layout. Two classes of products A and B are to be stored using **dedicated storage**. Class A items represent 20% of the input/output activity and require 8 storage bays. Class B items represent 80% of the input/output activity and require 8 storage bays. Design an optimal layout. Include all work needed to support your answer.
- 9.4 Two input/output docks serve a storage area, with the overall activity being about 50% for each dock. All movement is in full-pallet quantities. The storage area is subdivided into fifteen 10×10 feet storage bays, as shown below. Three classes of products are to be stored.



Class A items represent 20% of the input/output activity and have a dedicated storage requirement of 3 bays; class B items generate 65% of the trip activity and have a dedicated storage requirement of 6 bays; class C items generate 15% of the input/output activity and have a requirement of 5 bays. Indicate the optimal warehouse layout, showing all supporting calculations.

- 9.5 Consider a rectangular warehouse of dimension 3 by 3 bays. Each storage bay is of size 20×20 feet. There are two products, A and B, and one single dock located in the middle of the left-hand side of the warehouse. Product A requires four and product B has three storage locations. Product A represents 20% and Product B is 80% of the input/output activity. (a) Find the optimum dedicated storage layout. (b) Find the expected distance traveled for dedicated storage. (c) If randomized storage is used, such that each bay is equally likely to be used for storage, find the expected distance traveled. (d) Compute an upper bound for randomized storage that will yield an expected distance traveled equal to or less than that for dedicated storage.
- 9.6 Assume that each of two items has storage-area requirements uniformly distributed between 20 and 300. Consider a piecewise linear cost function with two linear segments. For owned storage space, the first segment is defined between 0 and 100 with fixed cost equal to 12 and variable cost equal to 20. The second segment is defined between 100 and 300 with a fixed cost of 20 and a variable cost of 15. For leased storage space, the first segment is defined between 0 and 150 with a fixed cost of 5 and a variable cost of 40. The second segment is defined between 150 and 300 with a fixed cost of 7 and a variable cost of 30. (a) Plot both curves. (b) Find the probability of a shortage. (c) Find the level of service. (d) Formulate a model for minimizing total storage space costs. (e) Find the optimal solution using a commercially available optimization program.
- 9.7 A manufacturing company wishes to store a unit on a pallet having dimensions of $24" \times 48" \times 20"$ and a weight of 2800 lb. The throughput is 75 dual cycles per hour. The total storage is 15,000 unit loads. The height of the building is 75'. A total floor and ceiling clearance of 2' is needed. Determine the storage dimensions. Write all specific assumptions.
- 9.8 A manufacturing company wishes to store a unit on a $36" \times 48" \times 24"$ pallet having a weight of 1400 lb and 75 dual cycles per hour. The total storage is 15,000 unit loads. The height of the building is 75', but clearances of 4.5' from the ceiling and 6" from the floor for rack support are needed. (a) Determine the number of stacks that can be accommodated with the given height of the load. (b) Determine the number of dual cranes needed. (c) Determine the number of bays needed. (d) Determine the storage dimensions. Consider a clearance equal to 6" between stacks and an availability factor of 85% for cranes.
- 9.9 Describe each type of storage device discussed in this chapter. For each device, outline typical applications, advantages, and disadvantages.
- 9.10 Describe each type of dock design considered in this chapter. For each design, outline typical applications, advantages, and disadvantages.

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Chapter 10

Site-Planning Design



10.1 Introduction

Site planning is a crucial aspect of facility planning and design. Every building has a context, i.e., a location, which can have a significant impact on the internal design of the facility whether it be a manufacturing or service sector facility. For example, the siting of the building will have a major impact on future expansion and growth, truck and vehicular accessibility, energy costs to operate the facility, maintenance costs of the grounds and operation of the building, as well as its visible presence and image to the rest of the community. These are important factors that must be accounted for in any facility design. There is also a constant interplay between the site and the internal workings of the facility and it is through a comprehensive design process that both the site and the facility design should evolve.

Site planning is one of the most difficult and interesting problems in facilities design. In Sect. 10.2, a general site planning methodology is described along with the assumptions and fundamental concepts needed to carry out a site evaluation problem. A comprehensive analysis of the attributes/criteria relevant in a site selection study is provided in Sect. 10.3. In Sect. 10.4, an urban site location example is used where the criteria of Sect. 10.3 and the methodology of Sect. 10.2 are conjoined. In Sect. 10.5, a factory project is utilized and again the criteria and methodology are demonstrated for locating a manufacturing facility on a site. It is felt to be important to see how the activity functions of the factory and the site plan activities must be conjoined. Section 10.6 summarizes and concludes the chapter. Finally, in the appendix to the chapter, the detailed planning issues surrounding site selection are summarized.

Each site is unique and has a variety of interrelated characteristics which together make the site decision extremely complex. The site plan originally shown in Fig. 1.4 (now repeated as Fig. 10.1) to motivate the topic of site planning in Chap. 1 is illustrative of the nature of the building design process and its interaction with the site. The location of the parking and truck turnaround areas, access roads, and staff

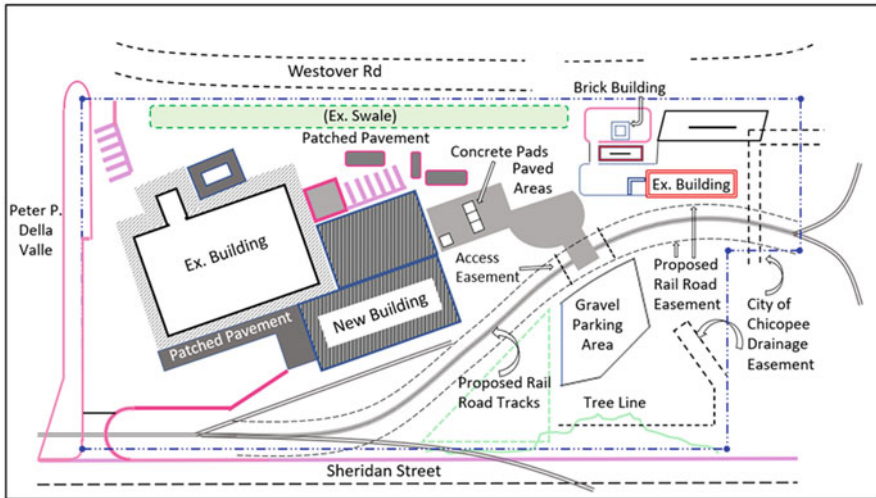


Fig. 10.1 Typical site planning problem

and visitor entrances and exits are critical to the orientation of the building, the design of the building envelope, and the general product flow through the plant.

A careful assessment of the facility, its intended function, and potential users should occur in addition to the evaluation of a particular site and its natural characteristics. In order to provide an overview of criteria which may enter into the site decision, Fig. 10.2 shows a fairly complete checklist of criteria that are totally or in part relevant to the site decision. The multiple attributes in the figure may seem overly detailed, yet each one is important to the entire site plan.

10.1.1 Motivation

Designers, by their nature, are usually bubbling with ideas, but the rigorous analysis and evaluation of these ideas do not necessarily flow easily from their creative personalities. Especially in complex manufacturing and service sector facility planning situations, the evaluation of ideas can become quite controversial. As evidenced in many environmental impact evaluations, site-selection decisions, and renovation questions, groups often become polarized into opposing factions, unwilling to discuss issues openly, to attempt to see other points of view, or even to talk to each other. Unfortunately, it is the environment that suffers because of these groups' inability to communicate with each other in an objective manner about evaluation problems.

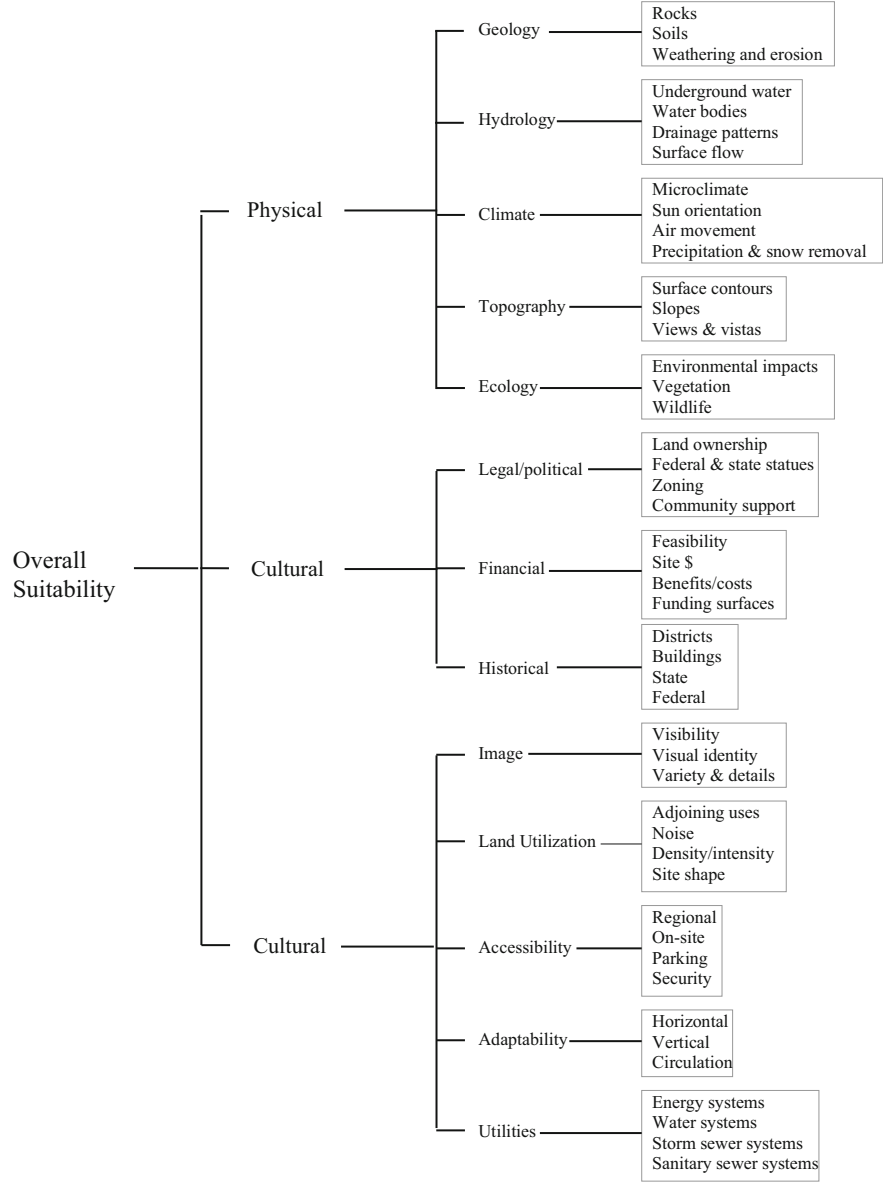


Fig. 10.2 Site-planning criteria classification

Some methods for objectifying the site-planning process are warranted in order to assure a more rational and open discourse on siting questions. The use of systematic procedures to guide and manage the site-planning process can be referred to as the process of “objectification,” whereby one person tries to make clear a world view to another person.

10.1.2 *Siting Problem Example*

In order to illustrate some of the previous concepts, let us examine briefly a very difficult siting problem, one having to do with the disposal of nuclear waste products. This is an example of one of the most difficult and complex siting problems ever known, and while one could be accused of trying to tackle an impossible problem, sometimes it is useful to examine extreme situations because it puts things into perspective when dealing with less problematic situations.

The disposal of nuclear waste products stems from our desire to seek peacetime uses of nuclear technology after the World War II. Unfortunately, the peacetime issues have somewhat backfired and now the proper disposal of these nuclear waste products utilized in nuclear power plants is of paramount importance. Some of the most critical issues are [1]:

1. What should be done with spent nuclear waste products?
2. Should alternative technologies be considered to deal with this disposal problem as opposed to underground burial?
3. Should nuclear waste be buried in deep geological burial vaults?
4. Should the geological formation be counted upon to remain stable for 10 millennia?
5. Can human beings be counted upon not to interfere with these burial vaults?
6. What is likely to happen to a state's economy and culture if an operation the size of the repository (about three square miles) opens even if the risks posed by radiation are not taken into account?
7. How is one to evaluate the **uncertainty** surrounding the following objectives:
 - f1. Costs of construction
 - f2. Maintenance and operating costs over 10, 000 years
 - f3. Environmental impacts
 - f4. Geological site stability (earthquakes, water table, and so on.)
 - f5. Reliability from contamination (leaks, material and container structural failure, and so on)
 - f6. Sabotage

Actually, the discourse on this problem is still very much alive, yet certain decisions have already been made to choose a site in Nevada as the nuclear waste repository. See Fig. 10.3, where the boldfaced items represent the current means of resolving the site planning problem. (For a further perspective on this site planning problem, see Keeney [2].) The most unfortunate thing about this problem is the *degree of uncertainty* surrounding the estimation of the consequences (over 10,000 years), and even the number of possible alternatives which, as Kai Erikson [1] points out, are beyond belief. Actually "doing nothing" may make the most sense here, as the other alternatives may become more feasible with the advancement of new technologies.

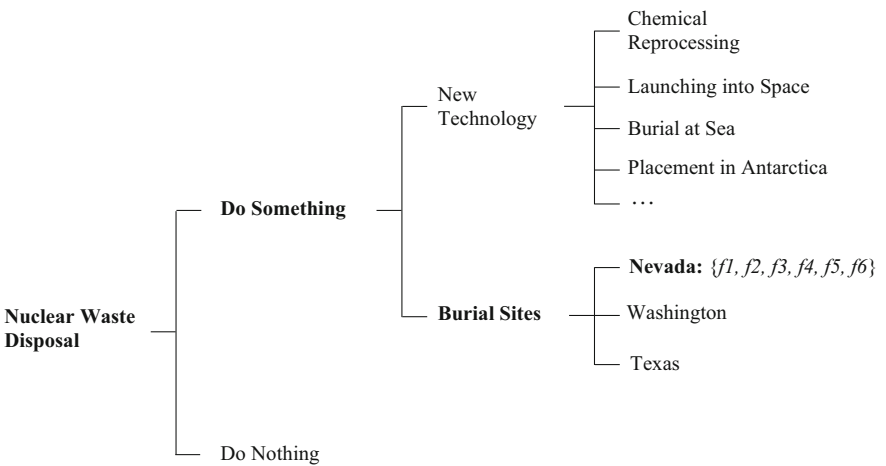


Fig. 10.3 Issue network of nuclear waste disposal problem

10.2 Site-Planning Methodology

Of central importance to the discussion are the notions of criterion, objective, and attribute. Sometimes people will use other nomenclature, but these concepts form the foundation for all that is to follow.

1. *Criteria*: Standards of judgement. All the relevant criteria are collected in a multidimensional vector $\mathbf{\Omega} = \{f_1(\bar{x}), \dots, f_l(\bar{x})\}$. This vector indicates the objectives to be achieved at a satisfactory level.
2. *Objectives*: Desired outcomes. Each single criterion or objective may be classified into one of two categories:
 - Quantitative (satisfied to a certain degree)
 - Qualitative (either satisfied or not)
 - Normally a criterion f_k is placed in $\mathbf{\Omega}$ as a quantitative objective. Otherwise, it should be considered as a constraint or goal to be achieved. Very often an objective cannot be measured directly but must be approximated or indirectly measured by another quantitative or dimension referred to as an *attribute*.
3. *Attributes*: Characteristic measures of performance.
 - Direct (e.g., dollars for minimizing costs)
 - Indirect (e.g., number of defects for maximizing quality)

10.2.1 Objective/Attribute Hierarchy

A tree diagram representing the relationship between objectives and attributes is useful to demonstrate the objective/attribute hierarchy in the nuclear waste disposal problem. These two complementary concepts are integrated in Fig. 10.4, although they may be viewed separately. When one starts to integrate such diagrams, the complexity of the site-planning problem becomes quite clear.

It is useful to construct a general mathematical model to formalize the search in solving site-planning problems. One possible formulation is given below:

$$V = g(\Omega_{DMU}, X, DS)$$

where

DMU—Decision-making unit (people involved, concerned or affected by the site-planning problem).

Ω_{DMU} —Set of criteria (objectives/attributes) used to evaluate each alternative.

The i th attribute is normally denoted by χ_i .

X —Set of alternatives, each alternative denoted by an n -dimensional decision vector $\mathbf{x} = (x_1, \cdots, x_n)$.

DS —Decision situation, that is, context, purpose and timing of the decision.

V —Overall utility of each $\mathbf{x} \in X$.

As in the nuclear waste disposal problem, one must clearly specify the set of criteria one wishes to optimize, and very often it will be a subset of all possible

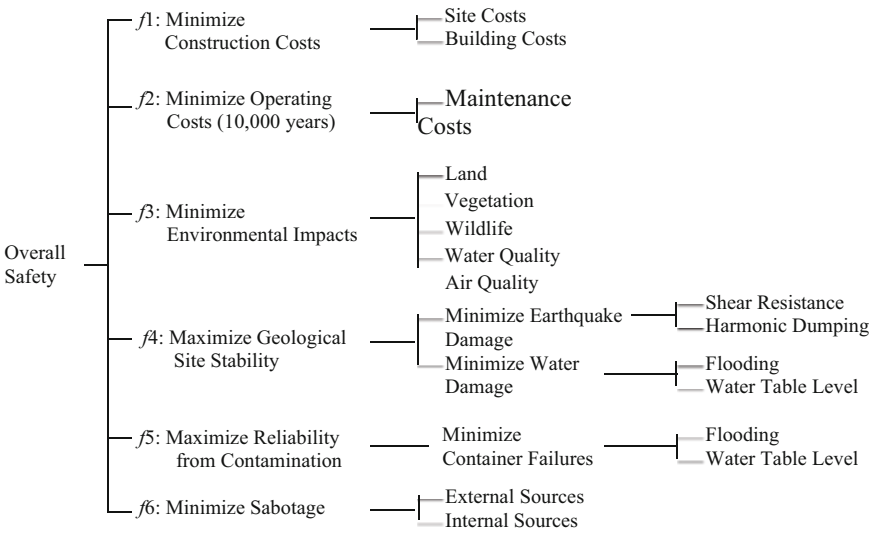


Fig. 10.4 Objective-attribute hierarchy

criteria. One must also specify who the DMU is, since in order to communicate and implement the models and results, those central to the DMU must be willing and able to implement the solutions. Finally, one must clearly specify the context, time, and place of the events surrounding the site-planning problem.

There are basically two types of values: *intrinsic* and *extrinsic*. Intrinsic values refer to things that are valued solely for themselves. Scientific research, art, or mathematics, for example, are often carried out for their own sake, and not for any immediately practical purpose. Extrinsic values, on the other hand, refer to things that not only are valued for themselves but also are dependent on a particular time and context for their existence. Architectural and engineering design problems usually fall into this category, because designers must work with clients, time and fiscal budgets, and site constraints. The value of a design concept is therefore highly dependent on the context for which it is developed.

Four assumptions underlie the design of an evaluation system for site-planning:

1. A list of performance criteria can be generated concerning the site to be evaluated; this list can be weighted in order of importance to reflect the different points of view of the participants in the evaluation process. Often some criteria are emphasized, while others are disregarded; weighting the criteria helps to resolve this problem.
2. The list of performance criteria can be made as complete as possible and each item can be carefully identified and worded, so that all items stand independently of each other.
3. Persons using the evaluation system should be able to make partial scores besides each criterion, according to the site being evaluated. For example, in choosing a site, an alternative may be worth only 5 points for its site drainage but receive 9 points for its view and vista qualities.
4. These partial scores can be synthesized into an overall judgment of the site. Merely scoring an alternative according to its criteria is not enough; there should be a way of arriving at an overall performance score from these partial scores.

Discussion of these basic assumptions follows.

10.2.2 First Assumption

A list of performance criteria can be generated concerning the site to be evaluated; this list can be weighted in order of importance to reflect the different points of view of the participants in the evaluation process. The performance criteria or evaluation aspects are essential to the notion of evaluation, because persons make both overall “off-hand” judgments and deliberated judgments during the course of the evaluation process.

The performance criteria are essential to the process of making deliberated judgments about an alternative site. For example, one might initially argue that moving the facility outside the local community would be an unwise strategy.

However, upon further deliberation, such a strategy might not seem unwise in terms of expansion, site costs, image, and other specific criteria. In this case, the offhand judgment would be altered in light of more deliberated judgments. The process of making overall offhand judgments is fairly typical of the evaluation process, and any evaluation system should be designed to accommodate both offhand and deliberated judgments.

Not all criteria will be of equal importance in evaluating the performance of an alternative site. Some skeptics feel all criteria are of the same value, some feel only one criterion is really important, and some argue that to try to differentiate and weigh the criteria is a waste of time. These skeptics, who in some cases may seem to have valid arguments, are being neither constructive nor cognizant of the need to place the evaluation process on an objective basis.

10.2.3 Second Assumption

While it may be difficult and require a certain amount of energy to weight the criteria, that weighting is essential to the evaluation process.

The list of performance criteria should be made as complete as possible, and each criterion should be carefully identified and accurately described. The criteria can usually be gathered from essentially three groups of people: the client, the users, and the designer(s). The general types of criteria generated by these persons usually include the following items:

Client	Users	Designer(S)
Economy (site/building)	Adaptability	Engineering feasibility
Maintainability	Usability	Aesthetics
Image	Comfort	Logic of the design
Manageability	Convenience	Concept
Security	Personal security	Environmental impacts
Flexibility for change		

10.2.4 Third Assumption

The above list can be expanded to include other, more detailed criteria (as shown in Fig. 10.2), but it is representative of the types of criteria germane to those persons who may be involved in the evaluation process.

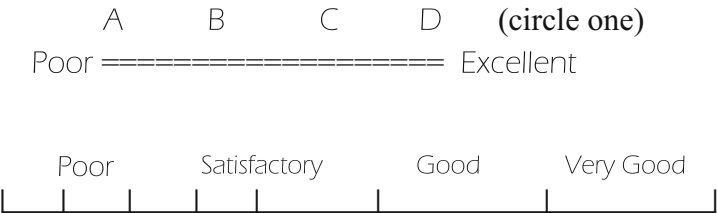
Besides making the list of criteria exhaustive, each criterion should be made independent of the others. In other words, the attainment of one criterion should not preclude or interfere with the attainment of another. For example, in a site-selection situation, the following criteria are relatively independent of each other:

- 1. Minimization of site acquisition costs
- 2. Minimization of building construction costs
- 3. Minimization of demolition costs
- 4. Minimization of site acquisition costs

The following two criteria, however, are not independent:

Criteria 3 and 4 are not independent because minimizing demolition costs is included in achieving criterion 4. Therefore, these criteria should be rewritten as a single criterion: minimization of demolition and site acquisition costs.

Those using the evaluation system should be able to make partial scores beside each criterion according to the site being evaluated. An included assumption is that the partial scores use a scoring scale that is additive—in other words, a numerical scale ranging from $-M$ to $+M$. (The values of $-M$ and $+M$ are discussed shortly.) Verbal scales or even graphic scales could be used; however, they do not readily permit the addition or summation of the individual partial scores. Two typical examples of scales not suggested are:



10.2.5 Fourth Assumption

A numerical scale is essential to synthesizing the partial judgments regarding each criterion. The simplest numerical scale is the $[0, \dots, 9]$ or $[1, \dots, 9]$ scale. Either pole of the scale can be used to represent an extremely good or extremely poor response. As an alternative, either the scale $[-5, \dots, 0, \dots, +5]$ or the scale $[-3, \dots, 0, \dots, +3]$ is recommended because they allow the choice of a neutral score, the 0 score. They also permit the assignment of negative scores, recognizing that a site evaluation may have negative aspects.

The fourth assumption concerns the procedure for synthesizing the partial scores into the overall performance score. A number of different basic conditions should be fulfilled by the scoring functions used to synthesize the partial scores. These conditions can be used in choosing an overall scoring procedure and are explained below. The different overall scoring functions and how they employ these conditions are explained afterward.

Axiom 1 If all the partial scores have the same value, the overall performance score is equal to the common value. Thus, the overall performance score will equal $+M$ or $-M$ if and only if each partial score is equal to $+M$ or $-M$.

Axiom 2 An increase in a partial score on any single criterion will ultimately result in an increase in the overall performance score for the site.

Axiom 3 The site achieves a perfect or “best” score if the partial scores on all the attributes are the “best” score.

Axiom 4 The site achieves a “worst” score if the partial scores on all the attributes are the “worst” score.

Axiom 5 This last axiom is a “pessimistic” one. Total failure for the site alternative occurs if any one performance criterion equals $-M$. For example, in a structural engineering evaluation, failure on any one criterion would result in the alternative design receiving an overall worst score.

10.2.6 Performance Functions

Type I Performance Function: A type I performance function is the simplest scoring function. It is a linear one in which the overall score is a weighted sum of the individual partial scores. The weights reflect the levels of importance determined for each performance aspect. This type of scoring function satisfies axioms 1, 2, 3, and 4, but does not satisfy axiom 5. In mathematical symbols, the utility value is defined as

$$V^j = \frac{\sum_{i=1}^p w_i x_i^j}{\sum_{i=1}^p w_i}$$

Type II Performance Function: This type of performance function is often referred to as the *minimum-link scoring function*. The lowest partial score for all the performance criteria is used as the overall performance score for the site. It fulfills axioms 1, 2, 3, and 5. In symbols, the scoring function is defined as

$$V^j = \min_i \{x_i^j\}$$

Type III Performance Function: The third type of scoring function is a weighted multiplicative relationship of all partial scores using the weights as exponents. It fulfills axioms 1, 2, 3, and 5. In symbols, the scoring function is defined as.

Table 10.1 Performance functions calculations for sample problem

Criteria/Attributes	Weights	Alternatives		
x_i	w	x^1 = New facility	x^2 = Renovation	x^3 = Do nothing
x_1 = energy systems	$w_1 = 0.15$	9	7	1
x_2 = office space	$w_2 = 0.13$	9	7	1
x_3 = flexibility	$w_3 = 0.11$	8	7	1
x_4 = site expansion	$w_4 = 0.10$	8	7	0
x_5 = accessibility	$w_5 = 0.08$	7	6	0
x_6 = image	$w_6 = 0.08$	8	5	1
x_7 = acquisition cost	$w_7 = 0.11$	1	6	9
x_8 = construction cost	$w_8 = 0.11$	6	4	9
x_9 = operating cost	$w_9 = 0.13$	6	3	3
Performance score (I)		6.35	6.32	2.88
Performance score (II)		1	3	0
Performance score (III)		6.70	5.71	2.47

$$V^j = \prod_{i=1}^p (x_i^j + M)^{w_i} - M$$

A Comparative Example: Table 10.1 summarizes the data for a sample problem with nine attributes and three alternatives. The weights have been adjusted so that their sum is equal to 1.0. As noted from the partial scores, $M = 9$.

As can be seen from Table 10.1, for performance function I, alternative 1 is better than alternative 2 by 0.03 points and better than alternative 3 by 3.47 points. Thus, when it comes to choosing between alternatives, if for some reason the best alternative cannot be implemented, it is important to quantify the difference between this alternative and the next-best alternative.

The performance functions for the attributes can be similar to the classes of functions shown in Fig. 10.5. The shape and the end points of the attributes obviously depend upon the problem at hand. V_a refers to the minimum value of the attribute, V_b to the maximum value. Also, $+M$ refers to the maximum score possible and $-M$ to the minimum possible. The attribute may be based upon a probability distribution function such as a normal distribution, gamma, uniform, or exponential distribution. For example, the distance dissipation from a noise source may be negatively exponential, so as the distance from a noise source increases, the value of the location increases according to the cumulative exponential distribution, much as in the plot at the top left of Fig. 10.5. In this instance, $V_a = 0$ and $V_b =$ distance boundary of the site plan. The performance function can then be interpreted as the cumulative distribution function of the attribute over the minimum-to-maximum range of the attribute. These functions are very useful in group decision-making settings to allow people to assign scores to alternatives for each attribute in an objective manner.

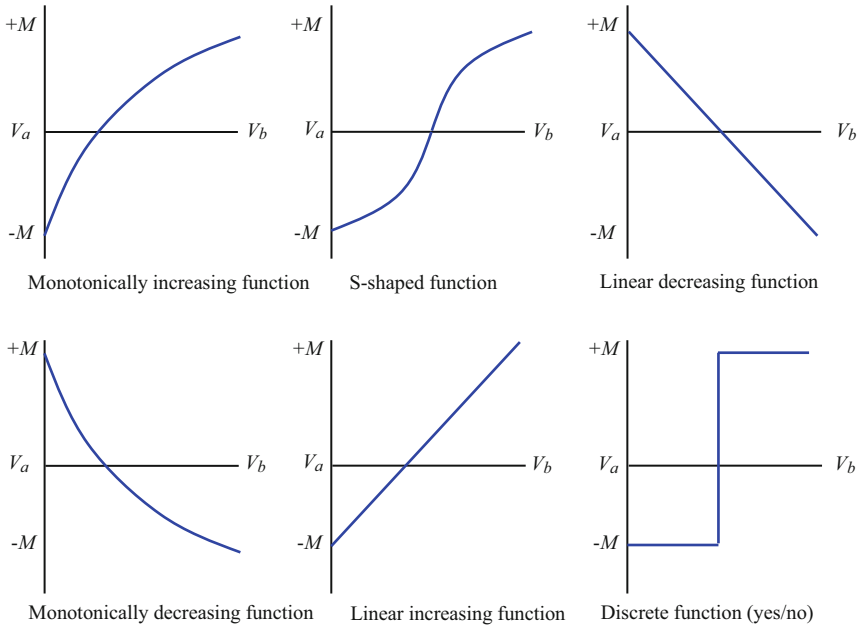


Fig. 10.5 Attribute performance functions

10.3 Site-Selection Criteria

We now discuss relevant, exhaustive criteria for setting up an evaluation system for site-selection problems. This discussion should give those confronted with these recurring problems a means of gathering the necessary criteria and of sorting out the germane planning issues. This section focuses on the process of screening and selecting alternative sites, not on the problem of determining the best use for a particular site. It is assumed here that the use to which a site will be put has already been determined.

We address each of the criteria in Fig. 10.2 in some detail. This material should not be construed as an environmental impact methodology. It is primarily a site-selection tool. There are detailed scientific and legal requirements for environmental impact statements which go beyond the scope of this chapter. Although many of the criteria included here would be found in most environmental impact studies, the reader is referred to other sources for the methodology of environmental impact statements.

10.3.1 Physical Criteria

The geology, hydrology, climate topography, and ecology of a site typically characterize both physical and natural features. Even though the sites under consideration may be within a few miles or blocks of each other, significant variation in their physical features may occur.

The physical criteria discussed here represent the most significant features of any site. They are the most noticeable, easily measured, and potentially important criteria for determining the value of an alternative site.

10.3.1.1 Geology

Studying the geology of a site will reveal the nature and depth of the underlying soil structure, rock and soil type, presence of fill, and other aspects of the site which are important to its evaluation and its planned use. A variety of data should be gathered about the site, concerning both its present state and past history, so that a complete record of its potential and underlying problems is available. These data are important for determining such problems as the presence of underground water, soil instability, soil erosion problems, and potential seismic concerns.

Rocks Knowledge of the type of rock, its depth, its structural bearing capability, and its drainage characteristics is obviously important to building planning. Through soil borings and laboratory tests, information about the rock structure and soils of the site can be gathered.

Soils The types and properties of soils may vary considerably over even a small site. Soil quality is primarily measured in terms of its ability to absorb water, its shear strength, and its compressive strength. Both field and laboratory tests are necessary to accurately determine the appropriateness of a site for building construction.

10.3.1.2 Hydrology

The hydrology of a site concerns the properties, distribution, and circulation of water on the surface of the land, in the soil, and in the underlying rocks.

Underground Water Even though a site seems never to change or else to change very slowly, a number of natural and man-made processes are constantly at work, altering the site's form and character. These processes include weathering, erosion, grading and filling, landslides, mudflows, stream flow, storm runoff, and volcanic and seismic activity. Water below grade is a critical factor in site suitability for building construction. The water table of a site is the upper limit of the underground water. Varying greatly in depth under the surface, underground water can markedly affect the future location of building foundations and the presence or absence of floor

levels below grade. Buildings should not, in general, be sited over underground water courses.

Water Bodies Water on or adjacent to a site can be a significant advantage for a number of reasons. Large water bodies moderate temperature and tend to even out daily or seasonal variations in temperature. This moderating influence increases with the size of the body of water. Additionally, water on the site can be used as a heat sink for cooling or as a heat source for heating systems; retention ponds can help reduce runoff and then supply irrigation systems or a closed wastewater recovery system as made-up supply. Finally, water can enhance a site because of its aesthetic properties and natural beauties.

Drainage Patterns The drainage patterns of a site are useful in determining the potential location of buildings as well as indicating where problems will exist prior to and after construction. Sites with inadequate drainage require grading and filling (and terracing if too steep), and these could be significant cost items in assessing a site's overall development potential. A potential site is often evaluated according to this classification: steep slope (over 20%); moderate slope (1–20%); flat (0–1%); well- or ill-drained; subject to erosion; suitable for building; suitable for outdoor recreations, etc.

Surface Flow Altering the surface flow and runoff characteristics of water is another concern that should be assessed prior to site selection. Water should be able to drain away from buildings along drainage courses that have previously existed (such as property lines and streams); local flooding should be avoided. Water should not move so fast that it causes erosion. The volume of water, the porosity of the soil, and the potential damage that can result from local flooding need to be assessed. Planted areas, streets, drainage swales, etc. require different slope minimums and maximums to accomplish proper management of surface flow. The prediction of the total amount of run-off is also essential in determining the capacity and costs of the storm sewer system.

10.3.1.3 Climate

The regional climate of an area, together with the microclimate of an individual site, deserves special attention during the site-selection process. The seasonal variation in temperature and humidity, the intensity and duration of precipitation, the patterns of air movement, the amount of sunlight, and other special characteristics such as storms or the amount of snowfall, are all likely to affect the design of a facility—especially the energy requirements of the building.

Microclimate Every site is likely to have a microclimate unique to its boundaries. This microclimate arises from relationships between buildings, vegetation, and water bodies, and the constant interchange of energy between the sun, the atmosphere, and the earth. In the temperate zone, which covers most of the United States, the best

microclimates tend to be on the south or southeast slopes, near water, and on the middle of slopes rather than at their foot or peak [3].

Sun/Orientation The influence of the sun and the orientation of a site to it are particularly important to consider during site selection. Although the latitude will probably be the same for all sites under consideration, the slope and orientation of a particular site to the sun in relation to the sun's path will be subject to some variation. In general, southward sloping sites will receive more solar radiation than level sites.

Air Movement Existing structures, topography, and vegetation will also affect the amount of solar radiation reaching the planned building. Therefore, in order to properly assess a site's orientation and the potential amount of solar energy incident to the building, the architect or planner must assess the geometry of the sun's path and how it varies with the time of day and the latitude.

The velocity and pattern of air movement over a site will markedly affect the location and orientation of buildings, as well as the position of entrances and even the design of the building's mechanical ventilation system (especially heating and cooling and the manner of exhausting unwanted heat and fumes). The usability of a site can also be affected by the predominant wind pattern, especially if no protection is afforded by tree cover, the topography, or surrounding buildings.

Precipitation/Humidity The amounts and intensity of precipitation and relative humidity in the region will help determine whether a site will be subject to problems of flooding, snow removal, or excessive dampness. While such problems may be intermittent or slow in developing, once they occur, they can cause widespread damage. Knowledge of the volume and intensity of rainfall, snow accumulation, and moisture is crucial to the design of an adequate storm drainage system and to the evaluation of a site.

10.3.1.4 Topography

The topography of a site is a study of the three-dimensional location of natural and man-made objects. The topography not only indicates the slopes on a site, it also begins to indicate where the potential vehicular circulation network may be located, where the best views are located, and where microclimates are likely to exist. In one sense, topography represents the environmental impact of the total sum of natural and man-made forces on a site.

In many cases, the topography of a site will suggest the design and disposition of the buildings, the path system, the utility locations, the use of open space areas, and the potential amenities and nuisances that go along with a particular site. In short, a site's topography is one of the key environmental determinants of its suitability.

Surface Contours Besides a detailed slope analysis in terms of surface runoff and overall drainage of a site, an analysis of surface contours is also important. Such an analysis helps determine how buildings can be located on a site, what path system is feasible, and how utilities and other services are to be interconnected.

Slopes The table below should be helpful in evaluating surface contours. Scoring values can be generated with these slope categories for use in an evaluation system (as described in Sect. 10.2).

Slopes	Comment
0–1%	Do not drain well, unless they are paved and carefully finished. Sewers may tend to ride up out of the ground.
1–5%	Suitable for most building construction. Parking lots should have grades under 5%.
6–10%	Streets should have a maximum of 8% grade. Most outdoor activity areas can be readily accommodated in this range.
10–20%	A 15% slope approaches the limit that an ordinary loaded vehicle can climb for a sustained period.
Over 20%	Most building construction, except for single-family housing, is unsuitable above 20% grades.

Views/Vistas The topography of a site naturally establishes certain viewpoints and vistas which a building can either take advantage of or be subject to. Both on-site and off-site views need to be assessed. Billboards, power lines, junkyards, parking lots, and other objectionable views can sometimes be screened by buildings and vegetation, but their presence around the site is often deleterious, even if the building is visually oriented toward itself.

Vistas, on the other hand, which are natural or man-made, have a dominant focal point and can be used to orient the design of the building concept—for example, orienting a building to an older facility or downtown area to show how the new construction relates to the past and where the “roots” of the community are.

10.3.1.5 Ecology

Environmental Impacts In general, ecology is the study of the totality or pattern of interrelationships between organisms and their physical environment. These relationships are dynamic; the delicate balance between man and his natural environment is always undergoing change. While much of this change is positive and appropriate, much is not. Considerable harm and damage to nature has become commonplace in man’s search to establish domain over the natural elements. In considering the ecology of a particular site, special attention should be paid to the vegetation and wildlife. (Other factors such as noise, air, and water quality are covered elsewhere in this site-selection analysis.)

In general, any new construction will change the environment in a variety of ways. The consequences should be measured so that any adverse effects on the environment can be identified and avoided. Many state and federal agencies now require an environmental impact statement when effects on natural resources are likely to occur with new construction activities. Although it may seem unnecessary to some, such an analysis should be done if significant environmental changes may be contemplated, so that even minimal harm to the environment can be avoided. The following

is a checklist of potential consequences to the environment which should be researched and analyzed to see whether the impacts are significant. The potential consequences are classified into four major areas.

Natural	Social/Economics
Water quality Air quality Sanitary sewage treatment Solid waste management	Employment opportunities Economic base of the region Social structure of nearby residential areas Removal of land from the tax rolls Public welfare and safety Citizen acceptance and opinion
O physical	Aesthetic and cultural
Utility availability: Water, gas, electricity Noise levels: Airport, railroad, highway Land use suitability and zoning Drainage and soils Roads and traffic congestion Geology, topography and site geometry	Historic buildings and districts Views and visual barriers

Again, as stated earlier, no attempt will be made to outline a specific methodology for an environmental impact statement. Of concern here is that the client and agency be well aware of whether such an impact statement is necessary for the project, and, if so, what the requirements are for its content and format.

Plants, flowers, and trees are constantly growing, decaying, and being replaced by both man-made and natural processes. Trees and other vegetation, if carefully managed, can reduce wind velocity, reduce airborne noise, filter the air, reduce glare, prevent erosion, provide visual privacy and shade, and help establish a stable, cool microclimate.

An examination of the local ecology of a site should also reveal which trees or shrubs are native and which varieties may be added for wind protection, shade, buffer zones, screens, or backdrops.

New construction is likely to disrupt the habitat of wildlife indigenous to the site. While this may not apply to most urban settings, choosing rural or suburban site locations for manufacturing or service facilities may create a problem for the preservation of certain wildlife species.

10.3.2 Cultural Criteria

The value of a site is highly dependent on the local community and society and their influence on the physical development that has occurred on and around the site. Legal, political, financial, and historical factors affect change on a site and ultimately influence the site's future development. All these factors and influences make up what is referred to as the cultural context of a site. The cultural context criteria discussed here are listed below:

Legal/Political	Financial
Land ownership	Feasibility of site development
Land use restrictions	Benefit/cost analysis
Zoning	Funding sources and mechanisms
Federal and state statutes	Historical
Review boards and commissions	Districts
Community support and opposition	Buildings

10.3.2.1 Legal/Political

Land ownership and property transactions must abide by state statutes and local governing regulations regarding land use, diversity, adjoining uses, and intensity of building development. Legal requirements will influence floor-area ratios, open space allotments, parking, and other essential physical parameters of a site. In addition, the political climate surrounding site-selection decisions is highly dependent on state legislative politics, as well as politics within the local community. Political influence is a major tool in site acquisition and related matters such as site financing.

Land Ownership Even though a site may be an ideal setting for development, land assembly and acquisition may be infeasible or prohibitively expensive. This is a critical problem in dense urban areas, which constantly face the problem of inadequate available open space on which to build. Individual property owners may also be unwilling to sell, which then forces the county or municipal government to use its power of eminent domain to assemble the needed properties. The use of eminent domain or urban renewal can cloud the appropriateness of this “ideal” setting for a new manufacturing or service building, especially since some members of the community may be dealt certain injustices (such as loss of family homes and neighborhoods).

Many different types of legal restrictions on the use of land may exist, such as easements, rights of way, deed restrictions, zoning regulations, building codes, and water or mineral rights. Most of the regulations and codes are necessary to insure economic, social, and functional order in the environment. However, many of these restrictions and controls are not very flexible and often put undue limitations on a design concept.

Existing zoning of the site will usually not be a problem, unless the new facility will disrupt the surrounding environment due to the type and extent of physical development that may follow. This is usually not the case with a public-sector facility, because it benefits the entire community, and related physical development is usually not deleterious. In some cases, however, where surrounding development is single-family residential or agricultural, uncontrolled speculation on properties adjoining the selected site could generate a blighting influence on the environment.

Therefore, the potential impact of zoning and land uses should be considered for both the site and the land adjoining the site.

Another factor to be considered (discussed later in more detail) is the access and parking requirements of the zoning ordinance and how these regulations affect the potential use of a site. This has special importance in relation to future construction growth, parking, and open space needs.

Another concern is to verify that no federal or state statutes will be violated in choosing a particular site. Numerous federal and state guidelines and statutes regulate the development of land and its potential users. Notable among these are the regulations imposed by the Environmental Protection Act. These regulations must be carefully scrutinized so that air, land, water, and other environmental qualities are not disturbed.

Review Boards/Commissions Consulting local and state review boards and administrative committees who may have policy guidelines or some voice in the location of the new or remodeled facility is of the utmost importance during site selection. State administrative offices may have a vested interest in fiscal policy, so consulting them is a real necessity. In many ways the feasibility of a site is highly dependent on the motivation review boards may have in either releasing a site for development or assisting in the necessary legislative action to acquire or develop a site. It is necessary to acquire review boards' cooperation and assistance early in the planning process, in order to avoid delays and roadblocks which could theater the entire project at a later date.

Community Support/Opposition Local community support and its impact on the site-selection process are important in site selection. The people's voice should be heard before, not after, the site is selected.

10.3.2.2 Financial

Feasibility of Site Development Land acquisition, grading, filling, demolition, and necessary licenses and fees can be critical factors in the feasibility equation when applied to a particular site. Costs, however, should not be used as crutches or excuses for choosing site alternatives. These are one-time costs, and over the life cycle of the building they play a rather diminutive role when compared with staffing, operating, and maintenance costs. Another consideration is the benefits which these expenditures are creating. This aspect will be discussed a bit more later on.

Existing sites owned by the client are often looked upon as the obvious choices for new buildings, whereas other sites not owned may be more desirable. Existing parcels can always be sold or traded for a desired parcel, and this type of land exchange can become an important means of site acquisition.

Demolition and relocation costs are usually included in land acquisition costs because of their strong interrelationship. Condemning land, removing existing structures, and relocating their occupants is usually the prerogative of county and state governmental bodies through the power of eminent domain. However, the

wanton use of this power can serve to alienate and divide a community, especially if relocation is done ruthlessly without due consideration for social and family ties, available supply of relocation resources, and adequate compensation for the loss of dwellings or businesses. This situation is most acute in inner-city and other densely built-up areas.

Benefit–Cost Analysis Given that a service-sector facility could be a public project, measurement of the benefits and costs of alternative sites is especially appropriate. Such a measurement accounts not only for tangible economic costs but also for the often-intangible social costs of locating a service-sector facility at a particular site. While measuring benefits and costs is not a simple matter, it can place the often-negative aspect of measuring costs on a more positive plane, because it forces the decision makers to examine what they are gaining by their outlays as well as who is gaining from them.

Funding Sources and Mechanisms Government agencies, whether municipal, state, or federal, need to be identified as to their financial involvement. The method of financing the costs of site acquisition, site development, and the construction of the entire project may play an important role in assessing the feasibility of selecting an appropriate site. In some cases, special utility hookup costs, grading and filing operations, license and fees, and necessary administrative costs will be required. Who is to pay for these items, and how important they are in assessing overall site feasibility, will need to be determined.

10.3.2.3 Historical

Districts/Buildings Planned change is becoming more and more affected by the existence of historic buildings and districts. Local, state, and national groups involved in the preservation of historic buildings and conservation of natural areas should be consulted with regard to planned change. Neglecting these groups could be a serious mistake in the site-selection process, since they could bring action to halt or delay the overall project.

Many sites have cultural significance and historical value. Older manufacturing or service facilities usually fall into the category of historical architectural monuments. While not everything that is old is really good, serious consideration should be given to preservation of these buildings and to their potential reuse and renovation. Additions to historic buildings become difficult design problems because of the conflicting goals of maintaining the architectural integrity of the existing building while adding a new piece of construction that reflects present technology, materials, and styles.

Certain alternative building sites are often considered in historic preservation districts. These can be advantageous if the available land allows new construction without disrupting the existing land and buildings. However, there are many instances when the removal of historic buildings is necessary, or when the addition of a large new structure is likely to overshadow the old structures. Architectural

historians should be consulted in such situations for a careful analysis of the consequences of the new construction.

During the site-selection process, consideration should be given to the use of existing buildings owned or leased by the client. At a time when new construction costs are skyrocketing and energy reserves are strained, existing buildings become an important resource. Site locations that generate a surplus of existing building resources may be looked upon by the taxpayer as unnecessary waste. The design of new facilities that does not take existing building resources into consideration is probably not wise politically or fiscally.

The problem of recycling and remodeling existing buildings may be at odds with the centralization policies of manufacturing or services, since reusing or maintaining manufacturing or service offices in existing buildings will, more often than not, imply decentralization and spatial disbursement. However, this spatial disbursement can be alleviated somewhat through the use of electronic technology (telephones, television, and computers) to link dispersed offices. A variety of possibilities may exist and should be evaluated during the site-selection process, since the overall new building area could be reduced with the judicious use of existing building resources.

10.3.3 Functional Criteria

This section includes criteria on how a site relates to the activities and operations of the planned facility. There are crucial systemic relationships that should be developed between a planned building and its site. The following criteria will be considered and briefly discussed:

Image	Adaptability	Accessibility
Site visibility	Horizontal and vertical growth	Regional accessibility
Visual identity	Circulation Adaptability	On-site accessibility
Legibility	Utilities	Parking
Spatial variety	Energy systems	Security
Detail	Utility configuration	
Land Utilization	Water supply	
Adjoining uses	Storm sewers	
Environmental nuisances	Sanity sewers	
Density/intensity	Security services	
Site potential		
Site shape		

10.3.3.1 Image

Selection of an appropriate site can significantly influence the overall impression made by manufacturing or service facilities upon the staff and community that use

them. A certain amount of visibility and aesthetic impact will help present a positive image. Therefore, the general siting and location of the facility should take into consideration the buildings, imagery and symbolic meaning. A new site away from an existing one downtown can represent a major change for the manufacturing or service facility and a chance to implement new procedures and equipment. On the other hand, remaining near an existing site (such as the down-town) upholds symbolic precedent. A community should carefully weigh these alternatives and their advantages and disadvantages in siting a manufacturing or service facility.

Site Visibility The visibility of a manufacturing or service facility from the surrounding residential and business areas can be a reminder of the building's functional role in the community as well as a landmark by which people can orient themselves. For example, religious gathering places are significant landmarks. Related to the site's visibility are the views it has of surrounding environs. These views can have a significant psychological effect on the manufacturing or service staff and users. For example, if one were locating a jail and a courthouse structure on the same site, this combination could have a negative effect. Lack of physical separation between the adjudication and correctional environments might affect citizens' trust in an impartial review of their cases.

Visual Identity The "sense of place" or visual identity of a site is important to users and staff of a manufacturing or service facility. How a person perceives a site and its building is difficult to quantify, involving a complex set of physiological events which make up the perceptual process. This is perhaps why a service facility location on a square in the town center may be advisable—because it has such a strong "sense of place." For a manufacturing facility, visible presence can enhance the product's image and marketability as well as draw visitors. Such a site is easily remembered and identified with. Obviously, a meaningful setting, as well as the expanse of open space and the neighboring land uses, will contribute strongly to the visual identity of a site.

Legibility The legibility of a site refers to the ease with which a user can find his way.

10.3.3.2 Land Utilization

The use of the land concerns not only the facility but also the land immediately surrounding it. The site and its context share overlapping features important to land utilization.

Adjoining Uses A manufacturing or service facility should not exist in a setting without certain supporting institutions and services. A manufacturing facility needs highway and railcar access, and often can benefit by locating in an industrial park. Also, for example, if one were siting a courthouse facility, then law offices, law enforcement agencies, pretrial detention facilities, county government offices, social service agencies, hotels, restaurants, parking, and public transportation services

should all be located within the immediate environment. Such services and facilities are often present at an urban facility but may be lacking in suburban or rural sites. Consideration should be given to the manner in which these services can either be accommodated nearby or else included in the new construction or remodeling of a manufacturing or service facility.

Environmental Nuisances An important performance measure in the context of a site is the amount of background noise, measured on the site in decibels (dB). Noise levels above 70 dB, whether from adjacent streets or industrial or commercial areas, may adversely affect internal manufacturing or service activities. Of course, adequate distance, solid walls, earth mounds, changes in elevation, and related physical devices can help, but they may not suffice where high-pitched noise or intermittent sounds are present. Olfactory and safety-hazard problems also may occur at the perimeter of a site. The effects of industrial activity, heavy traffic fumes, hazardous intersections, or other severe conditions at a site perimeter can markedly color the site’s desirability.

Density/Intensity The density and intensity of site development (on both the chosen and adjacent sites) comprise another important measure of land utilization. Density is the ratio of a building’s gross floor area to its gross site area, usually called the gross floor area ratio (FAR). Zoning regulations typically specify a range for this ratio. Thus, given the building program requirement and parking and open space needs, the feasibility of developing a site can be measured. For example, if a service facility requires a ten-story building with each floor at 25,000 gross square feet (GFS), the building coverage plus additional site spaces will require the following minimum site area:

Building coverage, first floor area	25,000 GSF
Parking and site requirements	30,000 GSF
Open space and access requirements	45,000 GSF
Minimum site area needed	100,000 GSF

Therefore, the gross floor area ratio of building area to total site area is $FAR = 250,000/100,000 = 2.5$. The zoning code may or may not allow this intensity of building development. The intensity may also have to be adjusted for future development purposes, which would further increase the gross floor area ratio.

An associated problem is that of measuring the psychological impact of buildings on an already overcrowded (or conversely, underdeveloped) area. Although opinions on the issue vary, certain social, psychological, and security problems seem to increase with increasing people density on a site. The reverse effect may occur with too low a density; it may result in feelings of isolation or inactivity which could affect the staff and users in a negative way.

Site Potential The potential for creating a viable site plan is a difficult but essential measure of the future performance of the site for its intended building activities and users. Is the site capable of accommodating the variety, sizes, and configuration of

intended activities? Does the site reinforce the spirit or mood of the planned manufacturing or service activity? In a more practical sense, can the site accommodate the range of vehicular and pedestrian modes that will be used to travel to and around the site? Is there adequate area for parking and its expansion? In another vein, will the site contribute to the general health and well-being of the staff members and users? Is there excessive air or water pollution on or adjacent to the site?

Site Shape The shape of a site has an important influence on the ultimate configuration of the perimetral walls of a building. Triangular, rectangular, polygonal, and other concave or convex shapes of sites will directly impact the building's geometry, which will, in turn, have a marked effect on its energy requirements. For example, a rectangular site can impose a similar shape on a building design. Whether the long sides of the building face east-west or north-south determines the effects of solar radiation and wind loads. Will individual staff members be able to take walks around the site, eat their lunch out of doors? In general, will the site be able to accommodate any unstructured or leisure activities associated with the general health and well-being of its daily users?

Building orientation affects heating and air-conditioning energy requirements. A rectangular building with a 2.5 length/width ratio absorbs considerably less solar heat if its long axis is aligned in an east-west instead of north-south direction. (The sun bakes east and west walls longer and with more intensity than even a south wall, which intercepts solar rays at less direct angles.) A triangular site, with its base side facing north, could be a tremendous asset in a hot climate by eliminating a southern wall—the area of greatest heat gains. In the north, however, this could be a serious loss, because the solar gains on a southern facade can lighten heating loads.

10.3.4 Site Accessibility

The accessibility of a site can be measured during the site-selection process on two fundamental dimensions: (1) the accessibility of the site to the region and (2) the ability of the site to accommodate the required vehicular and pedestrian flow to (and on) it. Related topics are parking availability and secure access to the site.

Regional In comparing various sites with regard to accommodating movement to the manufacturing or service facility, we need to consider such points as the transfer of raw materials to and from manufacturing facilities, the movement of finished goods from the manufacturing or service facility to warehouses, and the travel and accommodation of staff, professionals and visitors on and off the site. Locating a facility in an already congested area can severely curtail the scheduling of activities and the timely appearance of persons involved. The availability of regional transportation networks and mass transit systems is important in measuring site accessibility. In some non-metropolitan regions, new manufacturing or service buildings

have been located outside the town center, making access to the highway network more convenient for staff, professionals, and users traveling from other regions within the state.

On-Site On-site accessibility needs to be related to the site's ability to accommodate the required volume and variety of flows of people, goods, waste, and information related to the manufacturing or service business. The site's topography is a key indicator in considering the suitability of a road network, the probable grades of the roads, the location of entrances, the ultimate capacity of the network, impasses, sequences of views, and intersections of the network. The roadways are usually the predominant circulation system to be arranged on the site because of their large right-of-way requirement, their volume of traffic, and their importance to other traffic flow channels. Design of a roadway network, however, should consider not only cars but also buses, bicycles, trucks, and their relationships to pedestrian movement. Finally, the roadway network bears an important relationship to the placement and configuration of the utility network.

Parking Parking is a crucial variable in site selection because of its expanse of area and cost of provision. Related variables are the overall number of spaces provided, the assignment of spaces, whether parking is clumped in a single mass or distributed in smaller lots over the site, distances people have to walk from their car to building entrances, critical slopes, lot entrances, circulation within the parking lot itself, visual screening, and nighttime security lighting. Short-term, long-term, and metered parking are policy measures which can help organize the provision of spaces.

In most instances, zoning ordinances will regulate the number of parking spaces in terms of the building type and the amount of floor area to be constructed. Additionally, manufacturing or service sector facilities may demand priorities for certain staff and visitors. Courthouses, for example, have special parking provisions for witnesses and jurors.

Site Security The security of a site is directly related to accessibility, since many manufacturing or service facilities require travel to and from the facility after normal working hours. In manufacturing facilities, workers on the second and third shifts need to feel as secure as first-shift workers entering and leaving the site. In public courthouse facilities, nighttime prosecutor programs, night court operations, use of the legal library, and other activities may require secure access for after-hours users. Jurors will often deliberate late into the night; judges and law clerks will also require access for their late-night duties. Therefore, consideration should be given to special problems that could occur in providing secure access. One decentralized facility in a metropolitan area, although providing convenient access for its neighborhood users, presented a problem because security for the staff was very difficult to provide—so difficult that strong consideration was given to closing the facility.

10.3.4.1 Adaptability

The activities planned for a site will naturally change over the course of time, and the ability to accommodate growth and change depends on foresight as well as on the design of the building concept. Since the site chosen will be a major factor affecting possible facility expansion and growth, evaluating the capability for both is an important part of the site-selection process.

Horizontal/Vertical Growth In most building programs, allocating for little space for the requirements of the building’s inhabitants is more likely than allocating too much. Expansion, growth, and change are inevitable events that cannot always be foreseen in the conceptual design phase. Not providing opportunities for change unnecessarily limits the manufacturing or service building. While not every activity within the building undergoes growth and expansion, various activities do fluctuate in spatial requirements, especially the production and warehousing areas. Throughout the building programming process, consideration of both horizontal and vertical future expansion should be included in the site-selection process in order to provide flexibility for future planning needs. Limiting the planning horizon to between ten and 20 years is necessary, owing to the difficulty of discounting benefits beyond 20 years. While this is a limiting constraint, the building will likely change beyond the 20-year planning period.

The amount of expansion room needed for a manufacturing or service building is normally about 20% beyond what is planned for in the horizon period. Table 10.2 suggests a way of calculating the needed area.

In the design development of additional building area, both vertical and horizontal expansion should be examined. Horizontal expansion is more suitable for

Table 10.2 Parking area requirements

Gross area (sq ft)	Floors	Parking	Minimum area (acres)
Urban location			
25,000	1	Grade	1.5–2
25,000–60,000	2–3	Grade	2–3
25,000–60,000	2–3	structured	1
60,000–120,000	3–6	structured	1–1.25
120,000–180,000	6–10	structured	1.25–1.5
180,000	10	structured	1.5–2
Suburban or rural location			
25,000	1	Grade	2–4
25,000–60,000	2–3	Grade	4–5
60,000–120,000	3	structured	6–7
120,000–180,000	6–10	structured	7–12
180,000	10	structured	12

manufacturing facilities than for the certain service sector activities, because production areas usually require heavy machinery and material handling movement of items, and circulation efficiency is better achieved with horizontal expansion. Vertical expansion, however, may be far more suitable than horizontal expansion, for the service sector facility, especially in urban settings, because public and security circulation systems can be more compact. Horizontal expansion tends to create long corridors, which require additional security measures. A facility designed to expand vertically requires larger structural members, which are initially expensive and underutilized until the vertical expansion occurs.

In rural settings, expansion may occur in other buildings around the manufacturing or service space. Ancillary offices could easily be located in available space on or near the manufacturing or service facility. Annex buildings also provide alternative means for needed expansion in rural settings. In outlying areas with no existing manufacturing and service facilities, the use of multipurpose or portable buildings may be appropriate.

Site Circulation Adaptability The circulation system of the site is likely to be affected by future technological changes, not only in vehicle technology, but also in the use and development of computers, telecommunication systems, and related devices which directly affect transportation of people, goods, and services. This type of technological change is currently very strong in the manufacturing and service sector economy, and seemingly it will accelerate in the future. Coupled with advances in this type of technology, the energy crisis, development of expanded mass transit systems, and changes in vehicular parking requirements will all inevitably affect the circulation system of the site. Therefore, in choosing a site alternative, consideration should be given to the potential adaptability of the circulation network.

Site Utilities Utility availability and hookup are important items in site selection. Outlying rural sites are likely to be less desirable in this respect, since the availability of gas, sewers, and other utilities may be limited. Because the cost of operating new buildings is becoming more dependent on the availability of natural gas and electrical energy resources, utility availability becomes extremely important in site selection.

Site Energy Systems Serious consideration needs to be accorded to the possibilities the site may offer for incorporating new types of energy systems and energy conservation measures. Solar heating and cooling, the use of wind for cooling, ventilation, and power, as well as the use of water resources on the site for a variety of energy and systems purposes should be considered. As the costs of oil, gas, and electricity increase, the availability of such natural resources and systems on a site becomes very influential in the site-selection process.

Inevitably, future costs of providing energy are going to force greater economies in the design of movement systems, water supply, treatment of liquid and solid wastes, and the environmental control systems of buildings [6]. This inevitably

requires considering the types of utility systems necessary for the planned buildings and how future energy technologies may be incorporated into the site and buildings.

Utility Configuration The placement and configuration of utility systems on a site is a difficult three-dimensional design problem, owing to the importance of minimizing interference between systems and the incompatibilities of certain utilities. Coupled with this is the problem of aesthetics and the desire to place most utilities underground, away from view. With many underground systems, such as water, steam, and gas lines, no problems in the layout of branch and loop patterns should occur. However, care must be taken to prevent incompatible systems such as electricity and gas lines from being laid together.

Certain sites may already be developed to accommodate all needed utilities with a minimum of site cost and disruption to the existing site topography. Other sites, however, may not, presenting problems of acquiring all necessary utilities and locating them for building usage, especially in underdeveloped sites remote from urban centers.

On sites with rocks or high water tables, underground utilities may be prohibitively expensive, and overhead utility systems will be necessary.

Water Supply Water is one of the most important utilities for a site. Without water, a site may not be worth developing, or bringing water in may be so costly as to make development infeasible.

In urban areas, the availability of a water supply is usually not a problem. However, problems may occur where needs expand over and above the resources provided at the existing site. In rural or suburban areas, the problem of water availability may not be easily solved. The drilling of wells, building of a small reservoir or dam, utilization of treated river water, or contract negotiation with a surrounding municipality may have to be considered to provide needed water. In all cases, consideration must be given to capital and operating expenditures in acquiring a water supply, and long-term needs must be forecast to decide whether future supplies will be available at a reasonable cost.

Storm Sewers Usually natural or surface drainage of storm water runoff is incapable of properly diverting storm waters away from buildings. In order to prevent problems of erosion and flooding, an underground storm sewer system is often necessary. Given that the required pipe sizes are usually quite large, such a system is usually expensive and can become a significant cost element in the total site-cost equation. Where possible, attempts should be made to minimize or eliminate the underground storm sewer system. Another consideration is to make sure that the storm and sanitary sewer systems are kept separate to prevent pollution through the backup of sanitary wastes.

Sanitary Sewers Since sewer systems operate by gravity flow, every effort should be made to avoid the use of sewage lift stations where gravity flow cannot be utilized. Sewage lift stations are expensive both to operate and as an initial capital expense; they are also subject to frequent breakdown and sewage backup.

The treatment of sewage, whether on site or by pumping to another site, is another important consideration, since state and federal environmental quality standards are becoming more strict regarding sewage treatment. Disposal of the effluent on the site is appropriate when the soil is sufficiently porous, but care must be taken to ensure that any domestic water supply on the site is not polluted. All in all, the sanitary sewer system can be a significant site cost, and the proper handling of the effluent is crucial to the avoidance of environmental pollution.

Site Security Services Finally, we need to consider the provision of emergency security services, including police, fire, and ambulance services. If a manufacturing or service facility relocates to a more remote site, the quickness with which emergency services can respond may mean the difference between a major disaster and a minor one. Care should be taken in choosing a site so that such a problem can be avoided.

10.4 Manufacturing Site-Planning Example

The aim of this section is to create quantitative maps for searching out the best site-planning solution along with the integration of product flow data where necessary. In order to map the criterion to the site, one can utilize distance as a proxy attribute. In this way, a value map for each attribute will be generated. Certainly, if one has detailed data available for each parcel of the site, this proxy attribute method may not be necessary. Using distance, however, as will be shown, aids in the mapping of the criteria with less data gathering.

We wish to locate a new manufacturing facility **X** in an urban/regional setting in relation to three existing warehouse distribution centers, W_i , $i = 1, 2, 3$, in an area where there are regional highways and certain parcels of available land. The highways are indicated by the bidirectional arrows in Fig. 10.6. Three main placement criteria are critical: (1) cost of the site, (2) utility availability, and (3) accessibility to the highways. It is here assumed that three attributes have equal value to facilitate a simpler process of exposition.

Each of the three warehouses occupies a single parcel of land, represented by a square in the grid of Fig. 10.6 by the light green cells. The gray pattern-filled areas between the highways represented by the vertical two-directional arrows are regions where it is not possible to locate the new facility. The allowed available parcels are indicated by the rectangular areas with light brown background. For each allowed parcel the three numbers shown indicate, respectively, the scores for site-cost, utility availability, and accessibility. Finally, it is noted that the numbers of daily trips between facility **X** and each of the warehouses W_1 , W_2 , and W_3 are, respectively, 50, 40, and 30.

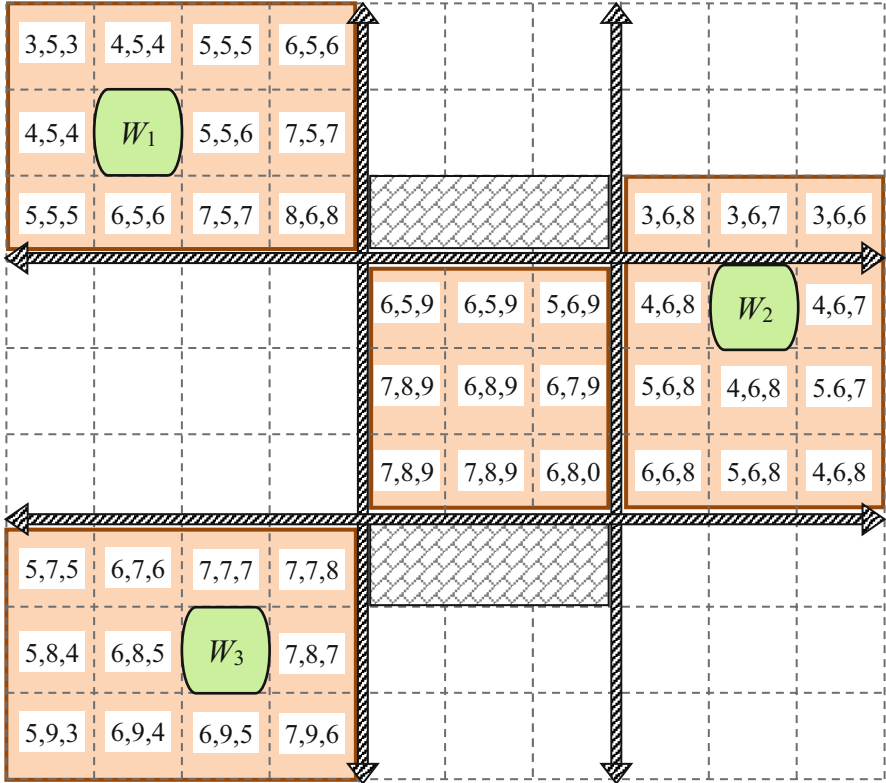
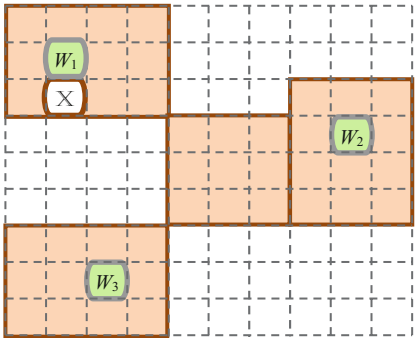
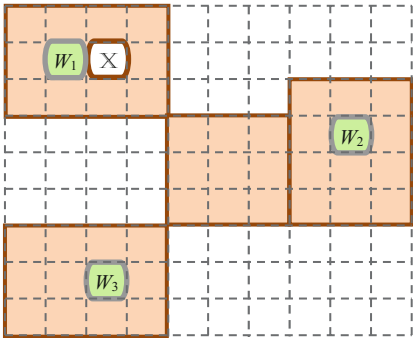


Fig. 10.6 Site-planning context with scores

A type I performance function and all data for this example were incorporated into GMAFLAD. The figures below illustrate the optimal and next best solutions from GMAFLAD.



Optimal solution, $Z = 78.53$



Next-best solution, $Z = 78.32$

10.5 Factory Project Case Study

The main goal of this case study is to demonstrate the site-planning methodology within the factory project concept. A small industrial facility will be considered. Figure 10.7 illustrates the open site plan that needs to be developed with a planning grid. The planning grid becomes important here to help identify the most suitable location for the new manufacturing plant. Approximately a 56,000-square foot facility is to be developed on the site. Access roads, parking, and expansion concerns need to be considered as well as all the natural and cultural concerns mentioned earlier in this chapter.

We will illustrate the planning methodology with a few selected criteria. In the first step, the site is partitioned into grid cells, so that one can apply the algorithms systematically. The lattice grid is similar to the one for the location example discussed in the preceding section, although the size of the grid cell is 10,000 square feet, which is a useful unit of measure in light of the design footprint of the manufacturing plant.

A distance function was matched for each criterion. Also, points (x, y) on the site that were either site attractors or detractors for the criteria were defined as lattice points. Thus, if one chose to use a *minisum* function with a weight vector, then those points defined on the site would be used to evaluate the entire site area for the best values. The various functions for calculating the most suitable location for each

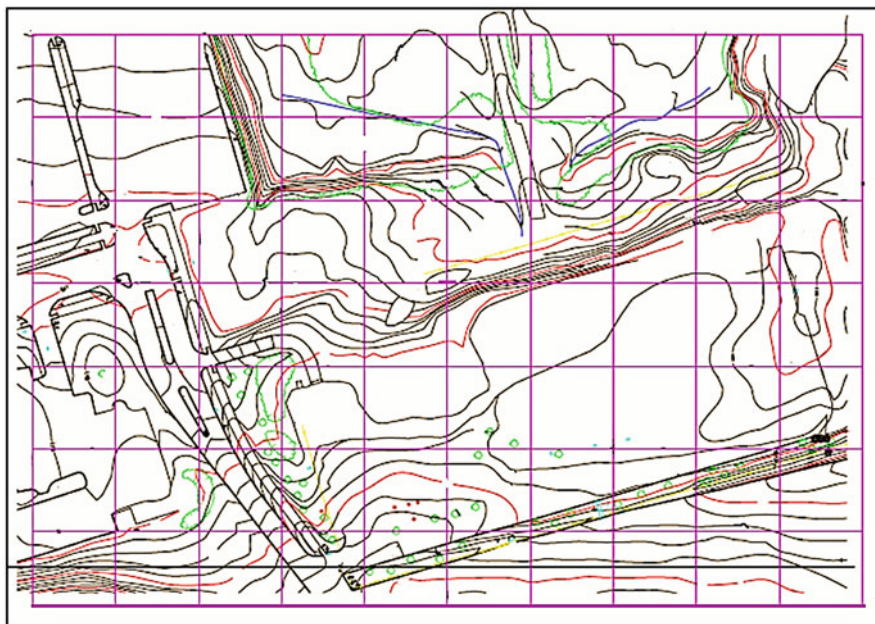


Fig. 10.7 Typical site-development plan with grid

Table 10.3 Criteria and distance functions mapping

Attribute	Objective	Attractor/Detractor points	Comments
x_1 Soils	Minimum	$x = (3,4,5,5,6,7,8,4)$ $y = (4,5,2,3,3,3,3,2)$	Closest to best soils
x_2 Slope	Minimum	$x = (3,5,9,7)$ $y = (5,4,5,4)$	Avoid steep slopes wherever possible
x_3 View/image	Minimum	$x = (3,4,9,10)$ $y = (3,1,5,2)$	Closest to boundary points
x_4 Accessibility	Minimum	$x = (2,4)$ $y = (3,1)$	Closest to two access points
x_5 Noise attenuation	Minimum	$x = (4,3,3,2)$ $y = (1,2,3,4)$	Away from road noise
x_6 Development costs	Minimum	$x = (5,6,7,8)$ $y = (3,3,3,3)$	Least clearing, grubbing, demolition costs
x_7 Surface drainage	Minimum	$x = (5,6,7,8)$ $y = (2,3,3,2)$	Most level site is most desirable

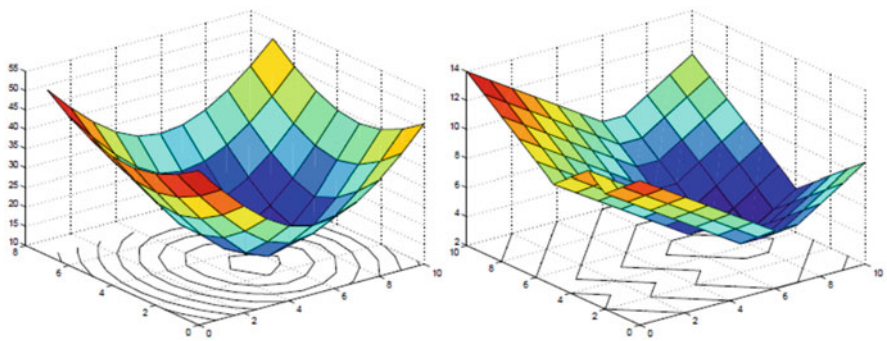


Fig. 10.8 (a) Minisum soils and (b) maximin slope criteria

criterion were discussed in Chap. 5. Table 10.3 summarizes the (x, y) coordinates of the attractor and detractor points for the attributes considered in the case study.

10.5.1 Soils

The first criterion has to do with the soils of the site and the fact that soil type is directly related to the design of the manufacturing facility. Sturdy, well-drained soils were chosen as best for the site. Figure 10.8 illustrates the contour function generated for the site. Here, Euclidean distance was used for this criterion. The lowest function value corresponds to the most suitable site location according to the objective, which in this case is to minimize the weighted distance to the best soils.

10.5.2 Slopes

The second criterion has to do with the slopes of the site and the fact that slope is directly related to the design of the manufacturing facility. Figure 10.8a illustrates contour function generated for the site. We would like to maximize the minimum distance to the steepest slopes, since the site needs to be as level as possible. The highest function value corresponds to the most suitable location according to this objective.

10.5.3 Views Evaluation

The third criterion has to do with the views/image of the site and is directly related to the design of the manufacturing facility. Figure 10.9a illustrates the contour function generated for the site. We would like to minimize the maximum distance from the view/image afforded by the site. The lowest function value corresponds to the most suitable site location according to the objective.

10.5.4 Site Accessibility

The fourth criterion has to do with the accessibility of the site and the fact that vehicular and truck access is directly related to the exterior and interior design of the manufacturing facility. We have weighted the importance of truck/vehicle travel to the northern entrance of the site and given less weight to the southern entrance, since the northern entrance is wider and more convenient. We used a minimun objective here. Figure 10.9b illustrates the contour function generated for the site. The lowest function value corresponds to the most suitable site location according to the objective.

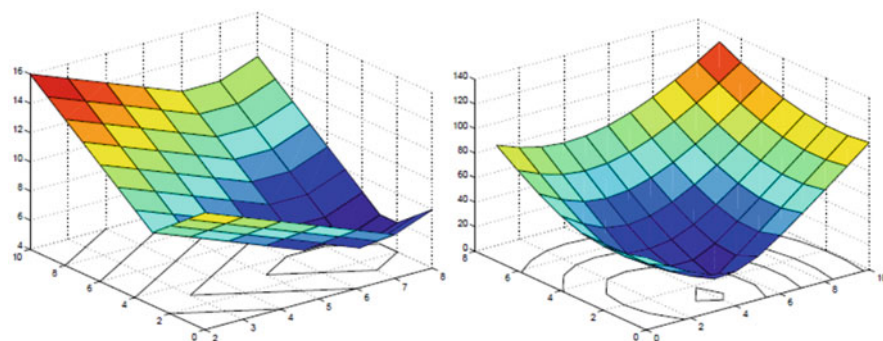


Fig. 10.9 (a) Minimax views and (b) minisum accessibility evaluation

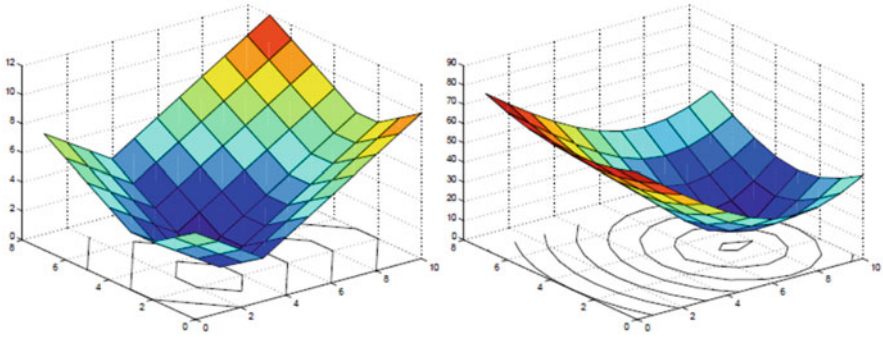


Fig. 10.10 Site-development costs

10.5.5 Noise Evaluation

The fifth criterion has to do with the noise of the site. Figure 10.10a illustrates the contour function generated for the site. The highest function value corresponds to the most suitable site location according to the objective.

10.5.6 Site-Development Costs

The sixth criterion has to do with the development costs of the site. Figure 10.10b illustrates the contour function generated for the site-development costs. The lowest function value corresponds to the most suitable site location according to this objective. Most suitable site location according to this objective.

10.5.7 Site Drainage

The seventh criterion has to do with the site drainage and the fact that the potential drainage patterns directly impact the design of the manufacturing facility. Figure 10.11a illustrates the contour function generated for the site according to the drainage criterion. The lowest function value corresponds to the most suitable site location according to this objective.

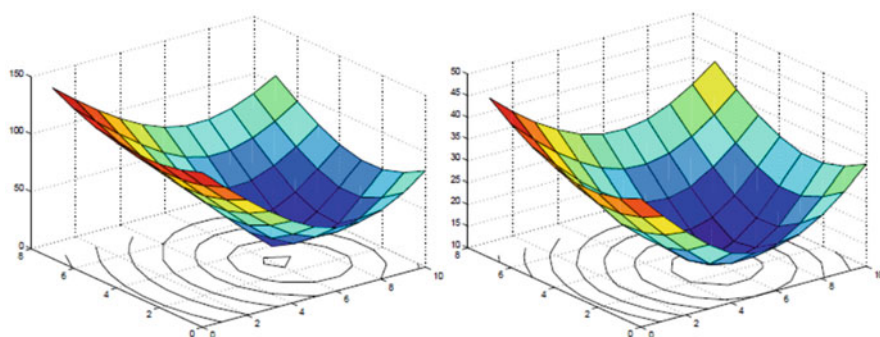


Fig. 10.11 (a) Minisum drainage criterion and (b) overall evaluation

10.5.8 Summary Evaluation

A type I performance function was used to combine all the criteria scores assuming equal weights. The corresponding surface and equal-value contours are shown in Fig. 10.11b. Table 10.4 summarizes the composite numerical values normalized across all the criteria. A MATLAB script was programmed to do all the calculations across all the criteria incorporating the different distance functions appropriate for each criterion. The results indicate that the site on or near lattice location (6,3) is the most attractive one. Figure 10.12 shows a final site plan for the 56,000 square feet factory, along with parking lot, access roads, and landscaping. This study was conducted by Malasmas et al. [4] at the University of Massachusetts.

10.6 Summary and Conclusions

This chapter has presented a comprehensive methodology and approach to site planning and building renovation. Both the methodology and site-selection criteria were presented in a brief but insightful way emphasizing the relevance of these topics. Several examples were used to illustrate the opportunities to enhance the factory project by applying this methodology. It is extremely useful and powerful, especially when coupling the criteria value functions with the distance measures.

Table 10.4 Overall site summary evaluation

Cell 0	1	2	3	4	5	6	7	8	9	10
39.6524	34.2215	29.2140	24.8596	21.4506	19.9832	20.1690	21.5206	24.4552	28.5425	33.4450
37.4930	31.6618	26.1813	21.2139	16.6294	15.4616	15.6394	17.1262	20.4220	25.1598	30.6927
36.3904	30.2832	24.5353	19.5491	15.2766	12.7686	12.4084	13.9486	17.3708	23.0541	29.1454
36.3735	30.2076	24.1877	19.7477	15.7323	12.6323	10.8150	13.0612	17.0925	22.9670	29.1378
37.7354	31.8888	26.5042	21.9930	18.3512	15.7896	14.9287	16.4104	20.0196	25.0257	30.7187
39.9406	34.5604	29.7011	25.6208	22.2710	20.3227	19.8746	21.0865	24.0742	28.3134	33.3542
43.0070	38.1026	33.7541	30.1630	27.3019	25.6555	25.3670	26.3894	28.8897	32.5030	36.9333
46.7384	42.2856	38.4073	35.2685	32.7936	31.3913	31.1665	32.0257	34.1540	37.2712	41.1766

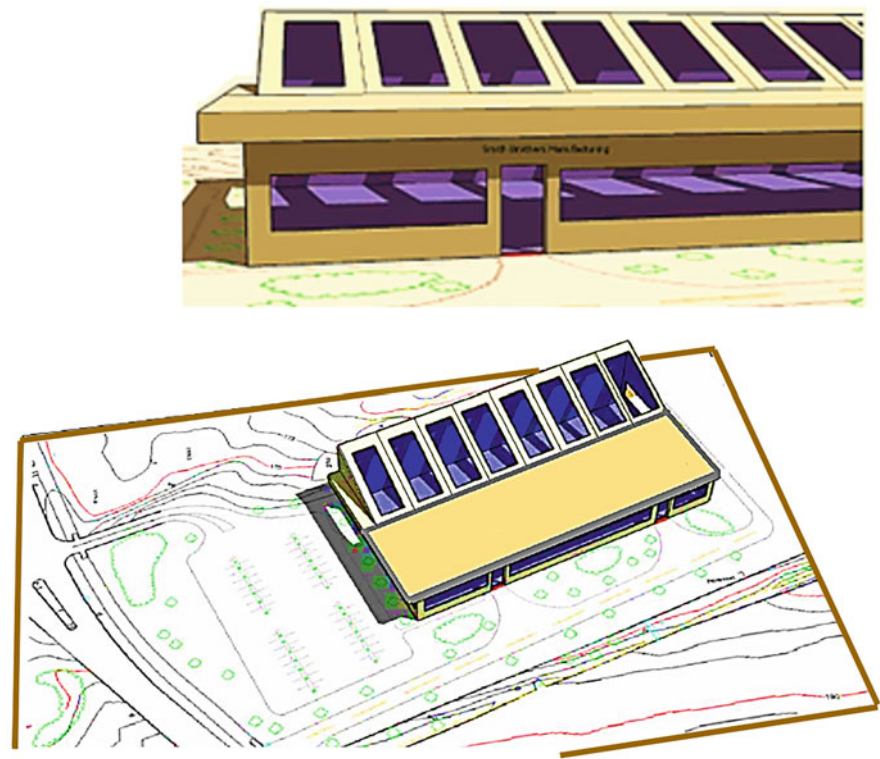


Fig. 10.12 Final site plan

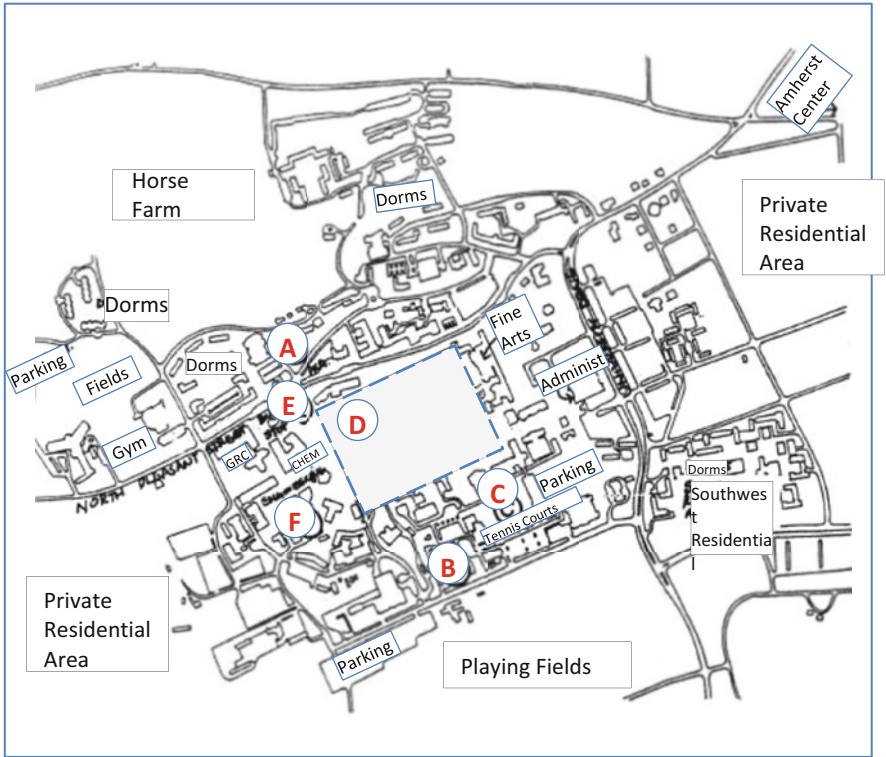
Table 10.5 UMass site plan attributes with six alternative sites

Site Alternative	χ_1 (0.20)	χ_2 (0.20)	χ_3 (0.20)	χ_4 (0.20)	χ_5 (0.20)
A	0.05	0.15	1.0	50	25
B	0.25	0.15	2.0	80	50
C	0.25	0.15	2.5	65	30
D	0.05	0.05	3.0	55	65
E	0.05	0.10	1.5	60	30
F	0.15	0.15	2.5	65	50

10.7 Exercises

10.1 A new multistory classroom building is to be located on the University of Massachusetts campus. A map of the campus with the potential six alternative sites is shown below. The alternatives were evaluated using five attributes listed along with their corresponding lower and upper limits. Table 10.5 summarizes the results of the evaluation and provides the relative weights

of the attributes. Using your understanding of the material in the chapter, select the best site and perform a limited sensitivity analysis of the weights to check how robust your selection is.



Attribute	Lower limit (V_a)	Upper limit (V_b)
χ_1 Accessibility to bus (miles) (\$)	0.0	0.25
χ_2 Accessibility to parking (miles) (\$)	0.0	0.50
χ_3 Site acquisition and development costs	\$250,000	3.00 \$/mil
χ_4 Building construction costs	20 \$/mil	80 \$/mil
χ_5 Environmental impacts, 0 (best), 100 (worst)	0	100

10.2 In New England Society, town meetings are a very significant element of community participation. At issue in Stowe, Vermont, is the relocation of the former St. John’s church building from its present site to somewhere else in the village. The church building, which is also a former schoolhouse, was recently acquired by the Stowe Historical Society. The Society wishes to use the building for research and storage. In order to elicit opinion as to where to move it, an online poll was conducted with the question: *Where should the Stowe Historical Society relocate the former St. John’s church for the group’s*

Table 10.6 Site-plan data and alternatives

Site alternative	A (0.185)	B (0.445)	C (0.164)	D (0.206)
1	70	76	37	82
2	29	56	42	47
3	21	41	85	35
4	15	97	60	39
5	11	14	39	61
6	1	21	58	99
7	89	51	6	32

own use? The majority of voters (20/41 or 49%) said they wanted the church relocated next to the Helen Day art center, (16/41 or 39%) felt another location in the village was preferred (but not specified), while the remaining (5/41 or 12%) said a location at Maple and Sunset streets was appropriate [5]. From your own perspective, what other criteria and factors need to be considered before a final site location decision is made?

- 10.3 Peruse the local newspaper, television news, or community information bulletin board for a possible site-location problem in your own community. It might be associated with a new church, fire station, community health care clinic, residential housing development, or other type of public or private land use activity. Identify seven to nine measurable attributes that are important in evaluating alternative site locations for the new facility or facilities. Do the interested parties have a well-defined set of alternative locations under consideration? If not, how could they be generated?
- 10.4 You are to select a site for a new facility where there are seven potential site locations. The key attributes for the facility and their weights of importance along with the seven sites are indicated in Table 10.6. The sum of the weights adds up to 1. For the three performance functions described in this chapter, evaluate the most appropriate site alternative. For the type III performance function choose the scoring scale $(-5, \dots, 0, \dots, +5)$. Which site do you recommend?

$$\text{Type I, } V^j = \frac{\sum_{i=1}^p w_i x_i^j}{\sum_{i=1}^p w_i}$$

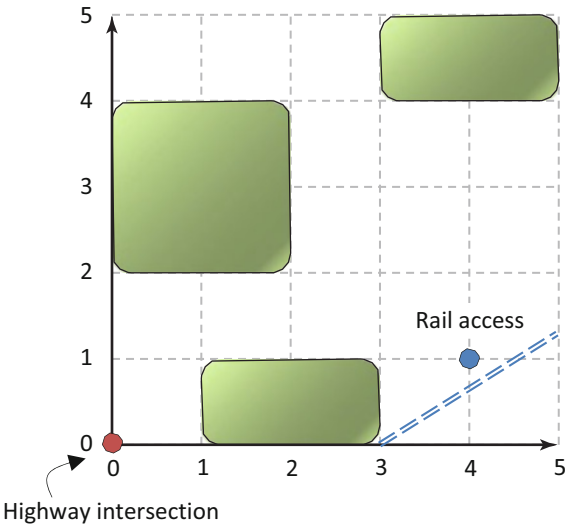
$$\text{Type II, } V^j = \min_i \{x_i^j\}$$

$$\text{Type III, } V^j = \prod_{i=1}^p (x_i^j + M)^{w_i} - M$$

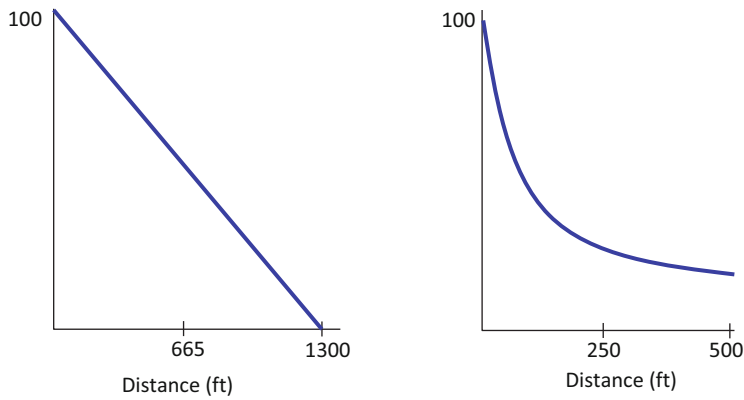
- 10.5 Develop performance functions for the following attributes using the scale $(-5, \dots, 0, \dots, +5)$ for a particular facility location project in your community.

Attribute	Lower limit	Upper limit
χ_1 Acquisition costs (\$)	V_a	V_b
χ_2 Site development costs (\$)	V_a	V_b
χ_3 Accessibility (meters/miles)	V_a	V_b
χ_4 Environmental impact (scoring scale or \$)	V_a	V_b
χ_5 Security/safety concerns (\$)	V_a	V_b
χ_6 Utility impacts (\$)	V_a	V_b
χ_7 Views or vistas (yes/no)	V_a	V_b

- 10.6 List the attributes that are most critical for the site plan of your own factory project. Refer to the various attributes discussed in this chapter. Set up the list of attributes and the weights of importance, and evaluate the given site. It is suggested that you use spreadsheets to perform the calculations.
- 10.7 You want to locate a new factory in an area that includes some forbidden regions where the factory cannot be located. On the accompanying grid site map each cell represents 10,000-square-foot (100' $\times$ 100') cells. The factory requires approximately 50,000 square feet (5 cells). Make any necessary assumptions about the shape of the factory, keeping it as compact as possible. It is desired that the factory have access both to the highway and to the railroad spur located on the site. Assume that the weights of importance for the highway and railroad are equal.

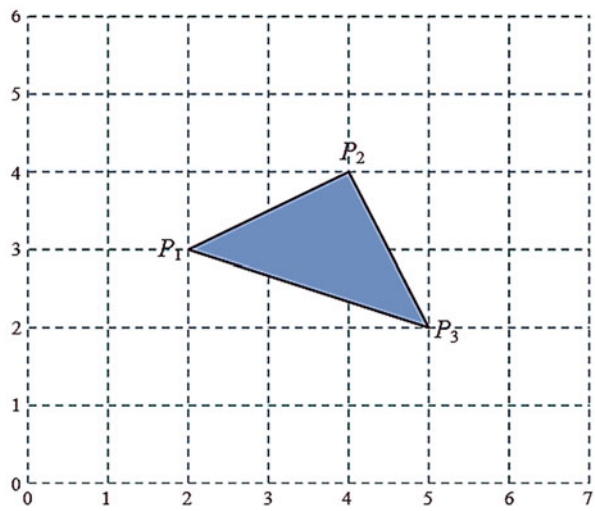


The highway performance function (on the left) and railroad distance attribute are shown below.



Using your understanding of these functions and the site map, find a location for the factory that is most suitable. You may also wish to use GMAFLAD to help in your site analysis. It is important to see that one must make tradeoffs between attributes.

- 10.8 Three existing facilities P_1 , P_2 , P_3 occupy the grided region shown below. You wish to locate a new facility X to occupy one cell of the site map and be closest to the existing facilities. Connecting the existing facilities there is a forbidden triangular region where the new facility cannot be placed. Critical flows between each of the existing facilities and the new facility are 15, 20, and 30 for P_1 , P_2 , P_3 , respectively. You may use GMAFLAD to aid in your site analysis.



10.9 Consider again Exercise 10.8. Now you wish to locate two new facilities *I* and *II*. Each requiring one cell of the grid. The critical flows between the existing facilities and the new facilities are given in the following matrix:

facilities	<i>I</i>	<i>II</i>	<i>P</i> ₁	<i>P</i> ₂	<i>P</i> ₃
<i>I</i>	—	10	15	20	30
<i>II</i>		—	25	30	15
<i>P</i> ₁			—	*	*
<i>P</i> ₂				—	*
<i>P</i> ₃					—

Appendix 10.1 Site-Planning

Geology Planning Issues

- Is there evidence of rock lying close to the surface or of filled areas; is there evidence of slides, floods, or subsidence which could affect foundations and the exact placement of the building?
- Is there presence of organic soils, soft plastic clays, loose silt, or fine water-bearing sand which could be deleterious to building foundations?
- How much will the soil type on each site limit the vertical expansion of the facility?

Hydrology Planning Issues

- What is the elevation of the water table?
- Are there large seasonal fluctuations in the water table?
- How will the water table affect the type and depth of the foundation system?
- What is the surface drainage pattern on each site?
- What problems may exist once construction is completed regarding surface drainage and runoff?
- Is the site located in a defined flood plain?

Climactic Planning Issues

- What climatological factors, such as temperature variation, precipitation, humidity, solar angle heating or cooling degree days, cloudiness and lead wind direction, fog, and other natural features, impinge on the use of the site? (Ranges and averages, and maximums and minimums, are likely to be most useful.)

- What are the favorable and unfavorable winds and how can these be used to heat and cool the building?
- What is the duration and intensity of precipitation that must be diverted by site drainage systems?
- What type of potential flooding problems may occur?
- Is any special microclimate associated with the site or would the planned design create a microclimate?

Topographic Planning Issues

- Are there certain topographic features that may significantly affect the design concept, views, or the road system to the planned facility; are there any other unique topographic features of importance?
- What existing vistas and visual focal points exist on the site?
- How will these be affected by the planned facility design?

Ecological Planning Issues

- Are there any irreversible, harmful effects to the environment through the construction of the planned facility that cannot be avoided?
- Are there any endangered bird or wildlife species that would be adversely affected by site development?
- What types of vegetation cover the site?
- Which trees and vegetation should be preserved during construction of the planned new facility?
- How will the use of advanced mechanical system concepts for heating and cooling in the building design affect the site?
- Does the state, local planning authority, or federal government agency assisting in the funding of the project require an environmental impact study of the planned facility's effect on the site?

Cultural Planning Issues

- Who has current ownership of the site?
- Are there any deed restrictions on the site?
- What types of legal controls, including zoning, affect the use and type of structures that can be built on the site?
- Are there any easements on the site? If so, who has them and how do they affect the construction of buildings on the site?

- What are the setback requirements?
- Do any new federal or state regulations affect the construction and use of the site, such as noise abatement requirements, or air quality or water quality standards?
- What agencies or units of government would have to review the site-selection process for final approval? How long does this review process take?

Financial Planning Issues

- What are the social costs and benefits of site development?
- Besides land acquisition and demolition costs, are there other costs, such as clearing and grubbing, excavation and filling, relocation costs, or licenses and fees, that might enter into the financial performance of a particular site? Who is responsible for these additional site costs?
- Are there any parcels not owned by the client that could be bargained for with private developers in exchange for some land or zoning change as a means of acquiring a desired parcel of land?
- How much income will be eliminated from the tax rolls by the development or use of a particular site?

Image Planning Issues

- Are the site and its neighboring buildings considered historical landmarks or part of a historical district?
- What measures would be necessary to integrate new construction into this historic area? Would these measures unfavorably influence the economic feasibility of the project or alter the basic design concept of the planned construction?
- What type of community reaction to new construction would be expected in the vicinity of the historic district?
- What is the past history of the site and how will it affect future change?

Land Utilization Planning Issues

- Are there any significant cultural or regional factors that should be preserved or accounted for in the selection of the site? For instance, if the client is in a rural area, are there any natural views or features whose preservation may underscore the image of justice in the community?
- If there is an existing facility, what image does it maintain or present to the community? Is it a viable image to preserve?
- As for the buildings and environment surrounding the current facility, how do they affect the image of the facility and the choice of a potential site close by?

- What kind of psychological image does the typical citizen have of the facility in the community, and how much effect would this image have on the site-selection process? In other words, does the facility appear overpowering, important, strong, or weak?

Administrative Planning Issues

- How much space would be made available by removing unrelated manufacturing or service-sector oriented activities from structures currently occupied by the facility?
- What are the types of uses adjacent to the site, and how will they affect and be affected by the planned change?
- What is the average rental cost per square foot in buildings on or adjacent to the different alternative site locations?
- Which offices within the facility do not need to be centrally located in the main building?
- Are there any dominant noise sources, odors, or other air quality problems adjacent to the site?
- What is the noise level on the site outside the buildings? What measures will be necessary to present the noise from disrupting the internal building activities?
- Will the coming of the site itself or adjacent parcels of land accommodate such services as required by the facility?
- Is it foreseeable that some of these outside services can be accommodated on the facility site itself by being incorporated into the facility design?
- If an alternative site does not already have ancillary facility services or space available to house such services, is it foreseeable that such services could be accommodated around the prospective site on adjacent parcels of land in the near future?

Accessibility Planning Issues

- What is the maximum travel time from the farthest part of the service region of the facility's client to each of the alternative sites?
- Where is the general residential location of the staff or users of the facility in relation to each alternative site?
- Will any of the alternative sites affect accessibility or the staff's travel time to their place of work?
- Are there contemplated changes of the regional transportation network that could affect the accessibility of any of the sites being considered?
- What is the predominant mode of travel used by the staff, professionals, and public to arrive at the facility?

- How will alternative sites be able to accommodate these travel modes?
- If any late-night work shifts or public service programs exist or are being planned, how would these affect the accessibility or security of a chosen site?

Adaptability Planning Issues

- What is the available area for future horizontal building expansion on each alternative site?
- Does the site have an irregular configuration, thus decreasing buildability?
- What is the floor-area ratio required by the zoning of the site, and how will this requirement affect future vertical expansion of the facility?
- Is there a height limit imposed by the zoning ordinance?
- What are the parking requirements for the site and building type as provided for in local zoning ordinances?

Site Utility Planning Issues

- Are there storm and sanitary sewers on or near the site?
- Is there a need for any sewage treatment plant on the site, or can existing systems be hooked into?
- What is the expected generation of sewage by the new facility?
- Is there a potable water supply on or near the site?
- Are there gas, electricity, telephone, steam, and other utility lines on or near the site?
- What is their exact horizontal and vertical location as well as capacity?
- What expenses would be involved in relocating these utility lines? Can they be relocated?
- What existing roadways exist on the site? What is their location, capacity, and condition? How will they relate to the planned change contemplated for the site?

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Chapter 11

Office Layout and Personnel Planning



11.1 Introduction

A general office activity area is an important part of the manufacturing facility. All the sales, clerical, accounting, and engineering staff as well as president and vice-presidents and plant managers may be accommodated here, and they form a necessary part of the manufacturing facility. The plant personnel will also utilize space in this part of the factory. Figure 11.1 shows the Johnson Wax Headquarters designed by American architect Frank Lloyd Wright for the company's president in 1939. In Canada and the United States, more people work in offices than in any other work setting. Approximately 42% of the US workforce is composed of office workers with very diverse occupations, and about 26% of the office personnel clerical workers perform tasks with a major procedural component. The rest can be categorized as knowledge workers, including managerial and professional workers [4].

Jobs within the office setting encompass a broad range of activities, from routine administration to creative problem solving and high-level decision-making. Clerical jobs range from data entry and processing positions to several categories of secretarial positions.

In most of the previous chapters, particularly in Chap. 4, the focus has been on a manufacturing environment in which the flow routed through the facilities by the material handling system has consisted of raw materials as well as intermediate and final products. Although the principles and procedures thus far discussed are of general applicability to both factories and offices, in this chapter the focus is changed to emphasize special features of office layouts.

Today people want to work in offices that make them feel at home. Office design should reflect the needs of the work and employees, as well as the structure of corporate philosophy. The focus is on a teamwork-oriented environment. It must attract employees, thereby influencing retention.

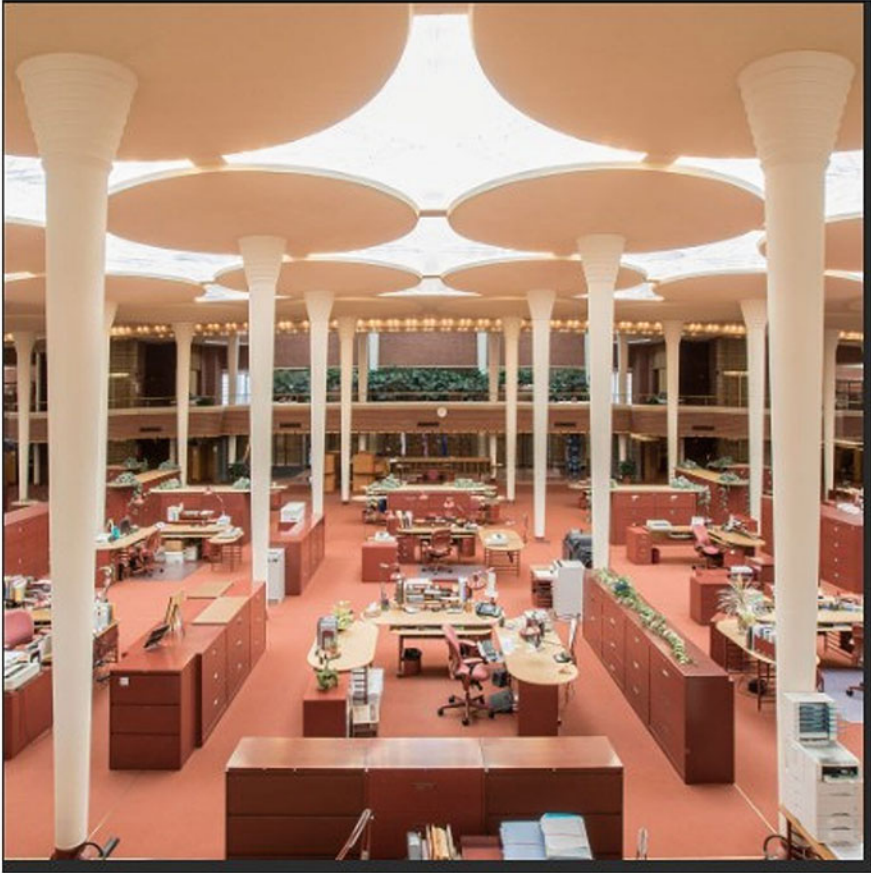


Fig. 11.1 Johnson wax administration building – Frank Lloyd Wright 1939

11.1.1 History of Offices

Offices developed from the need for organizations to coordinate, plan, and administer their activities. The mass production and distribution of goods required efficient methods of record keeping to track large numbers of transactions and coordinate ever more diverse endeavors. The office facility that we know today came into existence as a place from which an enterprise could effectively be controlled.

It is important to see where the layouts of offices were developed and what types of operations affected these designs. During the 1850s, the office looked more like a “small household,” revealing little functional difference between the home and office. One reason was that skills were scarce and it was hard to replace workers. These people had “higher status.” It was relatively unusual and thus a sign of prosperity for a company to build its own offices. During the late 1800s and early

1900s, technology was more routine and factorylike. Employees were low in status. Firms required a “cheap” workforce able to handle thousands of minute transactions quickly and efficiently. During the 1950s and early 1960s, the landscape office appeared. It was shaped primarily by three influences:

- Scientific management principles
- Human relations
- Cybernetics

Human relations meant that the office was supposed to promote a relaxed, status-free form of layout and emphasize noninstrumental aspects of workers. For example, people were called more by their first name. *Cybernetics* in the office was seen as a kind of communications device. In the 1970s and early 1980s, there was a departure toward an open plan. Modules were linked together to form a friendly, ambiguous network of work spaces, in which staff enjoyed both privacy and a sense of belonging to the communal life of the office.

11.1.2 Outline of Chapter

Section 11.2 gives an overview of the entire office spatial design. Section 11.3 provides detailed information on spatial guidelines for office activities and their space and equipment needs. Section 11.4 gives an overview of ways of organizing the office activities and of typical arrangements in the office layout, such as office landscaping and open office plans. Section 11.5 presents a case study involving the design of offices for an urban power and light company, whose alternative layouts were compared with simulation to provide a quantitative evaluation of the office layout design process. The simulation models of these office layouts are available for viewing on the textbook’s website. Section 11.6 integrates this chapter of the textbook with the factory planning project. Section 11.7 describes and illustrates the use of an excel program to calculate the unit cost of the product considered in the factory layout project, and Sect. 11.7 summarizes and concludes this chapter.

11.2 Office Spatial Organization Problem

The material that follows is adapted from an article by A. K. Leopold [9]. New trends in office space design combine style, functionality, and technology. A number of companies, from the West Coast’s Apple Computer to Pittsburgh’s Aluminum Company of America, are redesigning office facilities in a way that promotes performance by integrating teamwork and telecommunications. In 1994, the Chiat/Day Company, one of the largest advertising companies in the United States, eliminated permanent offices in Los Angeles and New York in favor of a nonoffice

look, vividly enhanced by the use of screaming primary colors. Their employees check out laptops and come in for meetings as needed.

Dr. F. Becker, former director of Cornell University's International Workplace Studies Program and a consultant for Fortune 500 companies on developing effective workplace strategies, emphasizes the fundamental idea that people should work under conditions that help them to be most efficient. Location and time should be of secondary importance. So, he asks, "Why not create an office where the probability of bumping into people for the exchange of ideas is increased?" New work environments often require less space and promote high performance.

The most important influences on the development of the office design are:

- Office technology.
- Office organization.
- Building construction.
- Real estate factors.

Office technology supports and transforms the tasks performed in the office, the equipment needed to carry out the work, and the pattern of communications. Office organization, on the other hand, is a complex of relationships between people, holding positions at all levels of the administrative ladder. Both of these are internal factors that either control or are controlled by those in the organization. The other two factors are external, subject to limited control by the company, due to the dependent nature of the market.

According to Vilnai-Yavetz and Yaacov [16], the planning and design of office layouts and workspace should recognize three separate dimensions: instrumentality, aesthetics, and symbolism.

Instrumentality is related to usability and goal attainment. It is similar to the concept of affordability, because physical artifacts can support or hamper desired activities. *Aesthetics* is related to space and environmental design. It is claimed to be independent of instrumentality, although it cannot be dissociated from organizational goals. *Symbolism* refers to associations elicited by the space. It views people as not only active participants but also observers and interpreters of the physical environment. Symbolism has been perhaps the main issue investigated by organizational researchers.

In the study by Vilnai-Yavetz and Yaacov, instrumentality was found to be related to employee satisfaction and effectiveness, whereas aesthetics was related only to satisfaction, and symbolism was not related to either satisfaction or effectiveness.

Offices differ from factories in at least three aspects [9]:

- The *product*, which is mostly information transmitted in the form of paper, meetings, e-mails, phone calls, and faxes.
- The *physical environment*, defined by an integration of factors such as lighting, acoustics, ventilation, and climate control. This environment can influence employees' behavior in numerous ways [6].

- The *social environment*, a reflection of status (level of importance) and aesthetics (resulting from wall decorations, floor covering, furniture, artwork, plants, and so on).

Two significant measures of effectiveness to evaluate an office layout are the minimization of total communication cost and the maximization of employee productivity. Highly satisfactory levels for both measures can be achieved when the office layout properly integrates the following criteria or evaluation factors [12]:

- **Suitability:** operational effectiveness.
- **Flexibility:** possibility of efficient change and growth.
- **Habitability:** features and facilities to enhance efficiency.
- **Advancement of administrative profession:** state-of-the-art offices planning and design.

When evaluating the degree of suitability or operational effectiveness, we focus on space allocations, work and traffic patterns, accommodations or required equipment, and energy conservation. The degree of flexibility should be enough to prepare the designers to face the challenge of future changes and expansions. Among habitability features, the following are most important: lighting, sound conditions, climate conditions, decor, and various employee facilities.

11.2.1 General Functions of Offices

The general function of the offices block is to process information, and the purpose of an effective office layout design is to effectuate this flow of information. As in the plant layout itself, the flow of information is basically equivalent to the material flow within the plant, thus its critical importance. Although there is no single best solution for an office layout, the selected alternative should be flexible enough to respond to changes in the information flow and its organization over time. Thus, the trend toward open offices and office landscaping with the use of movable partitions and furnishings is very sensible for office layout design. Some basic office functions occur in most office layouts, and these include:

1. Management.
2. Finance.
3. Sales and marketing.
4. General clerical services.
5. Engineering and technical services.
6. Production services.

The management group in large organizations includes the president and CEO, vice-presidents, and other executives responsible for the overall administration of the office. They need to be close together in a sort of chain of command, which could be located either centrally or preferably along a boundary wall, where more visual and

acoustical privacy is maintained. For smaller companies, a more simplified organization is recommended.

The finance group includes the accounting and purchasing, personnel, and data processing activities. Accounting should be close to the sales and marketing function, since they carry out the detailed activities of credit checking, order processing, inventory control, billing, and accounts receivable [14]. The purchasing function has a great deal of contact with outside vendors, so it should be close to the central reception area. Personnel also needs to be close to central reception to facilitate job candidate interviews and managing visitors. Data processing and central records storage should be more isolated from the traffic areas and shielded to avoid potential noise and security problems.

The sales and marketing group plays an important role in all the activities of the office, so it should be centrally located. In addition, it will receive many visitors, so it needs to be located close to the central reception area. Pricing, estimating, and correspondence functions are critical activities with the sales and marketing group [14]. Sales also needs easy access to the conference and training room for meetings, demonstrations, and conferences with engineering and the product design and development staff [14].

The general clerical area provides services to the entire office, such as central records storage, copying and binding of reports, library functions, mail handling, and general interoffice communications. Depending upon noise levels of the activities—for example, copying and binding, which should be more acoustically private—the clerical activities should be closely aligned with all the other administrative office functions.

Engineering and technical services may include such activities as product design and development, machine design and drafting services, quality control activities, and engineering and maintenance of machines and processes within the plant.

Production services include the plant foreman, supervisors, and other personnel who provide the critical link between the office administrative services and the manufacturing and assembly activities within the plant.

11.2.2 Organization Chart

The physical arrangement of the office activities will be a natural reflection of the work and information flow engendered in the organization chart. There are many possible organization charts, including those based upon the product line or a matrix organization, yet within the context of the factory project, the line organization shown in Fig. 11.2 is probably the simplest and most appropriate.

The overall spatial organization of the office layout for the factory project is shown in the relationship diagram (REL) in Fig. 11.3. All the main activity areas are represented within the diagram, as well as the critical flow relationships among and between the activities in the plant. The general office spatial relationship diagram

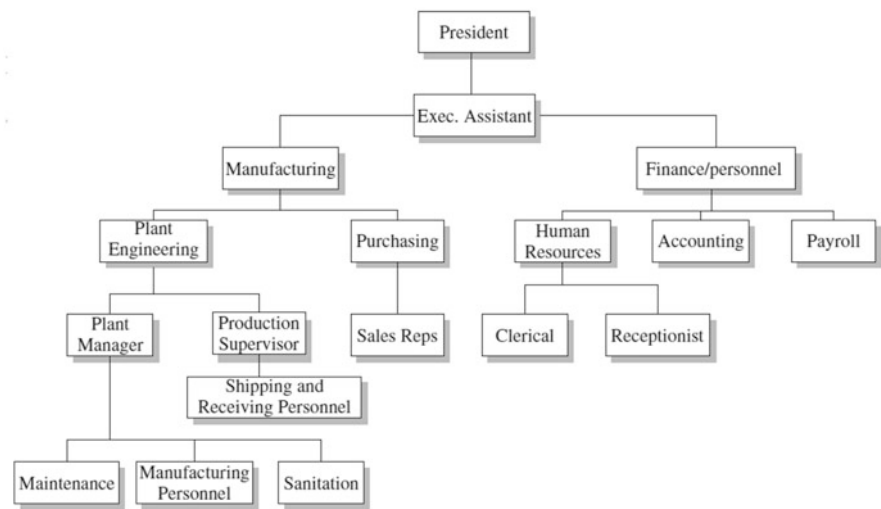


Fig. 11.2 Organization chart for factory office

appears in Sect. 11.3. Here we detail the spatial, location, and equipment requirements of the various activities in the factory office structure.

11.3 Office Space Guidelines

In this section, we provide general guidelines regarding the location, space needed, and building requirements for the factory office system performing all office functions necessary to have a smooth, effective, and efficient operation of the factory business. We use the following colors in the diagram shown below to represent various office functions:

- 1. Yellow for administrative functions (finance, managerial, etc.)
- 2. Green for general clerical services (accounting, sales, marketing, etc.)
- 3. Blue for engineering technical services (quality control, drafting, estimation, etc.)
- 4. Red for people accommodations (waiting, travel, etc.)
- 5. Orange for equipment furnishings, projectors, chairs, and tables.

Central reception is primarily an information and referral point. The receptionist must screen incoming phone calls, visitors, vendors, and sales marketing representatives before directing them to the appropriate department or person in the plant. The receptionist may also be assigned certain clerical or typing duties.

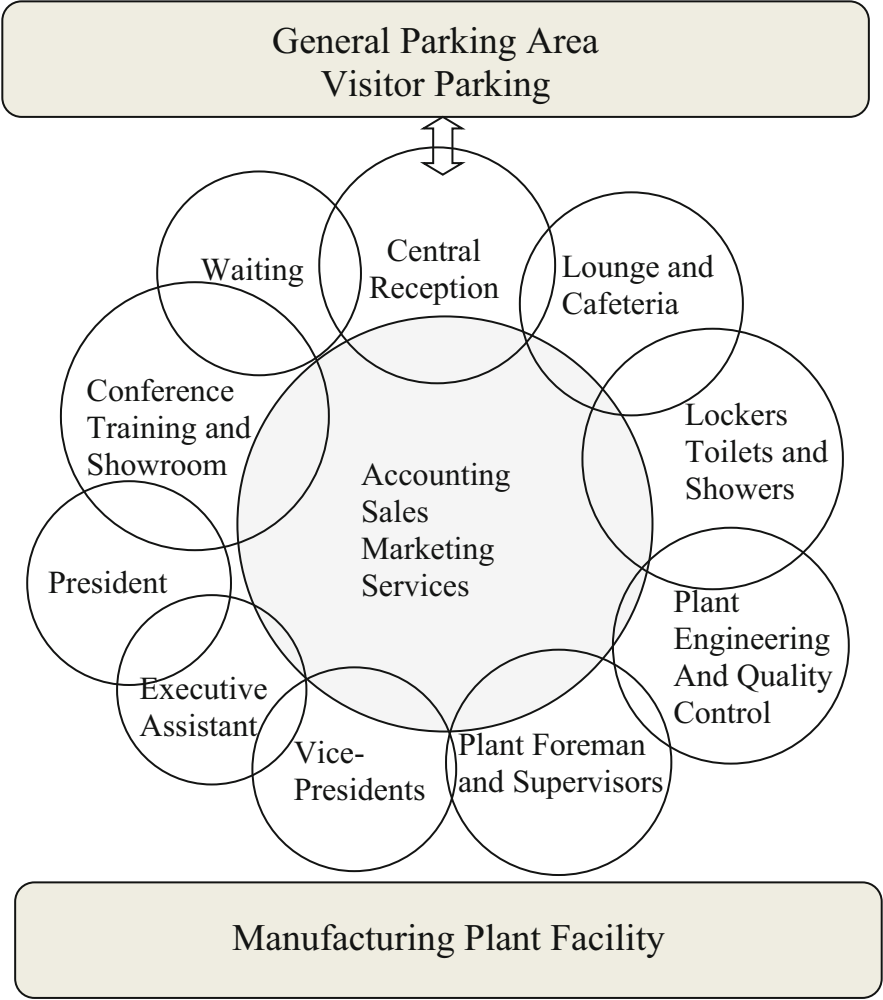
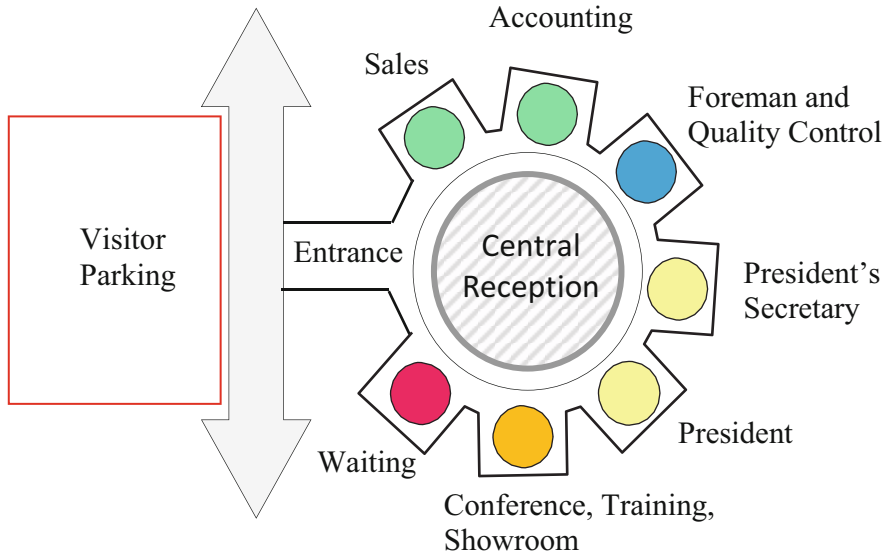
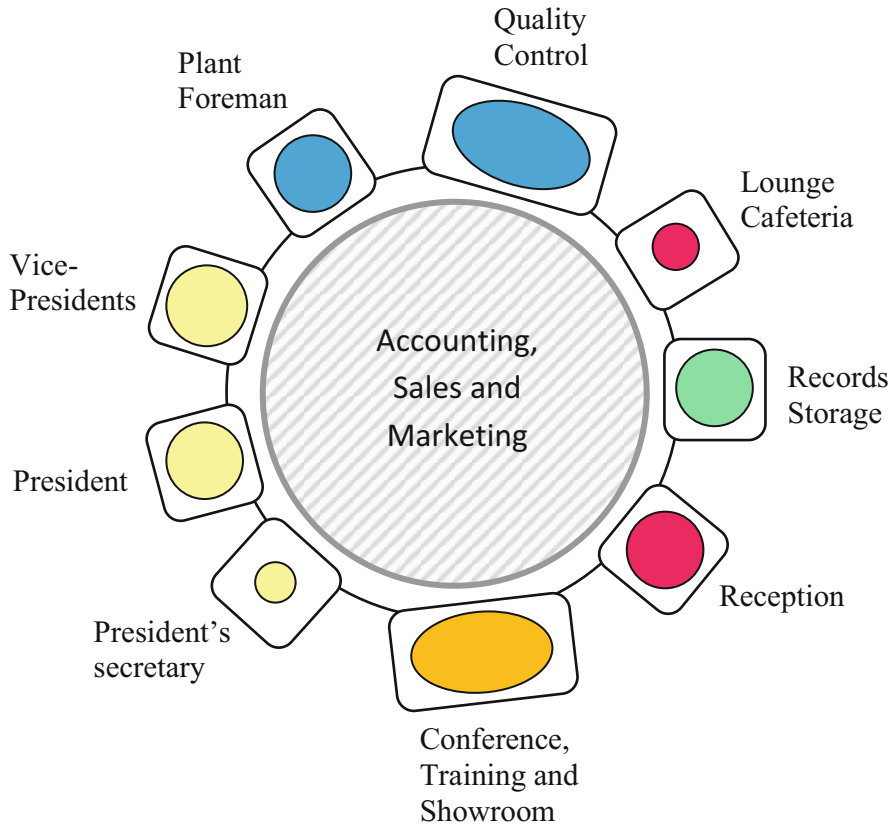


Fig. 11.3 General REL diagram for offices



- A. **Location:** At right angles or off to one side of the visitor entry path. Desk should be at least 10–12 feet from the entrance door to avoid congestion.
- B. **Building requirements:** Area 125–150 square feet for receptionist; 20 square feet per expected visitor in the waiting area.
- C. **Equipment Requirements:**
 - One large computer desk with area for PC + printer, telephone, and other inter-office communications
 - Filing cabinets
 - Mailboxes for office staff
 - Coat rack for visitors' overcoats and umbrellas
 - Large sofa and comfortable chairs, low tables, magazine racks
 - Graphic and information displays

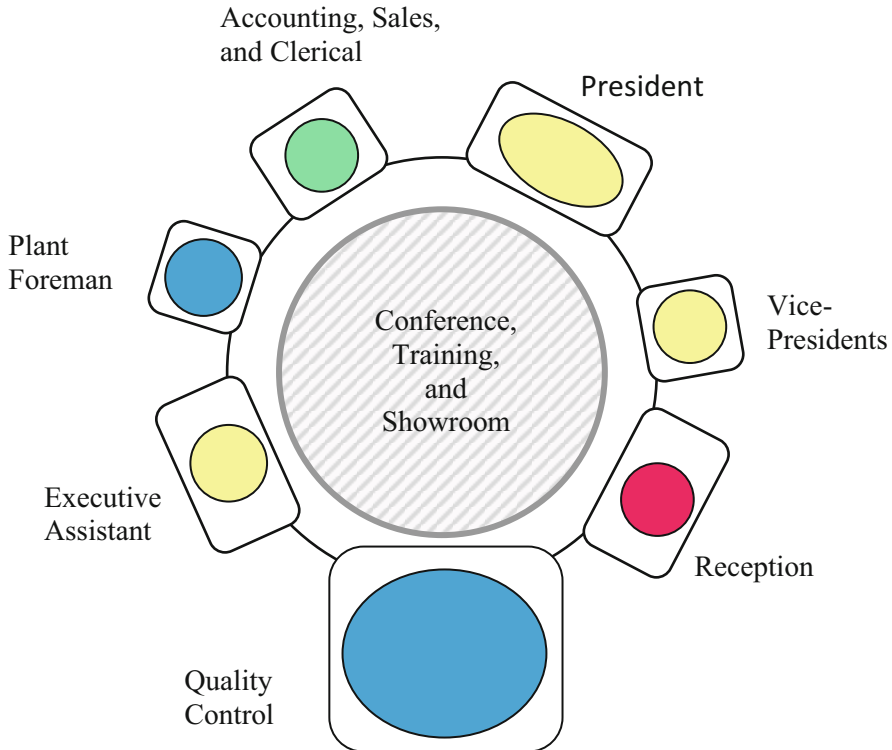
Accounting, Sales, and Marketing areas provide a critical function for the factory since they represent the backbone of the day-to-day office operations ranging from payroll, accounts payable, and sales to marketing and many other essential functions. The staff in charge of these functions must work closely with the president, vice-presidents, secretarial personnel, plant engineers, quality control staff, plant foremen, and other senior personnel.



- A. **Location:** Central to the entire office.
- B. **Space:** Area 125–150 square feet for senior accountant, and sales and marketing personnel; general staff members should have 45–85 square feet per individual, depending upon equipment utilized.
- C. **Equipment Requirements:**
 - Computer desk with PC keyboard, secretarial chairs, filing cabinets, telephone outlets, coat racks
 - Low-wall partitions where possible (42–80 inches high) with sound absorbent materials and tackable wall surfaces
 - Copying and printing area with work table (10 feet long), metal storage shelves, lockable closet with metal storage shelves for paper, toner, and other office supplies

The importance of the **Plant Engineering and Quality Control** area depends upon the type of product manufactured in the facility. Design and maintenance engineers may be necessary for product and equipment design and maintenance issues within the plant. Quality control engineers may be necessary, depending upon the processes used and product manufactured. Since these are professional staff, they

need offices and work areas commensurate with their activities and status within the organization. They may carry out small-scale research activities, and a small laboratory (laboratory with benches and sinks) may be necessary to conduct tests on the product or manufacturing processes.



- A. **Location:** Close to the president and vice-presidents yet convenient to the factory itself, along with clerical and records storage. They may have their own clerical staff separate from the main accounting and sales area.
- B. **Space:** 180 square feet for each professional; 125–150 for researchers and assistants; 80–100 square feet for mini-conference areas; and 65–125 for clerical staff.

C. Equipment Requirements:

Engineers

- Writing desk with PC, executive swivel chair, 2–3 chairs for guests, bookshelves, and so on.

Researchers

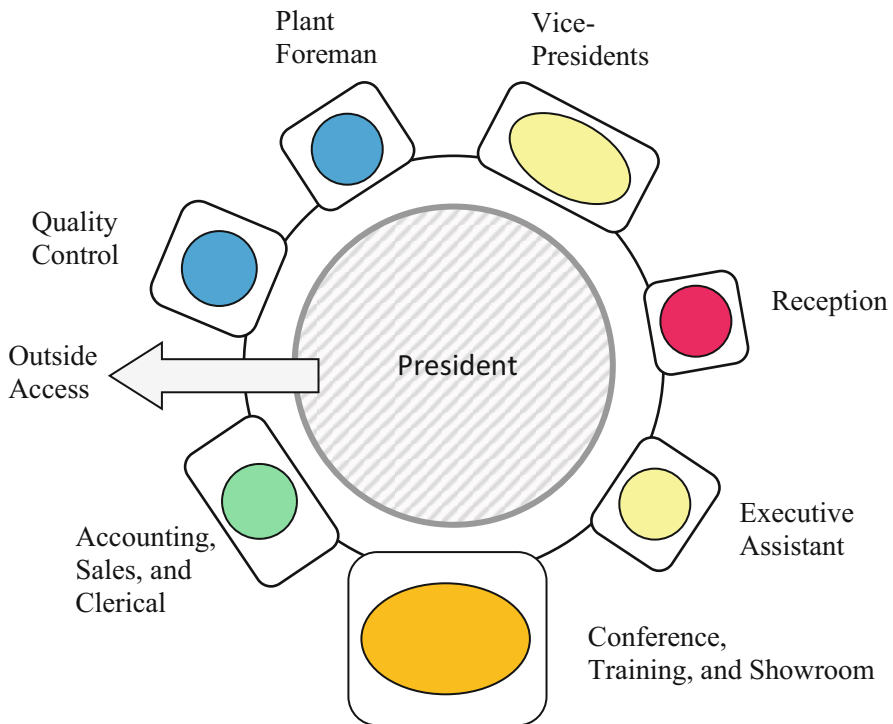
- Writing desk, bookshelves, low-wall partitions (52–62 inches high).
- Possible separate computer terminals.
- Mini-conference area with round table and 4–5 occasional chairs; chalkboard, tackboard; library bookshelves.

Clerical

- Writing desk, chairs, files, bookshelves, and low-wall partitions (52–62 inches high).

The **President and Vice-Presidents** should be located in a physical setting that conveys the importance of their positions and provides the necessary spatial arrangement for conducting the affairs of their offices. It is particularly important that the president's office setting be pleasant, since the president will often remain in the office for long periods of time, both to carry out administrative duties and to receive visitors. The president normally will have an executive assistant to screen mail and visitors, keep the appointment calendar, and perform other traditional secretarial duties.

The vice-presidents normally will work closely with the president and should be afforded separate and similar, although less lavish, office space. There may be vice-presidents for manufacturing and one for finance and personnel.

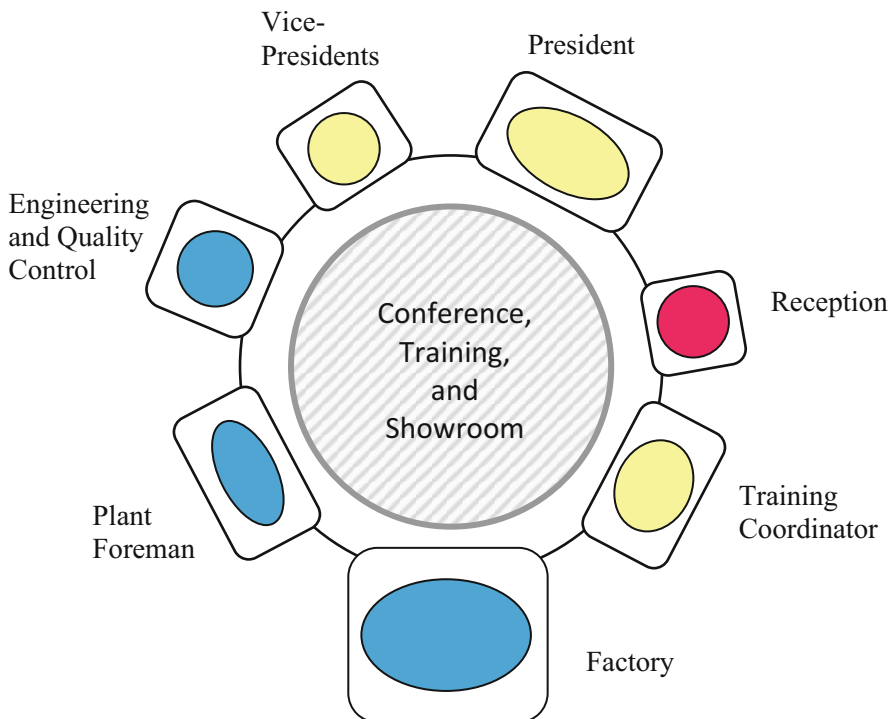


- Location:** At an extreme edge or boundary of the building.
- Space:** The president's personal work space should range from 180 to 300 square feet and include a small conference area of 100–150 square feet. Vice-presidents should have roughly 150–200 square feet and may also have a small conference area within their office for meetings with 2–3 people.
- Equipment Requirements:**
 - Large writing desk
 - Possible separate PC desk and printer
 - Bookshelves

- Four or five occasional chairs
- Sofa, lounge chairs, coffee table
- Floor and table lamps
- Coat closet
- Possible toilet and lavatory
- Small conference table to accommodate 4–5 persons

The **Conference, Training, and Showroom** space is important for the entire factory. Besides normal everyday meetings, training of staff is essential, along with accommodations for visitors and vendors and displays of company products and operations. Participants in the conference area should be able to carry out the following activities [1]:

- See each other's facial expressions.
- Hear words spoken at a normal conversational level.
- Exchange documents, papers, and other objects.
- Sit for long periods without feeling cramped or uncomfortable.
- Take notes and place notebooks, coffee cups, and the like on a horizontal surface next to or in front of their seating position.
- Use visual aids to supplement their discussion.



- Location:** Convenient to the entire staff but very close to the president's office and central reception and waiting.
- Space:** 15–20 square feet per person for meeting area; 20–25 for storage and equipment; 10–15 for entry alcove.
- Equipment Requirements:**
 - Round or oval 8-foot conference table, or 13- by 5-foot elliptical table.

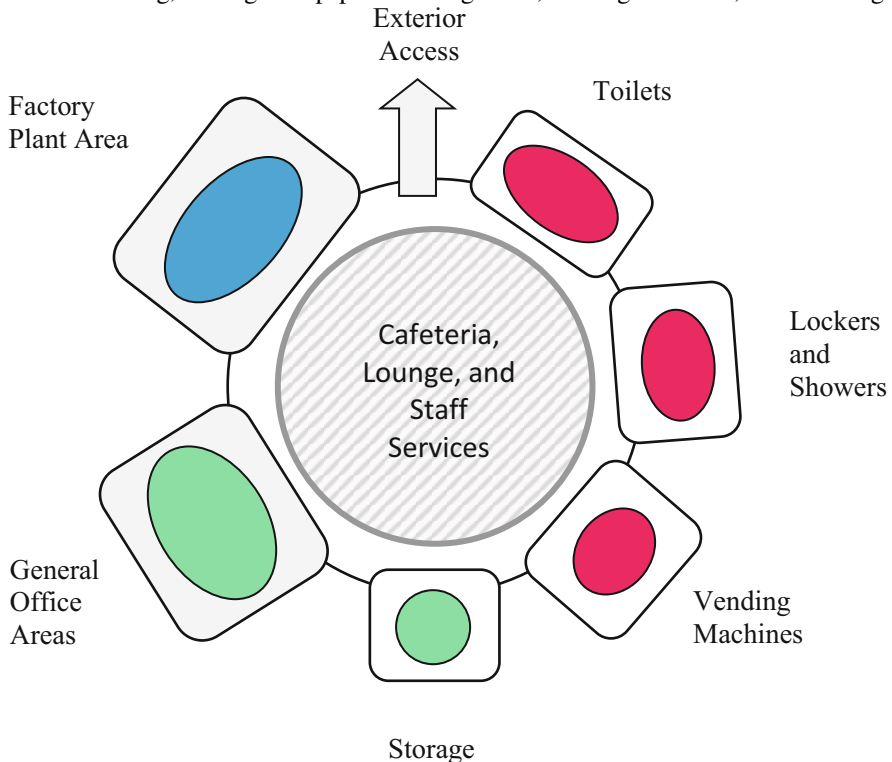
- Should accommodate 12–15 people in comfort.
- Fifteen lounge chairs with arms for long-term seating.
- Roll-down movie screen and storage for projectors.
- Whiteboard and tackboard.
- Possible coffee bar or kitchenette with sink.
- Closets or coat rack near the entrance.

The conference and training room should be visually and acoustically private to minimize external disturbances and prevent sounds from films or audio tapes from infiltrating the office work areas or disturbing private discussion in the individual staff offices.

The conference/training setting should be a warm, comfortable area where the colors, patterns, and textures and materials are conducive to extended discussion. The atmosphere should facilitate communication among the participants, especially for informal seminars. Illumination levels should be variable to allow a range of activities: structured discussions and lectures, informal group seminars, training laboratories, wall displays, slide shows, and possibly closed-circuit television.

Cafeteria, Lounge, and Staff Service areas are not considered by many factories to be essential parts of the physical planning problem. Certain factories may be located in urban or suburban areas where restaurants and cafes proliferate. Even so, some provisions for a cafeteria/lounge are desirable.

A cafeteria/lounge will be used by the entire staff. It will also be used for a range of activities: eating, reading newspapers and magazines, viewing television, or conversing.



- A. **Location:** The cafeteria/lounge should be located so that food and cooking aromas do not permeate the office work areas. A remote location is preferred.
- B. **Space:** 20 square feet per expected user; 80 for vending and kitchenette; visitors' toilet areas as needed; locker rooms, toilets, and showers.
- C. **Equipment Requirements:**

General

- Lounge chairs, sofas, occasional chairs, and so on
- Coffee and dinette tables
- Floor and table lamps if appropriate
- Wall-mounted clock

Kitchenette

- Single-compartment sink
- Two-burner range top
- Refrigerator
- Counter with cabinets above and below

Vending

- Coin changer
- Microwave oven
- Preparation counter
- Waste receptacle

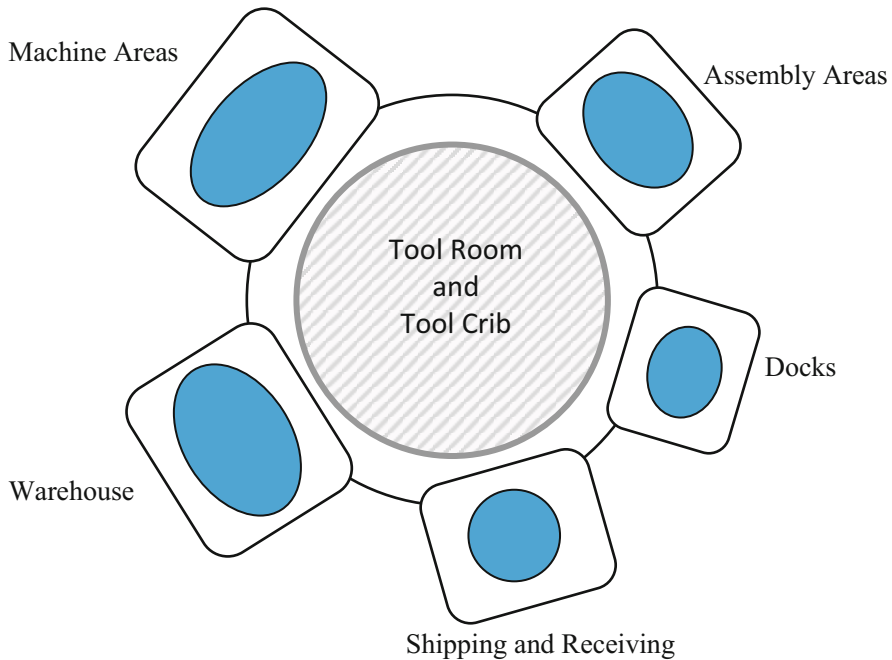
Locker and Shower Room

- Lockers provided for each employee along with benches.
- Showers as needed.
- Toilets, as many as needed according to the local building codes.
- Toilets should be readily accessible from the lounge and eating areas but not directly open to them.
- Facilities for both men and women should be provided and be handicapped accessible.

11.3.1 Ancillary Space Guidelines

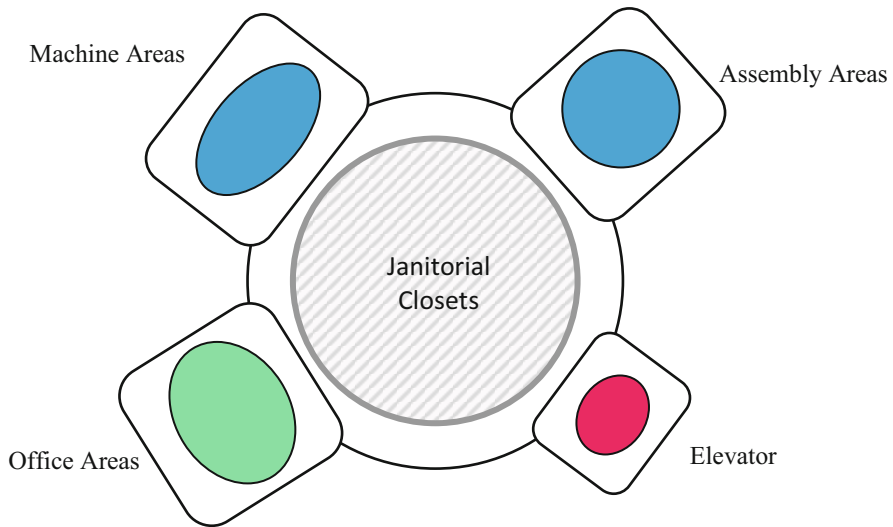
We discuss here some other space elements needed in the factory project.

Tool Room Tool rooms and tool cribs are provided for the maintenance, repair, and supply of special tools and equipment needed throughout the plant. Generally, they are centrally located, although there may be additional tool cribs due to a large or multi-faceted plant layout.



- A. **Location:** Centrally located to the entire factory if at all possible. If the factory is extremely large, then decentralized tool rooms may be appropriate, since there may be multiple stories or multiple buildings and walking distances may be excessive [4]. There should be room surrounding the tool room for possible expansion.
- B. **Space:** Minimum area should be 100–200 square feet with an adequate security perimeter. Secure access and egress should also be provided.
- C. **General Equipment Requirements:**
 - Modular storage racks and bins for tools, manuals, and materials for repair.
 - Cabinets and lockable racks for valuable precision tools.
 - Employee access areas should be provided with large, secure, durable counter tops to record and transfer items.
 - Room for material handling carts and trucks and possible monorail or jib cranes for heavy items [12].
 - Adequate lighting and power requirements and possible high-ceilinged spaces.

Janitorial and Custodial Janitorial and custodial closets are essential for the regular maintenance of the facility. Even though outside contractors may carry out the work, they need access to storage closets for the equipment and supplies needed to do their job.



- A. **Location:** Custodial closets should be located on each floor of the facility and preferably near an elevator.
- B. **Space:** 90–100 square feet should be adequate.
- C. **General Equipment Requirements:**
 - Shelving 15 inches deep with 15 inches between shelves.
 - Floor sink 2.4 by 2.5 feet with hot and cold water. Over the sink, a special holder should be mounted for air-drying floor pads after they are washed out.
 - Tool board with minimum of 8 clamps for hanging mops and brooms.

11.3.2 Miscellaneous Areas or Offices

Several small areas may be necessary within the facility, depending upon the particular product manufactured or certain special conditions.

Shop Supervision and Quality Control Offices Production supervision offices may be provided within the plant for the production supervisor on the shop floor. These may also be necessary for certain quality control or visual supervision requirements. These would be relatively small (80–125 square feet) and conveniently located to the area where they are needed. They also could be pre-fabricated or portable [3].

Plant Maintenance Certain production facilities may require special maintenance areas to maintain and repair valuable equipment and material handling devices (conveyors, forklift trucks, and so on) or make emergency repairs. This area may be separate from the tool room.

11.4 Personnel Requirements and Office Arrangements

This section gives the student a conceptual view of the main types of personnel requirements and layouts used in the physical arrangement of desks, equipment, storage units, furniture, and any other items contained in an office.

11.4.1 Personnel Requirements

Personnel can generally be classified as production or factory personnel and management personnel. Factory personnel can be further subdivided as direct or indirect. The factory direct personnel cost is typically known as the labor cost component of the direct product cost. Indirect personnel costs include factory indirect and office and management personnel costs.

Direct personnel costs can be determined on a per-unit-of-product basis, while indirect personnel costs do not lend themselves naturally to such a determination, because they generally do not depend on the volume of production. An important problem in accounting is to divide the indirect costs in a rational and fair manner among the products being manufactured or the services being rendered by an organization.

The following typical facilities are generally available in a diversity of companies to accommodate the personnel:

- Employee parking
- Locker rooms
- Restrooms
- Food services
- Health services
- Barrier-free compliance

11.4.2 Types of Office Arrangements

The basic principles of layout planning covered in Chap. 4 apply to the specialized layout application considered in this chapter, although the communication process, economics, and flexibility principles are the most important in deciding which specific type of layout should be used in each particular case of office layout planning. A significant amount of research supports the view that the productivity of administrative personnel, including clerks, secretaries, supervisors, and directors, is highly affected by working conditions, available equipment, and a number of specialized items that range from decorative to functional.

Office layout planning has evolved from a traditional arrangement that emphasizes a rectangular arrangement of desks to the modern open-plan layout that

promotes the use of teamwork and telecommunications to enhance operational efficiency. Typically, an office must be big enough to include work space, walking space, and storage space. Main types of furniture include desks, workstations, storage units, chairs, and large tables. The operational interaction between offices is best described by a relationship chart that emphasizes control and communication, instead of a from-to chart, which emphasizes physical movement of products and is more appropriate for planning the layout of production departments. Due to this distinction, a computerized procedure such as FLAP, GMAFLAD, or STEP, introduced and reviewed in Chaps. 4 and 6, is more useful to guide decision making concerning office layout planning. Nevertheless, if a from-to chart is available, CRAFT can also be used for this purpose.

To discuss their special features, it is convenient to classify office layouts into the following types. Our discussion is adapted from the work by Kontz [9].

1. Conventional or traditional office.
2. Landscape office.
3. Open-plan office.

The **conventional arrangement** is typical of the offices of the past, although it is still useful as a functional layout in small organizations. The use of computers allows a significantly reduced size of the arrangement, as compared to arrangements in the pre-computer age. This layout, as depicted in Fig. 11.4, is essentially a rectangular partition-free arrangement of desks or workstations, with private offices for higher-ranking personnel usually located around the main area. This arrangement promotes the concept of equality among employees, although it does separate employees from supervisors. Figure 11.4 shows a three-dimensional office layout for a factory similar to the one considered in the factory layout project.

The **landscape arrangement**, illustrated in Fig. 11.5, has been now used over more than six decades. Its main motivation is the elimination of the separation between employees and supervisors. This concept is implemented by omitting permanent interior walls and adding furniture pieces and storage devices that act as partitions. The presence of plants and the nonrectangular arrangement of desks results in a relaxed working environment for both employees and supervisors. Typical measures of effectiveness associated with this kind of arrangement are operational and communication costs.

The most popular in modern office layouts is the **open-plan arrangement** introduced five decades ago, but rediscovered during the last three decades. The distinctive measure of its effectiveness is its ability to accommodate specific needs of the workstations included in the layout. One such workstation is shown in Fig. 11.6. The individualized workstations included in an open-plan layout tend to form a systematic arrangement based on operational needs, rather than a somewhat arbitrary, although seemingly convenient, rectangular arrangement. The layout tends to form a systematic arrangement based on operational needs, rather than a somewhat arbitrary, although seemingly convenient, rectangular arrangement. In this layout color-coordinated furniture replaces “the proverbial battleship gray and industrial

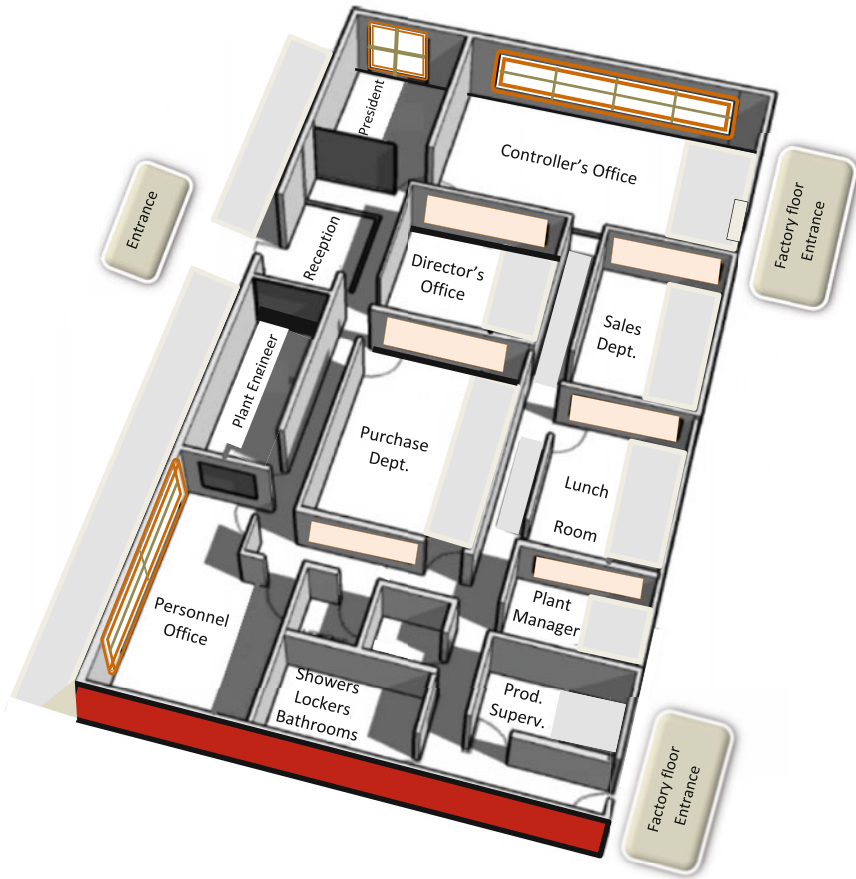


Fig. 11.4 Conventional office arrangement

green” distinctive of the conventional arrangement. Figure 11.7 shows an illustration of the arrangement.

The open-plan layout is particularly effective when integrated with modular furniture. This makes it possible to accommodate efficiently more individuals, lower operation and maintenance costs, and enhance employee productivity. Although, in general, the morale of employees is usually improved by the open-plan layout, some executives may feel that their status is lowered if they do not have private offices. Fabric on panels, carpeting, acoustic ceilings, and sound screens, consisting of insulation and fiberglass shells, may be needed to absorb the additional sound generated in an open-plan office.

Some specific drawbacks of the office plan are the lack of privacy needed for conducting personal business and the complaints of excessive noise. It is important that the design fit the needs of the workers. Modules should not be too low, and

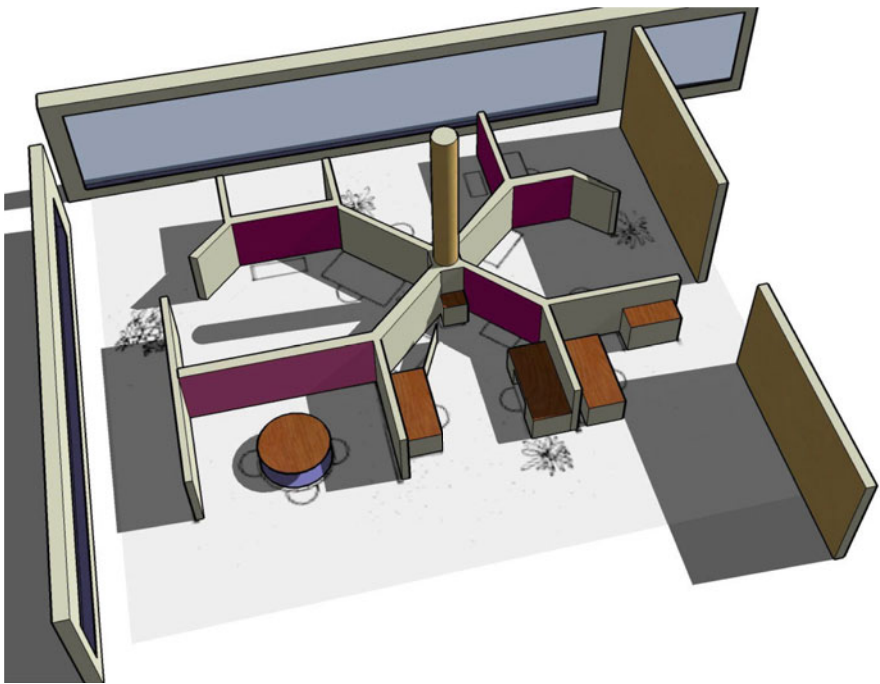


Fig. 11.5 Landscape office arrangement



Fig. 11.6 Typical workstation in open-plan office arrangement



Fig. 11.7 Open-plan arrangement

desks should be flexible enough to be considered comfortable by those who use them. Currently, the return to private offices with excellent working conditions and use of top-quality equipment is being regarded by some employers as an effective alternative to working at home, which became the norm as a result of the Covid pandemic during the 2019–2022 period.

11.4.3 Office Layout Example

We wish to design a layout of an office with 11 activities (departments). We illustrate the quantitative layout approach to office development with some of the tools of Chaps. 6 and 8.

In the following list of activities (offices), we show the square-footage requirements for each office. Where appropriate, also, we have identified the number of personnel greater than one and the nonassignable square footage, which constitutes the circulation and wash rooms and other spaces necessary in the layout. This rounds out the spatial requirements to around 5000 square feet. From this, we have constructed a 70- by 70-foot square template for the office. This office template will be utilized by GMAFLAD to generate the layout.

1. President (PR) (250)
2. Executive Assistant (EA) (125)
3. Vice President (VP) (200)
4. Production Manager (PM) (200)
5. Accountants (AC) (4) (600)
6. Sales Representatives (SR) (4) (400)
7. Engineers (EN) (4) (600)
8. Clerical (CL) (5) (500)

The following diagram shows the **graph decomposition** of the flow matrix.

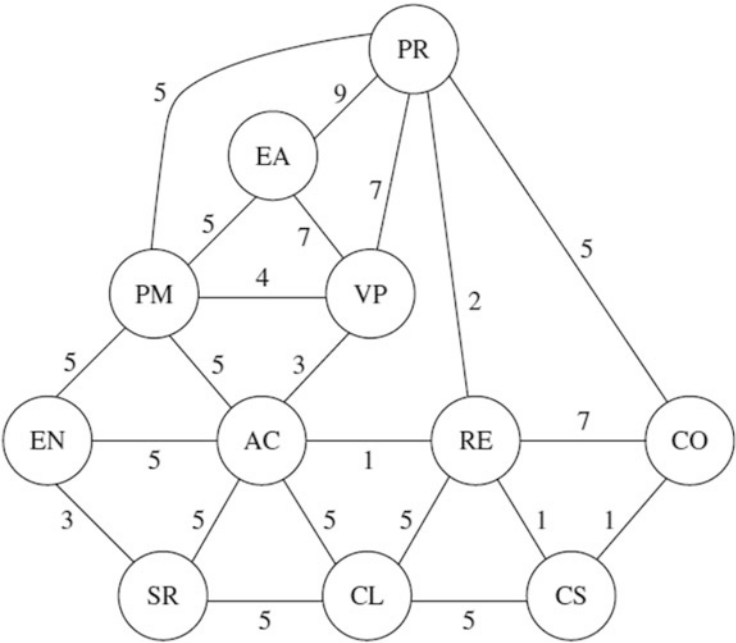


Figure 11.8 shows the optimal solution from GMAFLAD. It is a very sensible and flexible layout alternative from which the circulation layout can be planned.

Fig. 11.8 GMAFLAD optimal solution for alternative 1

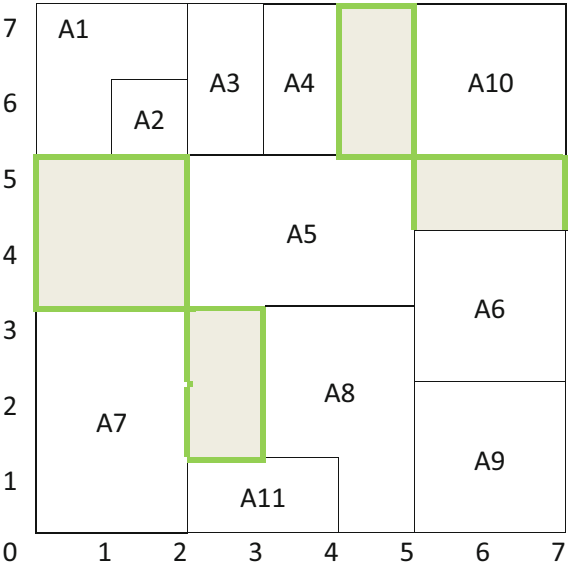




Fig. 11.9 GMAFLAD optimal alternative 1

Figure 11.9 illustrates the conversion of the GMAFLAD diagram into a 3-D office setting corresponding to Fig. 11.8. Finally, in order to provide another quantitative measure of the work and people flow relationships within the office arrangement and their effects on the dynamic use of space and the personnel involved, the case study that follows is a very useful illustration. It is based upon the customer and material flow relationships discussed in Chap. 8. Queuing networks could also be used to assess alternative office arrangements much in the spirit of simulation.

11.5 Utility Company Office Case Study

This case study concerns the office layout and personnel planning for an urban utility company in the northeast. The company wished to move from an existing facility into a new one—a renovated historical building in the downtown area. All the material in Chap. 10 about the reuse of existing historic buildings was relevant to this problem. Along with the layouts, a detailed simulation model of the operation of the office alternatives was carried out in order to quantitatively evaluate them.

On these layouts, the cashiers and the credit and customer account servers are situated at appropriate locations. Customers will enter either via the Suffolk Street entrance or the parking lot. The arrival-rate and the service-time distributions were projected from data collected by the company. Customers will wait in queue if a server capable of performing the transaction they desire is not available. Cashiers will also serve drive-ups and will select the next customer from the queues on a first-come, first-served basis. After completing a transaction, the cashier will make a computer entry. If customers are backed up, then the cashiers will put off making computer entries until the queue is empty. The customers' average driving time in the parking lot and average walking time from one location to another will depend on the distance and the respective driving or walking speed. Drive-up customers will wait until a drive-up cashier is available.

11.5.1 *Alternative 1*

The first alternative was to locate a U-shaped counter in the center of the facility so that walk-ups can come from either the parking area or the street. One drive-up teller was situated in the parking lot for those customers wishing to not walk into the facility (Fig. 11.10). This alternative with the central customer service counter is conveniently situated in the center of the renovated facility, under a high ceiling.

11.5.2 *Alternative 2*

The second alternative was essentially the same as the first, except that there were two drive-up tellers in the parking lot to accommodate those customers wishing to pay from their vehicle (Fig. 11.11).

One real concern was the adequacy of the drive-up tellers to accommodate customers who drove to the facility. The simulation can also show the flow relationship between the customers entering the facility from their vehicles and those using the drive-up tellers. This is very revealing with the animated simulation models.



Fig. 11.10 Alternative 1

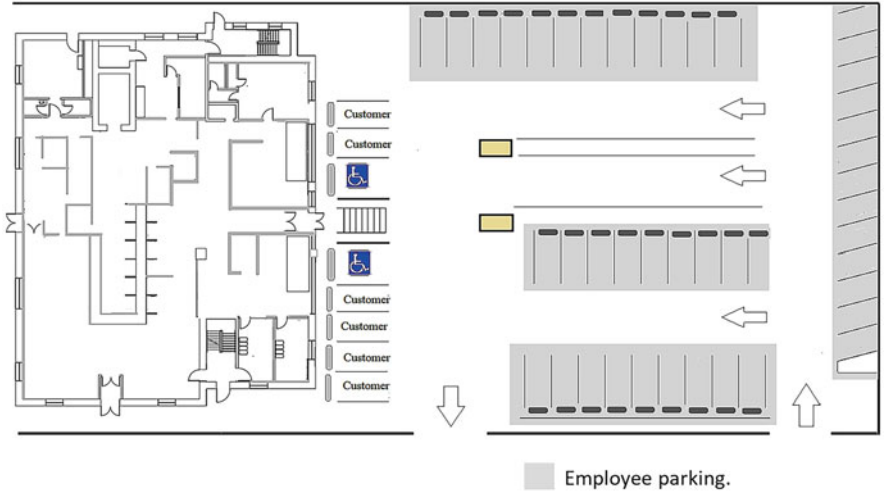


Fig. 11.11 Alternative 2

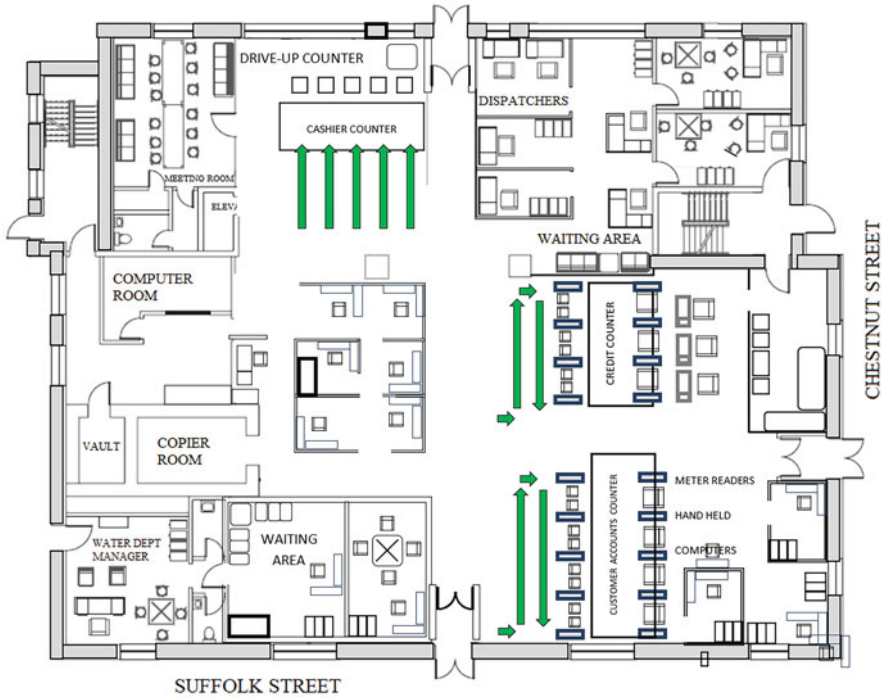


Fig. 11.12 Alternative 3

11.5.3 Alternative 3

After the first two alternatives were analyzed with the simulation model, the third alternative was developed in response to the excessive queuing times and the long paths taken by customers walking in from the parking areas and the street. It is a linear counter arrangement (Fig. 11.12).

11.5.4 Alternative 4

The fourth alternative is somewhat similar to the third, having a linear counter arrangement and two drive-up tellers (Fig. 11.13). It is interesting to note that the final alternative, which turned out to be the most desirable, was arrived at after analyzing the simulation results of the customer flow and the personnel workload processes.

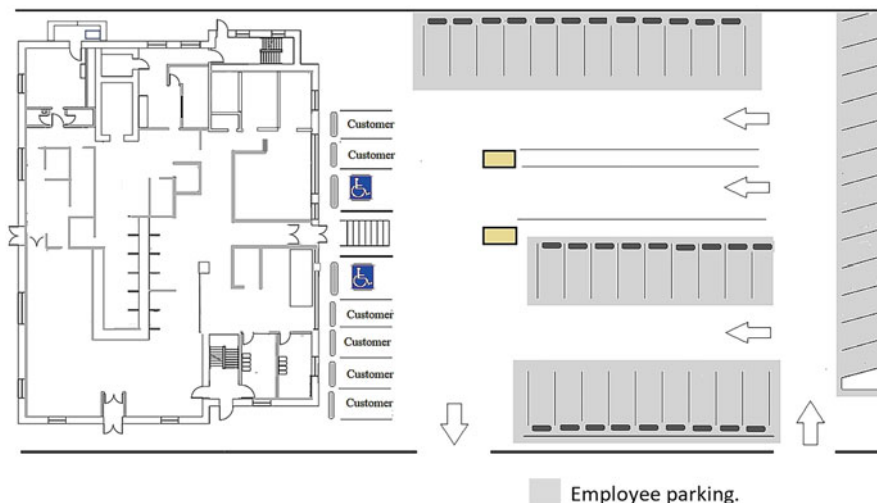


Fig. 11.13 Alternative 4

11.5.5 Analysis and Conclusions

The following arrival rates to the facility were assumed in the simulation model:

- Cashiers
 - 128 drive-ups/day, average time: 1 min 9 sec
 - 290 walk-ins/day, average time: 1 min 18 sec
- Credit
 - 12 walk-ins/day, average time: 6.42 min
 - 27 call-ins/day, average time: 3.78 min
- Customer Accounts
 - 36 walk-ins/day, average time: 4.30 min
 - 37 call-ins/day, average time: 2.54 min
- Water Department: 5% of 8100 customers/month travel to this department to pay their bills.

Further Assumptions Seventy percent of customers enter via the parking lot, 30% enter via the side street. If cashiers are backed up, computer entries are postponed until they are free. Cashiers operate on the policy of first-come, first-served when serving both walk-ins and drive-ups. In the Water Department, an additional cashier is available to handle customer traffic, and all cashiers handle all types of customers.

The simulation experiments results were analyzed over 30 independent days of operation. Simulation programs written in SIMAN and animations developed in

ARENA IV. The 95% lower (L) and upper (U) confidence intervals are shown in Table 11.1 surrounding the mean value (bold faced) obtained from the simulation experiments.

When one examines the results shown in Table 11.1, it is clear that alternative 4 is the best overall solution from a customer traffic and personnel operation viewpoint. This type of simulation analysis is beyond the scope of the factory project. If the students have access to a simulation tool, however, then it would be a useful means of showing different office arrangements and their capabilities.

11.6 Factory Design Project: Section IV. Personnel Requirements and Calculation of Product Unit Cost

The product has been developed (Section I of project), the overall manufacturing process to build the product has been integrated (Section II of project), and an initial factory layout with suitable material handling system has been designed (Section III of project). Section IV of the project now focuses on the type and quantity of personnel required, and the determination of the product cost per unit. Section V of the project will be devoted to the planning of office layouts.

Up to now the machine and material components of the direct cost of the project have been determined, as well as the material handling cost, which is generally viewed as an indirect cost. In order to calculate the product unit cost, a few assumptions are made. First, the total personnel cost (direct labor cost plus indirect personnel cost) is increased by 30% to account for fringe benefits. Additionally, the nonpersonnel costs are increased by 10% to account for costs not directly included, such as building costs, utility costs, and office equipment and supplies.

11.6.1 Conceptual Overview

Figure 11.14 outlines the types of personnel needed in the factory design project, along with their classification as either direct or indirect personnel.

Once the unit cost is determined, a profit margin is chosen to arrive at the selling price. The price must be realistic and competitive. If an unreasonably low or high price is determined, all relevant information should be reviewed and revised as deemed appropriate. Typical reasons for unrealistic prices include poor estimates of market demands, unreasonable standard times (which may affect the number of machines, amounts of materials, and personnel quantities), incorrect costs for production and material handling equipment, unrealistic costs for materials, as well as unreasonable salaries and wages.

Table 11.1 Simulation output results

Statistic	Alternative 1			Alternative 2			Alternative 3			Alternative 4		
	95% L	Mean	95% U	95% L	Mean	95% U	95% L	Mean	95% U	95% L	Mean	95% U
Average time in system												
Drive-ups	3.67	3.76	3.85	2.75	2.81	2.87	2.72	2.77	2.83	2.27	2.32	2.37
Parked	4.94	5.01	5.07	4.97	5.05	5.13	4.42	4.51	4.59	3.65	3.69	3.74
Walk-ins	3.07	3.16	3.24	3.41	3.52	3.64	3.16	3.26	3.36	2.42	2.48	2.55
Maximum time in system												
Drive-ups	9.30	10.10	10.80	6.80	7.56	8.31	6.68	7.38	8.08	5.59	6.22	6.85
Parked	10.70	11.10	11.50	10.80	11.40	11.90	10.10	10.60	11.10	9.58	10.10	10.70
Walk-ins	12.20	13.00	13.90	12.00	13.20	14.40	11.20	11.80	12.30	11.00	11.70	12.40
Avg. cashier utilization	0.81	0.82	0.83	0.81	0.82	0.84	0.81	0.82	0.83	0.56	0.57	0.58
Avg. credit utilization	0.19	0.20	0.22	0.18	0.19	0.21	0.18	0.19	0.21	0.18	0.19	0.20
Avg. cust. acct. utilization	0.13	0.14	0.14	0.12	0.13	0.14	0.13	0.14	0.14	0.12	0.13	0.14
Avg. # cust. in bldg.	2.41	2.47	2.54	2.51	2.59	2.68	2.22	2.30	2.37	1.73	1.78	1.83
Max. # cust. in bldg.	8.39	8.97	9.54	8.60	9.13	9.67	8.13	8.60	9.07	7.01	7.37	7.73
Max. cashier queue	4.70	5.20	5.70	4.55	5.10	5.65	5.05	5.57	6.08	2.86	3.17	3.48
Max. computer backup	17.40	20.60	23.70	18.80	22.90	27.00	18.60	22.50	26.30	5.95	6.80	7.65
Max. drive-up queue	4.93	5.30	5.67	4.02	4.30	4.58	3.91	4.17	4.43	3.58	3.87	4.16

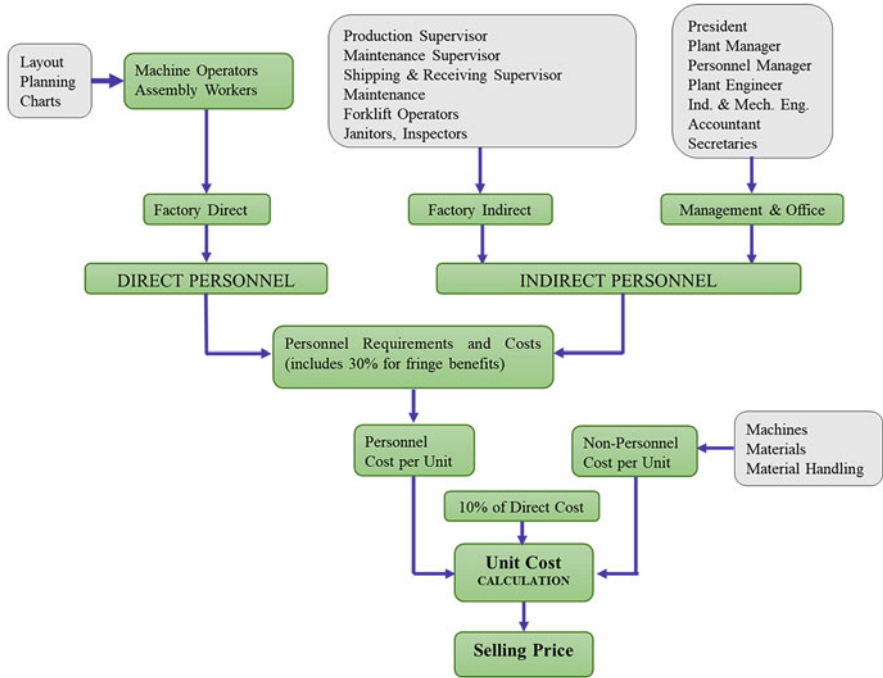


Fig. 11.14 Overall conceptual approach for Section IV

11.6.2 Organization of Report

The report for Section IV consists of an introduction providing the appropriate relevant background information and the purpose of the section. In addition, a separate section must address each objective of Section IV of the factory design project. The organization shown below is recommended:

1. Introduction

- Relevant background
- Scope of section
- Organization of report

2. Corporate Structure

- Introductory paragraphs
- Diagram showing the structure with well-identified positions and reporting relationships

3. Personnel Requirements and Costs

Factory direct personnel and costs
Factory indirect personnel and costs
Management personnel and costs
Appendix showing sample calculations

4. Unit Cost Calculation (Using the template described in Sect. 11.7)

Introductory paragraphs describing the scope of this section
Summary of computer results
Discussion of results

5. Personnel Facilities Requirements

Identify minimum requirements and costs
Appendix with relevant details on personnel facilities

6. Summary, Conclusions, and Recommendations

Figure 11.15 shows the checklist to be used for grading the report for Section IV of the project (Personnel Requirements and Costs).

11.6.3 Positions and Job Descriptions

The following positions are suggested for the factory design project. The positions selected will depend on the size and complexity of the project. Additionally, in some cases it may be necessary to consolidate more than one position on an individual employee. A summary of the functions defining the job content of each position is given.

Fabrication Team Leader

- Assists manufacturing supervisor with job assignments, work monitoring, and adjusting work flow to assure timely completion of customer orders.
- Assists in the training and continual development of team members.
- Helps to assure customer satisfaction by continually exceeding their expectations.
- Helps to create, follow, and monitor safety guidelines to ensure employee safety.
- Acts as a liaison between fabricators and/or assemblers and manufacturing supervisor.
- Directly reports to the manufacturing supervisor.
- Directly supervises fabrication team members (table saw, drill press, etc.)

Group No _____	Product Description	Grade _____	Date _____
Names 1. 2. 3. 4.			
Organization and style			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Introduction of report is lacking ☐ Technical English style can be improved ☐ Organization can be improved			
Corporate Structure			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Unrealistic structure for the factory designed in this project ☐ Insufficient description of content of report ☐ Neatness can be enhanced			
Personnel Requirements and Costs			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Missing source of salary data ☐ Personnel description is inadequate. ☐ Salaries are unrealistic. ☐ Fringe benefits are not included ☐ Sample cost calculations are missing (Appendix 1 of report)			
Unit Cost Calculation			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Introduction missing or incomplete ☐ Summary of results is lacking ☐ Unrealistic unit cost ☐ Discussion of results is missing or incomplete			
Personnel Facilities (Appendix 2 of Report)			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Not clear ☐ Minimum effort ☐ Incomplete			
Comments			

Fig. 11.15 Checklist for section IV

Fabricator

- Responsible for all machining operations and to manufacture a quality product.
- Works directly with the team leader and manufacturing supervisor to improve fabrication processes.
- Inspects all work at the end of each production process to ensure that the company's quality standard policy and procedures are met.
- Maintains a clean and orderly workstation to assure a safe environment.
- Reports directly to fabrication team leader and manufacturing supervisor.

Assembler

- Responsible for prioritizing, organizing, assembling, packing, moving, staging, and processing material within the packing department with regard to efficiency, quality, and safety.
- Packs and palletizes material for final shipment.
- Restocks assembly and packing workstations.
- Cleans and organizes assembly workstations.
- Reports directly to assembly team leader and manufacturing supervisor.

Maintenance Team Leader

- Assists production support personnel supervisor with job assignments, work monitoring, and adjustment of work flow in order to meet maintenance schedules.
- Assists in the training and continual development of team members.
- Helps to create, follow, and monitor guidelines resulting in employee safety.
- Helps to create, follow, and improve preventive maintenance procedures in order to increase efficiency.
- Directly reports to the production support personnel supervisor.
- Directly supervises maintenance technicians and custodians.

Custodian

- Primarily responsible for cleaning of the office areas and exterior grounds; may be called upon to help in production areas.
- Follows established cleaning procedures.
- Turns in daily task sheets.
- Disposes of refuse in a safe manner.
- Promotes a safe work environment by maintaining and encouraging a hazard-free workplace.
- Directly reports to the maintenance team leader and production support personnel supervisor.

Maintenance Technician

- Responsible for repairing inoperable machines as well as conducting preventive maintenance.
- Helps to act as a safety monitor in the facility by observing and removing potential hazards or pointing out potentially dangerous actions.
- Follows and assists in improving established preventive maintenance procedures.
- Directly reports to the maintenance team leader and production support personnel supervisor.

Shipping and Receiving Manager

- Supervises warehousing and shipping operations to assure timely delivery of customer orders.
- Supervises the ordering and receiving of raw materials and supplies.
- Maintains relationships and negotiates prices with suppliers.
- Oversees the work of clerks within the shipping and receiving departments.
- Directly reports to the production support personnel supervisor.
- Directly supervises the shipping and receiving clerks, and forklift operators.

Receiving Clerk

- Responsible for receiving, inspecting, and recording all purchased parts and material, as well as pulling stock from warehouse for internal processing.
- Checks bill of materials from incoming shipments to ensure order accuracy.
- Assists truck drivers in unloading trucks, using forklift as necessary.
- Delivers incoming materials to proper locations in warehouse.
- Follows all applicable safety guidelines.
- Directly reports to shipping and receiving manager.

Shipping Clerk

- Supervises the warehousing and shipping activities of the company's product to assure timely delivery of customer orders.
- Assures daily on-time delivery, pickup, and movement of product orders.
- Helps to prioritize daily tasks.
- Directly reports to shipping and receiving manager.

Forklift Operator

- Responsible for helping to load and unload trucks as well as retrieving raw materials from the warehouse to fabrication departments and properly storing finished goods.
- Assists drivers in the loading and unloading of trucks when available.
- Directly reports to shipping and receiving manager.

Sales and Marketing Manager

- Works to develop and implement strategic marketing and sales plans to achieve corporate sales objectives.
- Develops sales forecasts and analyzes the market to determine customer needs and identifies new market opportunities.
- Analyzes and controls expenditures of the department to conform to budgetary requirements.
- Approves and implements advertising campaigns and sales promotion activities.
- Reports directly to the President and supervises the Marketing Representative and the Sales Representative.

Marketing Representative

- Implements strategic marketing plans.
- Develops advertising campaigns.
- Analyzes the market to evaluate customer needs.
- Recommends price schedules and discount rates.
- Reports to the Sales and Marketing Manager.

Sales Representative

- Implements sales plans.
- Develops sales promotion activities.
- Uses sales historical data to evaluate both the effectiveness of sales and the degree to which market penetration goals are being met.
- Prepares periodic sales report showing sales volume, potential sales, and areas of proposed expansion.
- Reports to the Sales and Marketing Manager.

Finance Manager

- Directs the organization's financial planning.
- Reviews all requests for capital expenditures.
- Develops plans and strategies for the direction and administration of company's financial and administrative activities.
- Obtains objectives based on corporate goals and policies.
- Oversees compliance to appropriate federal, state, and other various policies regarding withholdings and income.
- Reports directly to the President and supervises the Payroll Accountant and the Accounts Payable/Receivable Clerk.

Payroll Accountant

- Compiles and maintains personnel records.
- Prepares weekly/monthly payroll, administers benefits, and compiles payroll data to process payments to vendors.
- Reviews wages computed and corrects errors to ensure accuracy of payroll.

- Maintains general payroll information in database system (i.e., names, addresses, direct deposit).
- Follows local, state, and federal policies regarding withholdings and income tax.
- Reports to the Finance Manager.

Accounts Payable/Receivable Clerk

- Selects invoices to be paid and prints checks.
- Attaches supporting documentation and forwards for appropriate signature(s).
- Receives checks from authorized signer(s) and mails checks to vendors.
- Reports to the Finance Manager.

Information Technology Manager

- Monitors computer and software resources in order to encourage optimum usage.
- Maintains up-to-date equipment for the plant.
- Stays knowledgeable about new advances that can help company achieve goals and run more efficiently.
- Reports directly to the President and supervises the Technical Support Technician and the Database Support/Trainer.

Technical Support Technician

- Provides technical support throughout the plant.
- Assists all computer users with basic computing troubles.
- Updates/upgrades computing systems when needed.
- Reports to the Information Technology Manager.

Database Support/Trainer

- Helps to create and maintain databases.
- Backs up online databases.
- Provides training for new software throughout the plant.
- Reports to the Information Technology Manager.

11.7 Unit Cost Calculation Template

The excel UNIT COST TEMPLATE.xlsx program is especially suitable to assist with the calculation of the unit cost for the factory layout project. The excel program was designed by Madelynn Allison and Payton Garland in November, 2017 [2]. The template consists of a *master sheet*, twelve *part sheets*, and the *unit cost calculation sheet*. Each of these sheets is described below. The steps of the program are illustrated with a product consisting of Part 1 to be manufactured and a second part from an outside vendor.

PART ID	OPERATION	MACH 1	MACH 2	...	MACH 15	Mat. No.	Mat. Quant.	Weeks/Year	Days/Week	Hours/Day
VOLUME		12000	6000					52	5	8
1	1					1	10			
18300	2					2	7			
	3					2	3			
	4									
	5									
2	6									
	7									
	8									
	9									
	10									
3	11									
	12									
	13									
	14									
	15									
	16									

Material	Cost
1	12
2	23
3	
4	
10	

Machine	Factor	Setup
1	0.97	0.12
2	0.97	0.12
3		
4		
15		

Number of units of product per year= 18300

Fig. 11.16 Illustration of master sheet

Master Sheet

This sheet accepts up to twelve parts and up to fifteen machines, with a maximum of five operations performed on each part. For each part the user provides an ID, volume per year, and for each operation the corresponding standard time, type of material, material cost, and machine used, along with the setup time for each machine. An illustration of the master sheet is shown in Fig. 11.16 for Part 1 with a production volume set equal to 18,300 units.

- The following instructions are provided for the generation of the master sheet:
1. Fill in the Part ID and Part Volume on the first column on the left of the sheet. For every operation 1–5 that is performed of a part fill in the standard time (in hours) on the second column of the sheet. Leave blank spaces corresponding to those operations not performed.
 2. Under the utilized machines, in the yellow boxes on top of the sheet, type the cost of the machines.
 3. On the two columns (with white background) immediately after the 15 machine columns, fill the Material Number (type) and the Quantity of Material used in the corresponding operations.
 4. At the right side of the top of sheet the default values for weeks per year, days/week, and hours/day are shown. These values can be changed if a different work schedule is used.
 5. At the right side of the sheet and below the work schedule, there are the Material Type and Material Cost columns. Fill in the corresponding costs in the column with white background.
 6. Fill out the availability factor for each of the machines and the set-up time in hours per day.

Weeks/yr	Days/Week	Hours/Day		Units/yr	No. Operation	F.T. Operators	Mach. Type	Mat. Type	PART 1	
52	5	8		18,300	3	7.8	2	3		

OPERATION	Mach. Type	Mach. Cost	Scrap %	UNITS/yr	St. Time (H)	SETUP/Day (H)	Avail. Factor.	Mat. Type	Mat. Cost	Quant.
1	1	12000	0.1	25103	0.3	0.12	0.97	1	12	10
2	2	6000	0.1	22593	0.083	0.12	0.97	2	23	7
3	1	12000	0.1	20333	0.3	0.12	0.97	2	23	3
4	0	0		18300						
5	0	0								
				18,300						

OPERATION	Mach. Type	HOURS/yr	Frac. Mach.	Total Mat. Cost
1	1	7530.9	3.8	45473.1
2	2	1875.2	0.9	5661.4
3	1	6100.0	3.1	36833.2
4	0	0.0	0.0	0.0
5	0	0	0.0	0.0
			7.8	87967.8
			Mach. Cost/yr	5278.1

T=15 yr,SV=10%

Operation	Mat. Type	Mat. Used/yr	Mat. Cost/yr
1	1	251028.8	3012345.7
2	2	158148.1	3637407.4
3	2	61000.0	1403000.0
4	0	0.0	
5	0	0.0	
		Material Cost/yr	8052753.1

Fig. 11.17 Illustration of part sheet

Parts Sheets

The *part sheets* are linked to the *master sheet*. Once the master sheet is completed the part sheets are automatically generated. Each part sheet calculates annual costs of materials and machines. These along with the direct labor cost constitute the *direct cost* per year for the corresponding part. Fig. 11.17 shows and illustration of the part sheet.

Unit Cost Calculation Sheet

The template shows entries with white background to be filled with the following data provided by the user. All entries with colored background are filled in automatically by the excel UNIT COST TEMPLATE.xlsx program.

1. Cost/unit for bought parts to be assembled with the manufactured parts.
2. Annual quantity for bought parts. After this, the cost/year for bought parts fills in automatically.
3. Annual salary for factory operators.
4. Annual salary for management personnel.
5. Annual salary for factory indirect labor.
6. Material handling cost/year.
7. Office and warehouse areas used.
8. Cost/unit for office and warehouse areas.
9. Direct Cost fraction added to calculation of unit cost (0.10 is suggested). The unit cost is calculated once all the above information is provided.

In the calculation of the unit cost we assume benefits equal to 30% of the direct cost, but this can be changed if necessary. Figure 11.18 shows an illustration of the unit cost calculation sheet. As shown in the figure, the data entering process consists of six simple steps.

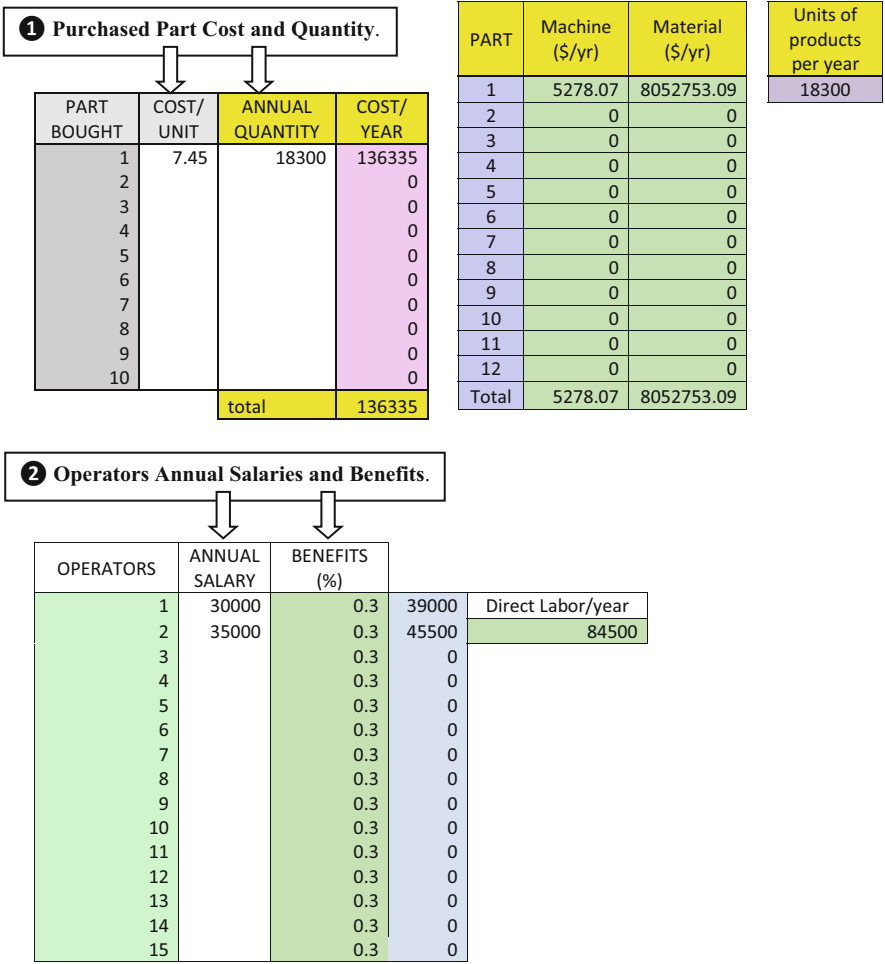


Fig. 11.18 Illustration of cost calculation sheet

③ Salary for Management Personnel.				
↓				
MANAGEMENT PERSONNEL	ANNUAL SALARY	BENEFITS (%)		Management (\$/yr.)
1	35000	0.3	45500	87100
2	32000	0.3	41600	
3		0.3	0	
4		0.3	0	
5		0.3	0	
6		0.3	0	
7		0.3	0	
8		0.3	0	
9		0.3	0	
10		0.3	0	

④ Salary for Indirect Labor.				
↓				
INDIRECT LABOR	ANNUAL SALARY	BENEFITS (%)		Indirect Labor (\$/yr.)
1	35000	0.3	45500	93600
2	37000	0.3	48100	
3		0.3	0	
4		0.3	0	
5		0.3	0	
6		0.3	0	
7		0.3	0	
8		0.3	0	
9		0.3	0	
10		0.3	0	
			Labor & Personnel \$/yr.	265200

Fig. 11.18 (continued)

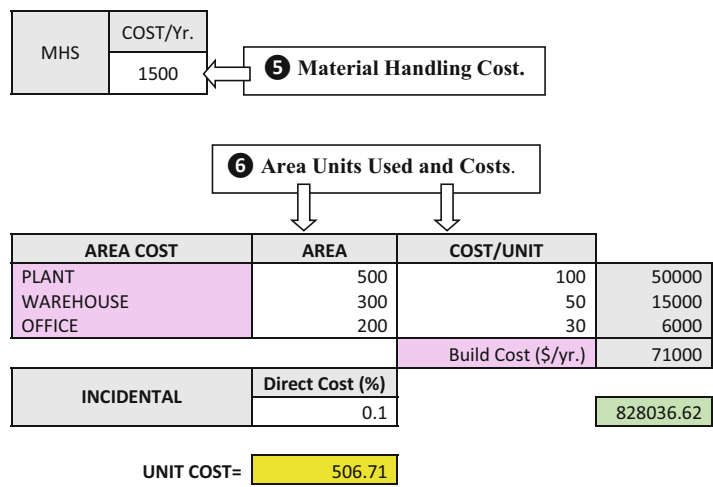


Fig. 11.18 (continued)

11.8 Factory Design Project: Section V. Office Layout Planning

This section outlines the steps followed for the office layout planning of a company manufacturing the revolving desktop organizer chosen as the product for the factory layout design project. Although a single product will be considered, several products can be assumed to be manufactured without a substantial modification of these steps. Essentially, the section includes: (a) view of overall conceptual approach; (b) organization of report; (c) description of the procedure to be followed; and (d) checklist to grade the report prepared by each team.

11.8.1 Conceptual Approach

Figure 11.19 summarizes the procedure to be followed in Sect. V. In Sect. IV it was decided what kind of personnel and how many of each kind are needed. The next step is the organization of the personnel into offices using the concept of functional similarity, and the design of a closeness relationship chart for these offices. After this, typical layouts are selected for the offices; here it is possible to have a mix of standard arrangements for the entire office layout, or use one arrangement only.

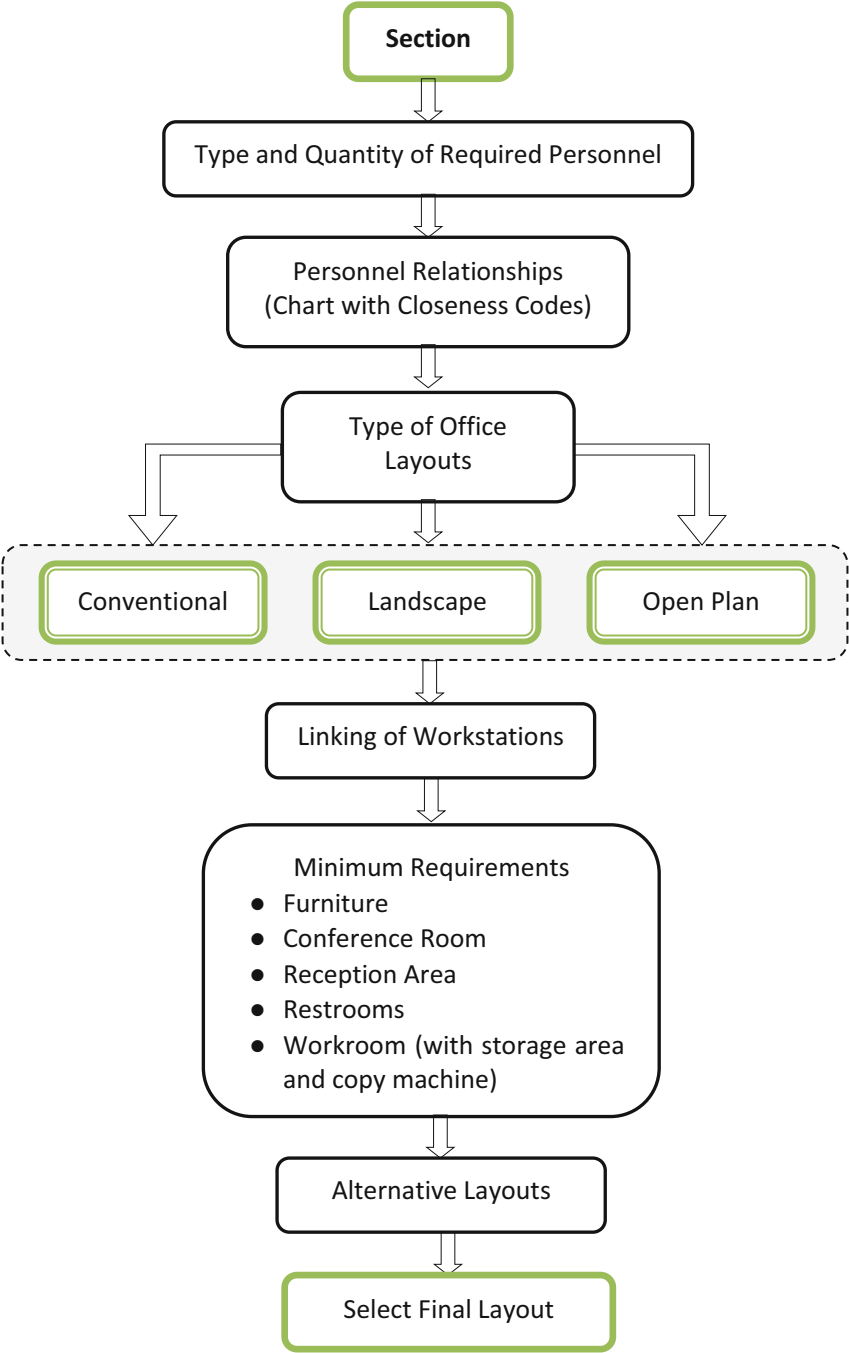


Fig. 11.19 Conceptual approach for Section V

Workstations within each office are linked following a pattern that would enhance operational efficiency; typical patterns to do this include [9]:

- Zigzag
- Spine
- Pinwheel
- Side-to-side/back-to-back

The minimal requirements for the office layout are identified next, keeping in mind the facilities needed for an effective and efficient operation, the concept of flexibility, and the cost of the facility and its operation. Total space required is determined for each office. Using a computerized procedure, such as FLAP, CRAFT, GMAFLAD, or STEP, each member of the team determines one alternative layout, and then, after evaluation of these alternatives, the final layout is selected, most likely having features from each alternative.

When a computerized procedure requires a from-to chart it can be obtained from the relationship chart by consistently assigning a number of trips to each closeness code (for example, A = 10, E = 7, I = 5, O = 2 and U = 0).

11.8.2 Report Organization

The report for Section V must include as a minimum the following sections.

1. Introduction

Relevant background
Scope of section
Organization of report

2. Personnel Relationships

Introductory paragraphs
Chart with closeness codes FLAP, CRAFT, GMAFLAD, or STEP runs with discussions

3. Office Layout

Minimal requirements
Alternatives (2–3 sketches)
Selected layout (drawing)
Discussion

4. Summary, Conclusion, and Recommendations.

Figure 11.20 shows the checklist used when grading the report for Section V.

Group No _____	Product Description	Grade _____	Date _____
Names 1. 2. 3. 4.			
Organization and style			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Introduction of report is lacking ☐ Technical English style can be improved ☐ Organization can be improved			
Personnel Relationships			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Unrealistic structure for the factory designed in this project ☐ Insufficient description of content of report ☐ Closeness ranks and selection order are missing ☐ Computer input/output not shown			
Office Layout			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Inadequate minimum requirements ☐ Alternative layouts show little creativity and weak effort ☐ Discussion of alternative layouts is not included ☐ Selection of final layout is not documented			
Selected Office Layout Drawing			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Alternative layout sketches are missing ☐ Drawing of selected layout is incomplete ☐ Neatness can be enhanced			
Comments			

Fig. 11.20 Checklist for grading the report for Section V

11.8.3 Selected Office Layout

Figure 11.21 [5] shows the 102.5' × 71' office layout selected for the factory layout design project which manufactures the revolving desktop organizer described in Sect. 3.2. The following areas are included (dimensions are shown after the position title):

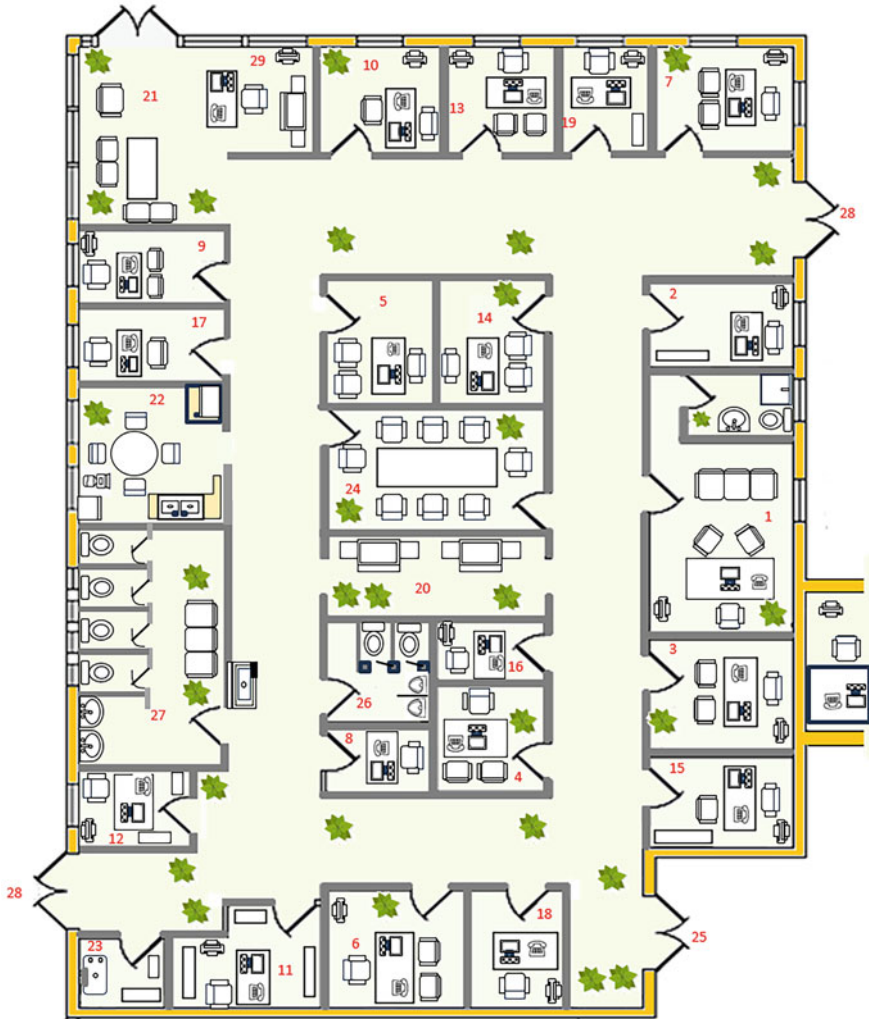


Fig. 11.21 Selected office layout: Drawn by Jason W. Clepper [5]

Offices

1. President, $25' \times 13'$
2. Executive Assistant, $13' \times 8'$
3. Industrial Engineer and Plant Manager, $13' \times 11'$
4. Human Resources Manager, $11' \times 10'$
5. Finance Manager, $11' \times 10'$
6. IT Manager, $12' \times 11'$
7. Sales and Marketing Manager, $13' \times 11'$
8. Human Resources Personnel, $10' \times 10'$

9. Payroll Accountant, $13' \times 8'$
10. Accounts Payable/Receivable, $11' \times 10'$
11. Technical Support & Training, $9' \times 8'$
12. Database Support, $13' \times 8'$
13. Marketing Representative, $11' \times 10'$
14. Sales Representative, $11' \times 10'$
15. Plant Manager Assistant, $13' \times 8'$
16. Human Resources Manager Assistant, $10' \times 6'$
17. Finance Manager Assistant, $13' \times 8'$
18. IT Manager Assistant, $11' \times 8'$
19. Sales and Marketing Manager Assistant, $10' \times 8'$

Special Areas

20. Work Room, $20' \times 10'$
21. Reception Area, $17' \times 13'$
22. Break Room, $27' \times 13'$
23. Janitor Closet, $13' \times 7'$
24. Conference Room, $20' \times 12'$
25. Plant Entrance, $12'$
26. Men's Restroom, $10' \times 7'$
27. Women's Restroom, $13' \times 9'$
28. Office Entrance/Exit, $7'$
29. Receptionist Work area, $11' \times 8'$

Legends

	Refrigerator		Sink		Shower		Water cooler
	Laser jet printer		Couch		Urinal		Water fountain
	CPU		Keyboard		Desk		Plant
	Monitor		Toilet		Executive chair		Microwave
	Telephone		Cabinet		Copy machine		

11.9 Summary and Conclusions

This chapter has developed the principles for the calculation of personnel requirements and office layout planning, especially as they relate to Sections IV and V of the factory layout design project. It has discussed the history as well as the general principles related to the spatial planning of the offices, including both spatial and equipment requirements.

Also presented was a case study of a renovated historical building for an office layout, including simulation of the customer flow in the office. This case study

illustrates the importance of the dynamic evaluation of the layouts with analytical and simulation models, which is very revealing and critical to the office layout success. This chapter concluded with a detailed description of the office planning requirements for the factory project.

An excel program to calculate the unit cost of the project was presented and illustrated in order to provide the students with a comprehensive and easy-to-use computerized procedure to achieve this essential activity in their project. To those who want to expand their knowledge on the general topic of office planning and design, we recommend the work by Harris, Engen and Fitch [7], Kleeman [8], Leopold [10], Pulgram and Stonis [11], Sule [13], and Tweedy [15].

11.10 Exercises

- 11.1 (a) What are the three most used types of office layouts? (b) Indicate the underlying concept in each case. (c) Mention distinctive characteristics of each layout. (d) Which type of layout is most appropriate for teamwork and telecommunications?
- 11.2 Discuss the recommended criteria to judge the overall worth of an office layout. What is the essential purpose of each criterion?
- 11.3 Indicate which special areas should be included in an office layout. Provide general guidelines on location and size, depending on number of employees.
- 11.4 What facilities are typically included in an effective plan of personnel requirements?
- 11.5 Explain the fundamental differences between planning office layouts and planning production departmental layouts. Provide examples to illustrate these differences.
- 11.6 Discuss several ways to provide visual privacy in office layouts. Consider the three best-known layout types separately.
- 11.7 (a) Discuss the implications of the following objectives in office layout planning: Criteria for minimizing communication costs and maximizing employee productivity. (b) Discuss the important factors considered in planning reception areas.
- 11.8 If we are interested in using a construction procedure for layout office planning, what are the fundamental steps to be followed? If we want to use a construction computer program, which one would you recommend?
- 11.9 The open-plan layout is particularly effective when integrated with modular furniture. In this case, what are some possible benefits that can be derived from this strategy.
- 11.10 Should the office activities within a factory be centralized or else subdivided throughout the production facility? Could there be duplicate offices allocated on the plant floor and the main office for certain personnel? What advantages and disadvantages would this duplication present?
- 11.11 What is office landscaping? What are its pros and cons?

- 11.12 In your own words, what have been the most significant effects of computers on the office organization and layout of the offices?
- 11.13 Discuss each of the most important influences in developing office layouts.
- 11.14 What are the separate dimensions that should be recognized in the planning and design of office layouts and workspace? Discuss each dimension, providing illustrative examples.
- 11.15 Discuss the typical forces in today's office world that are driving the rethinking of office planning and design.
- 11.16 Describe in some detail the main steps of Sect. V of the design project, addressing office layout planning.
- 11.17 Assume the following closeness relationships for a business facility consisting of five offices. Propose a layout for a rectangular office area, assuming area requirements equal to 30, 20, 25, 40, and 30 for offices 1, 2, 3, 4 and 5, respectively. Find the score of the layout using $A = 8$, $E = 4$, $I = 2$, $O = 1$, $U = 0$, $X = -8$.

$$\begin{array}{c}
 A_1 \quad A_2 \quad A_3 \quad A_4 \quad A_5 \\
 \begin{array}{c} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \end{array} \left[\begin{array}{ccccc}
 - & I & U & O & O \\
 & - & U & O & E \\
 & & - & A & X \\
 & & & - & A \\
 & & & & - \\
 & & & & & -
 \end{array} \right]
 \end{array}$$

- 11.18 For the following office activities, develop a planar graph decomposition and then lay out the office by hand to get a feasible solution within a rectangular perimeter boundary.

A_1 Reception and Waiting (RW) (1000).

A_2 Clerical (CL) (600).

A_3 Accounting (AC) (500).

A_4 Engineering (EN) (500).

A_5 Executive Offices (EO) (1000).

A_6 Conference (CO) (400).

A_7 Copying and Storage (CS) (200).

$$\begin{array}{c}
 A_1 \quad A_2 \quad A_3 \quad A_4 \quad A_5 \quad A_6 \quad A_7 \\
 \begin{array}{c} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \\ A_7 \end{array} \left[\begin{array}{ccccccc}
 - & A & U & U & U & I & O \\
 & - & E & I & U & I & I \\
 & & - & I & I & U & I \\
 & & & - & I & I & U \\
 & & & & - & E & U \\
 & & & & & - & U \\
 & & & & & & -
 \end{array} \right]
 \end{array}$$

- 11.19 Generate an organization chart of the office personnel examined in Exercise 11.18. Compare your planar graph decomposition with the organization chart. Describe the alternative layout it would generate, and compare it with yours.
- 11.20 Use the program STEP to generate a planar graph solution, and compare it with the planar graph solution you generated by hand in Exercise 11.18.
- 11.21 Use the program FLAP and generate a layout solution with the data in Exercise 11.18. Compare the solution with FLAP and the one you generated.
- 11.22 Use the program GMAFLAD and generate a layout solution with the data in Exercise 11.18. Compare the solution with GMAFLAD and the one you generated.

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Chapter 12

Final Synthesis



12.1 Introduction

At this stage of the factory project, one should begin to assemble all the production, manufacturing, material handling, office, and personnel elements previously designed into an organized whole. The final layout of the factory project is required. This is a demanding but ultimately most rewarding task. Figure 12.1 displays the accumulation of activities (Sections I–V) resulting in Section VI. Not only will we specify the requirements of Section VI, but also we will give an overview of how all the professionals in the facility project work together to produce the final building result. We shall also discuss some of the important building systems integration activities in the factory project along with the use of existing buildings as a possible building envelope.

12.1.1 Overview of Chapter

In the first section of this chapter, we address the role of the Industrial Engineer (IE) in the building process and the notion that the facility whether it be new or remodeled construction will be a leased facility. In Sect. 12.2, we address the issue of new vs. remodeled construction. This is an important concept faced by anyone involved in facilities planning and is an important cornerstone of this last chapter. In Sect. 12.3, we describe the major concerns of structural engineering for the facility and the various components of the building system: (1) roofs and floors; (2) walls and columns; and (3) code considerations. Section 12.4 deals with the systems of the building: heating, ventilating, and air-conditioning (HVAC); electrical/lighting; plumbing; and vertical transportation. Section 12.5 deals with the issue of functional adaptation of remodeled facilities for new uses. Section 12.6 deals with the important issue of building economics. Finally, Section 12.7 deals with

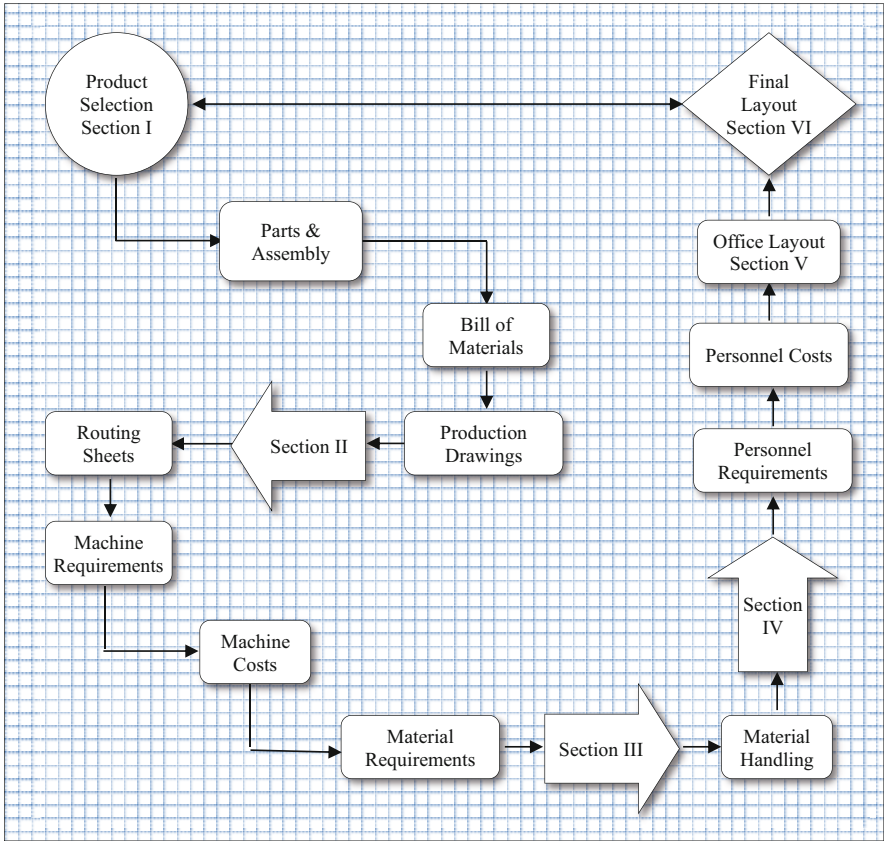


Fig. 12.1 Factory project final Section VI

Section VI of the factory project and the final requirements for putting together the final section of the report and suggestions for presenting the solution and grading it. To those who want to expand their knowledge on this topic, we would like to recommend, in addition to the bibliographical references directly related to our discussion, the work by Brubaker and Hutchison [2], Sule [5], and Swartz [6].

12.1.2 Professions Involved in Facilities Planning

While the industrial engineer is to a great extension the determiner of the factory layout, there are numerous other outside experts whose expertise must be involved in realizing the final factory building. These include the architect, structural engineer, mechanical and electrical engineers, and various other disciplines associated with the building industry. Figure 12.2 illustrates a possible architectural

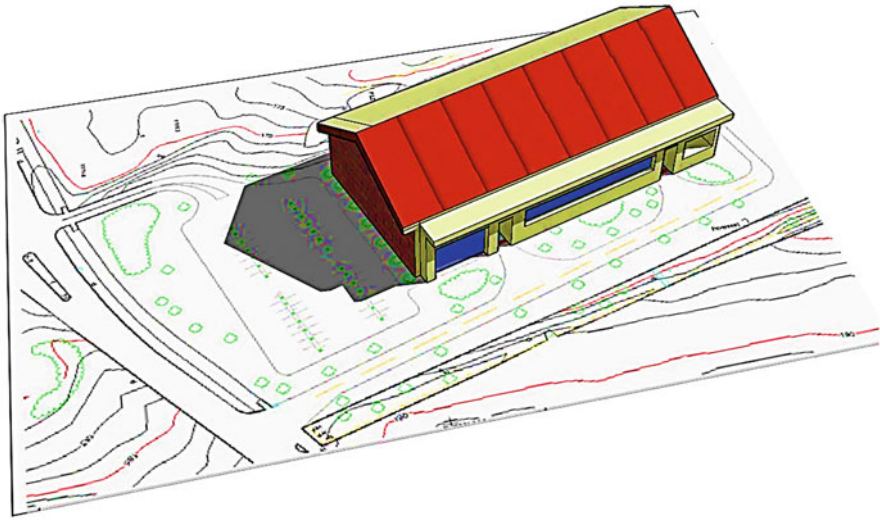


Fig. 12.2 Factory project architectural realization

realization of a factory project and its site plan that is based on the project illustrated in Chaps. 8 and 10.

The architect is necessary for the overall design of the facility and the coordination of the engineering and construction trades in realizing the entire project. The architect is responsible for linking the client and the engineering team, gathering of the zoning and building code and other local legal permits, coordinating the building trades, overall construction process, and almost everything else related to the overall building design process.

The structural engineer is responsible for the roof structure, internal columnar framework, and flooring and foundation system. The mechanical engineer is responsible for the heating, ventilating, and air-conditioning and often the plumbing and sanitary systems. The electrical engineers are responsible for the power, lighting, equipment, and elevator systems, and electrical needs of the facility. All personnel just mentioned need to be licensed professionals in the state in which the construction is being carried out.

12.1.3 Leased Facility for Project

Given the nature of the factory project, which is the essential unifying vehicle in this textbook, we take the viewpoint that the facility will be a leased facility, rather than a single client-owner, newly constructed facility.

Whether this leased facility is a new (pre-engineered or prefabricated) structure or an existing one, we want the industrial engineer to realize that he or she is not

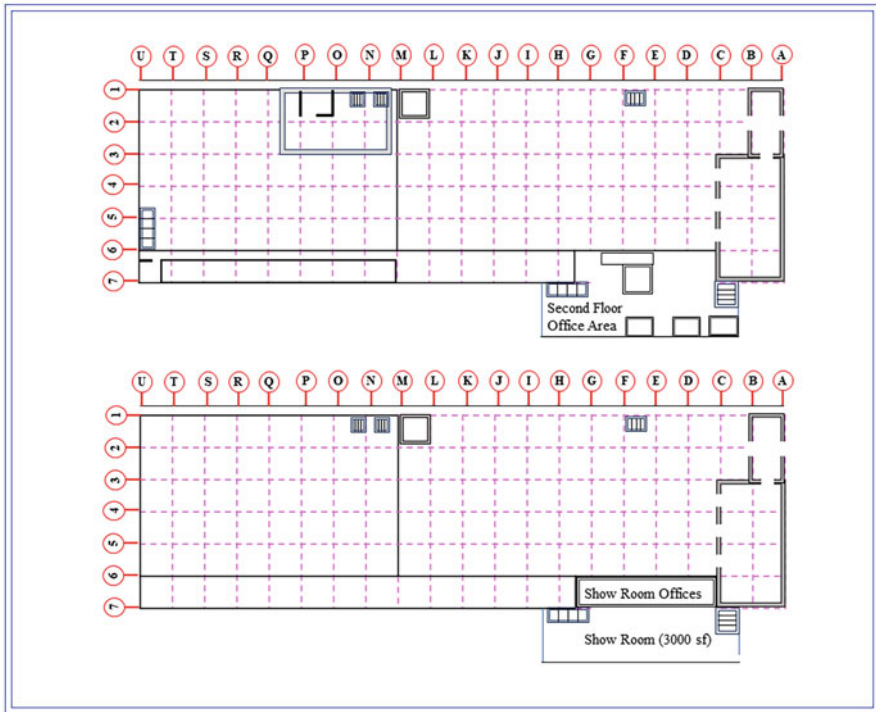


Fig. 12.3 Factory project building shell

responsible for the entire building design, but must respect the expertise of the other professions involved in the building construction process. It is extremely important, however, that the IE be involved in the integrative design process, because the IE knows the true function of the plant and processes, and there are critical dimension issues (column locations, ceiling heights, warehouse design, and rack dimensions, workplace ergonomics, and so on) that link the IE's role with that of the other players in the construction game. Thus, we will not go into great detail about HVAC design, lighting design, or plumbing design, but address the general planning and design issues surrounding these systems, which the IE should know and respect.

Figure 12.3 is a factory layout developed by one of the authors. It is a new plant layout for an existing operation moved from an older facility. It represents a two-story building where manufacturing is to be located on the lower floor and on the mezzanine part of the second floor, with a showroom for the products on the first floor and the offices on the second floor. The building has a 25-foot structural grid system (columns are spaced 25 feet on center), which is fairly typical for factory buildings.

We encourage the consideration of existing structures for the factory project, since upon graduation most IEs involved in facility layout planning do so in redesigning existing facilities. Even new additions or expansions are often coupled with existing buildings. The accommodation of new manufacturing products in an

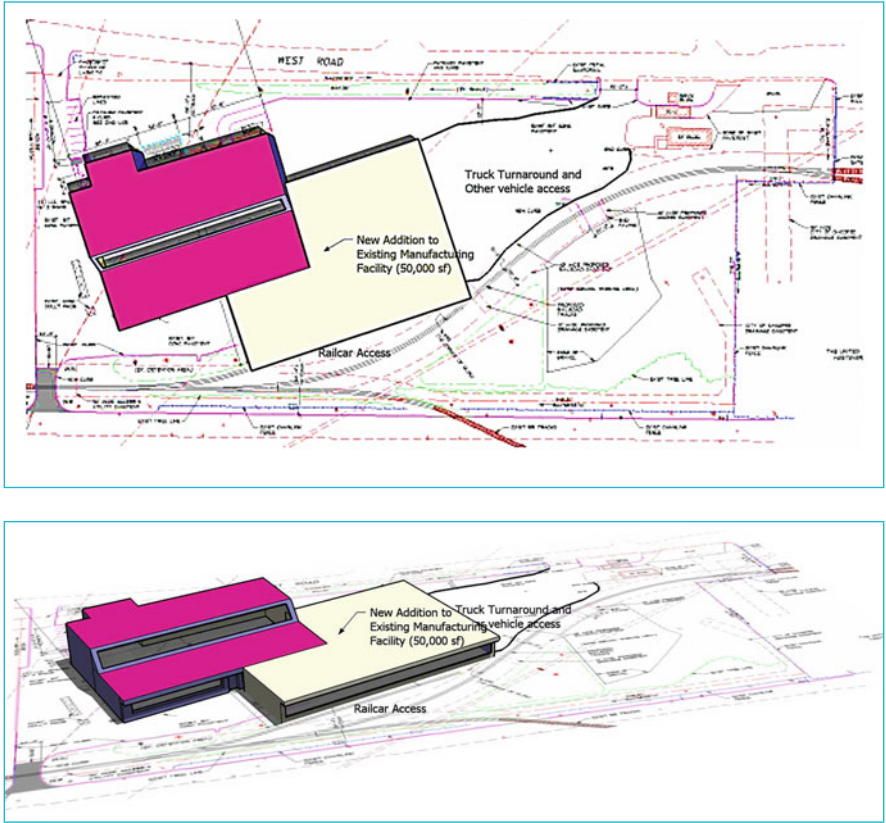


Fig. 12.4 Typical existing building plus addition factory issues

existing building frequently results in physical changes to existing facilities, as is illustrated in the drawings in Fig. 12.4.

12.2 New Versus Existing Buildings

One major issue in facility planning for manufacturing or service sector facilities is whether to renovate an existing facility or to construct a new one. The question is central to planning facilities for all types of uses. Among the reasons for the timely emergence of this issue, the following are probably the most significant: *unforeseen growth in demand for new or existing products, increased numbers of employees or equipment and resource changes, the ever-present decay in building materials and systems over time, and the heightened limitation of energy and fiscal resources for new construction.*

Table 12.1 Attributes/Criteria for evaluating existing buildings

I. STRUCTURAL Structural indicators Roofing Floors Walls Code considerations	IV. FINANCIAL Site and acquisition costs Construction costs Demolition costs Structural system Architectural Mechanical systems Administration
II. MECHANICAL/ELECTRICAL Heating, ventilation, air-conditioning Electrical/lighting Plumbing Fire extinguishing systems Vertical transportation	V. CULTURAL Historical Historic events Historic persons Community interests
III. FUNCTIONAL Adaptability Flexibility	Architectural Design conception Architectural expression Engineering Urban design Architect Age

There are numerous advantages to reusing existing buildings. Existing buildings are usually structurally sound, finely crafted, rely more on the use of natural light and ventilation, and normally harbor a degree of variety and interest far beyond most modern building designs. Continued use of these facilities can be a cost-effective means of conserving fiscal resources and, at the same time, maintaining a continuity in the historical and cultural values of the local community.

A major disadvantage of an existing facility is that the functions of the plant layout must be fitted to the building, rather than the building being fitted to the functions of the plant layout. This will often cause difficult logistical and practical space accommodation problems.

Contrary to what may be expressed by local historical societies, not everything that is old is good and will work well, and not everything that is new is necessarily bad. However, it is equally true that progress does not have to go hand-in-hand with destruction. Life-cycle cost equations cannot put a dollar sign on age, craftsmanship, or style. Thus, a delicate balance must be struck so that all sides can be heard, all avenues explored, and all criteria considered before the decision is made to hire a wrecking crew or a preservation architect.

Several performance criteria entering into the renovation decision-making process are displayed in Table 12.1. The table includes most of the significant criteria normally relevant to this problem. In the discussion that follows, each criterion is explained as to its importance and its relationship to the others. Procedures for evaluating alternatives related to existing vs. new construction have been discussed in Chap. 10. Finally, in the Appendix to this chapter (Appendix 12.1), a collection of detailed renovation planning issues is assembled to assist clients, professionals, and students in assessing how this restoration issue may be best resolved.

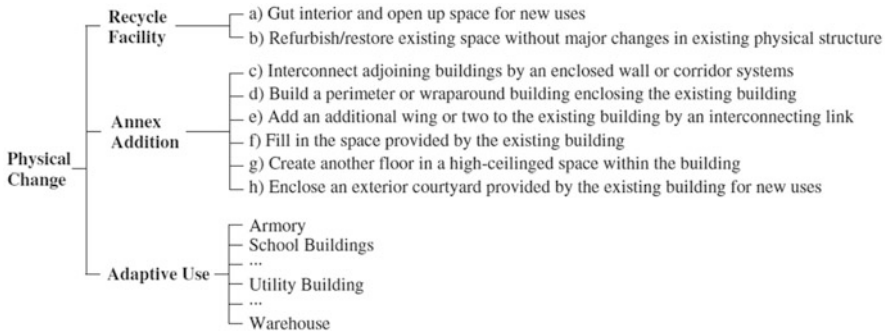


Fig. 12.5 Decision tree

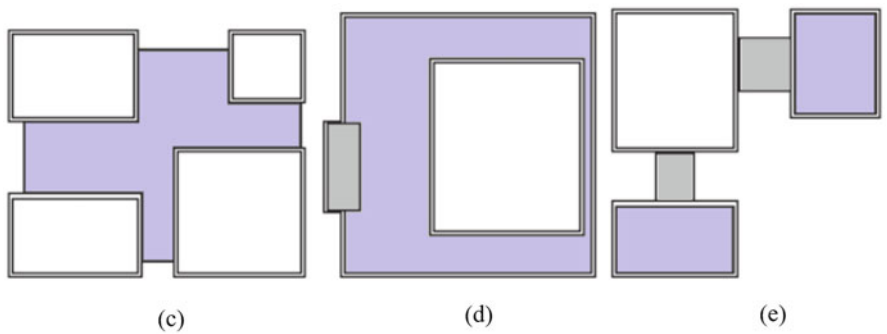


Fig. 12.6 Annex alternatives: (c) interconnect; (d) perimeter; (e) addition

Finally, it is important to realize that there are numerous ways in which additional space may be added to an existing, old, or historic structures to accommodate further growth and expansion needs. The physical alternatives are displayed in Fig. 12.5. How the existing facility and its possible expansion interacts with the site plan (Chap. 10) is important here. There are basically three alternative branches of this decision tree.

The first branch represents taking the existing facility and refurbishing its interior. This first alternative may be premised on freeing existing spaces for facility uses and perhaps moving nonrelated building activities outside the facility (see Fig. 12.6).

The second branch of alternatives incorporates a variety of ways of physically appending new space to an existing facility (see Fig. 12.7).

Finally, the third branch represents the adaptive use of nonmanufacturing buildings for manufacturing or service sector use. Many existing schools and institutional or governmental facilities can be appropriately modified to be reused for a manufacturing operation. However, one should exercise some caution here, since what may appear to be an easy reuse can contain hidden constraints and infeasibilities that make the project unsuitable.

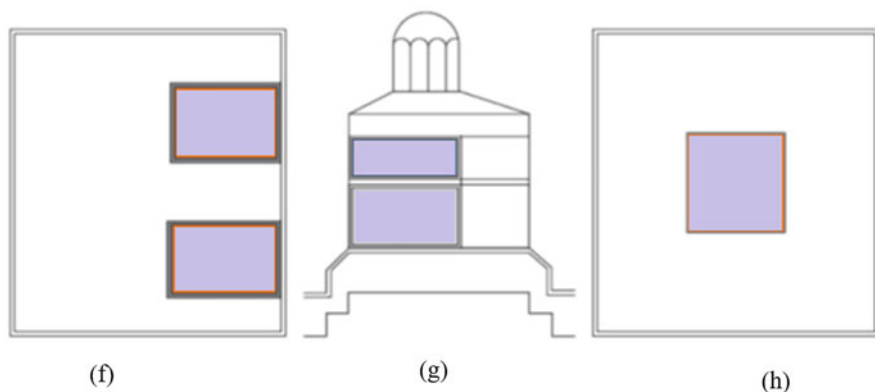


Fig. 12.7 Annex alternatives: **(f)** fill in; **(g)** add floor in large space; **(h)** enclose courtyard

Besides these physical alternatives, operational and technological changes can also improve space utilization and building efficiency so that major physical changes are not necessary.

12.3 Structural Engineering

For the factory project, since the product to be manufactured is generally a small item with a limited number of parts (20–30), the most likely structural system will be a single-story factory building with steel or masonry bearing walls and heavy-timber or light-gage steel bar joist framing. Since no heavy machinery is likely to be used, unusual floor loading, long spans, or advanced structural systems are not likely to be needed.

Column-bay spacing for the steel frame should most likely be 20–30 feet. Larger spans are desirable, but for a pre-engineered or prefabricated structure these are probably not economically justifiable. Also, based on past classroom experiences, since the total square footage of the factory project should run from 30,000 to 50,000, use of existing buildings becomes a reasonable realization for the project.

For the factory project previously described in Chaps. 6, 8, and 10, Fig. 12.8 illustrates the start of the structural design process for an appropriate truss system.

Unless a building has been severely overloaded or damaged by accident or exposure, it should be as structurally sound as the day it was built. This is certainly true of the many existing factory facilities built in the United States, and many studies have shown that existing facilities have lifespans far outdistancing those of contemporary buildings.

Not all existing buildings were constructed of the same materials or systems and consequently not all are equally sound. The era in which a facility was constructed

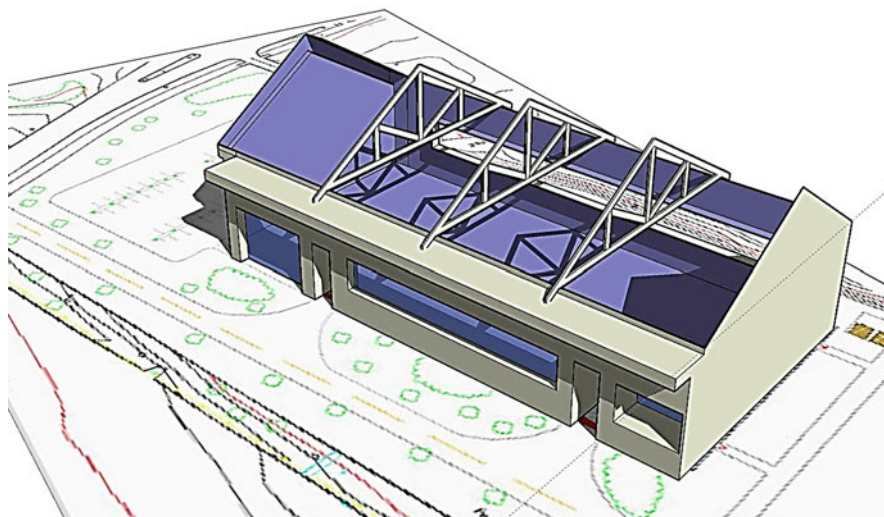


Fig. 12.8 Factory project structural realization

can have a significant bearing on the structural feasibility of its proposed restoration scheme.

Certain danger signals should be recognized during the assessment of the structural quality of a building. Cracks are important indicators of structural settlement and instability or overstress. Cracks that have remained unchanged for a long period of time (static cracks) usually will not indicate any serious problems and are most likely the result of building settlement. These cracks can be cosmetically treated so they are not apparent. Cracks that change over time (dynamic cracks) in floors and walls or around heavily loaded areas are more serious and should be examined in detail by a structural engineer. Static cracks are usually the result of unequal settlement, thermal movement, or secondary damage. Dynamic cracks, however, represent excessive overloading, improper structural design, or improper past remodeling practices. For dynamic cracks, structural tests may be necessary to determine the extent of the problem. Additional indicators of structural quality are sagging floors, evidence of roof leaks, moisture penetration in walls, and sticking windows and doors. In general, cracks should be examined by a structural engineer and their cause determined before proceeding.

12.3.1 *Roofs and Floors*

The roof system and shape for a new facility will likely be flat or slightly pitched, or perhaps a pitched roof-truss structure can be used to allow natural light into the workplace. Ceiling heights will likely be in the range of 18–30 feet. Floor systems

will most likely be concrete, carefully leveled to accommodate the requirements of the vehicles and transport devices of the material handling system (MHS).

The roof of an existing building is important because it protects the rest of the building from sun, rain, snow, and other natural elements. Because the roof is so exposed, it should be inspected regularly and repaired, otherwise serious structural problems in the rest of the building could develop.

Roof framing in existing facilities can be complicated due to the typical arrangement of steep roofs, clock towers, cupolas, and dormers. Given this complexity, maintaining the roof can be a major expense of a renovation project. In some cases, an analysis of the roof load-carrying capacity is necessary to determine if conversion to different uses is appropriate. When the addition of another floor or a mechanical penthouse is being considered, the addition could drastically alter the architectural character of the building. Finally, in the spirit of energy conservation, heavily insulating the roof can significantly conserve on heat loss and heat gain, but care must be taken to ensure that adequate ventilation of the space under the roof is provided to avoid overheating of the roof materials (which eventually could propagate wood rot or deterioration in the metal trusswork). Care must be taken in northern climates where snow loading is a problem.

The floor loading capacities of existing buildings are often overdesigned because architects of the past usually overstructured their floor designs for safety reasons. They did this because they did not have the precise understanding of the capability and behavior of structural materials and systems that is available today. Therefore, many existing buildings are capable of carrying present-day staffing and equipment loads. When converting spaces from one use to another, however, care should be taken to ensure that the new loading does not severely overstress the capacity of the existing floor system.

When considering the addition of a new floor within a building to enhance the utilization of a high-ceilinged space, care should be taken to ensure that there is adequate height to accommodate the required ceiling heights and depth of the structure. At the same time, the new floor should be carefully integrated into the existing structure, meeting all code and architectural requirements. In one such project, a specially designed thin two-way grid of steel beams and poured concrete was necessary to provide an extra floor in a limited-height vertical space.

12.3.2 Walls and Columns

With regard to the layout and location of the walls and columns in the factory, it is important to realize that the design of the MHS or circulation layout of the facility will often provide the underlying framing template for the structural system. The MHS or circulation layout should also provide the overhead conduit for the HVAC, electrical, and plumbing systems of the facility. Careful design of the MHS (Chaps. 7 and 8) is crucial to the building's systems as well as the structural system. See Fig. 12.9 for the factory project example previously considered in Sect. 4.12.

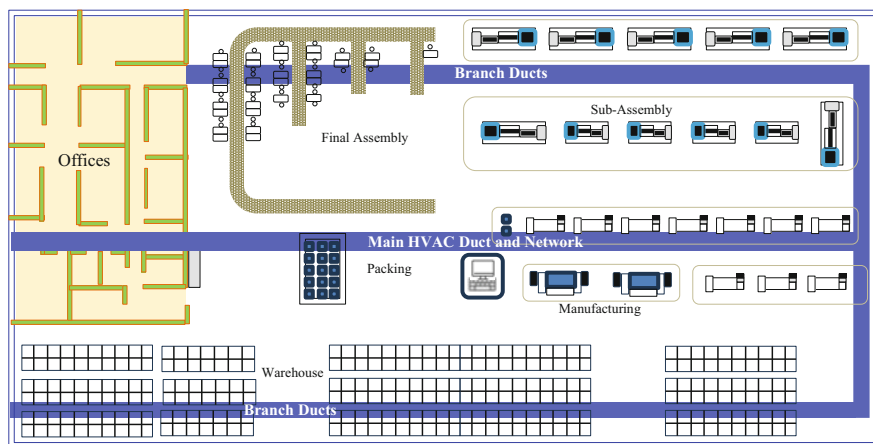


Fig. 12.9 HVAC structural plan integration

Square or round columns will likely occur in new steel-and-concrete framed facilities. Each column effectively uses between 6 and 16 square feet of floor space [4], so minimizing the number of columns in a structural system is a wise choice. However, increasing the spans in a structural system increases the depth of the beams and may increase the overall cost of the structure, so careful analysis is needed in dimensioning the bay sizes.

Wall partition systems in the new buildings will likely be confined to the offices, where visual and auditory privacy are paramount to the functioning of the office activities.

When it comes to the conversion and remodeling of interior spaces, structural changes in wall systems are important determinants for the range of potential changes. Many existing facilities have oversized masonry concrete load-bearing partitions and vaults that severely restrict the possibilities for space reuse. Any alterations to or openings through these load-bearing partitions are tricky structural problems, requiring the consultation of a structural engineer in most instances. These changes can be significant cost items in the total preservation-cost equation.

The removal of non-load-bearing walls should not present any problems. Frequently, clients use open-plan office arrangements that foster easier administrative control, flexibility, and conservation of energy resources. When a building is capable of being opened-up like this, its potential for reuse becomes very high. One consideration here is to make sure that in opening-up the interior of the building, its interior architectural character is not totally disfigured.

12.3.3 Building-Code Considerations

For either a new or an existing facility, the following general checklist should be used to examine the code requirements that may have to be met during the remodeling process:

(a) Fire Safety

- Fire detection systems (heat and smoke)
- Fire suppression system (sprinklers and extinguishers)
- Fire alarms
- Adequate material fire ratings

(b) Exits

- Usually two separate exits per floor
- Proper exit identification
- Special exit regulations for rooms and other large assembly spaces
- Exit distance and exit width requirements

(c) Stairways/Elevators/Escalators

- Enclosed stairway construction requirements
- Width, hand-rail projections, etc.
- Need for smokeproof tower
- Ventilation system requirements
- Number of necessary elevators
- Fire protection for escalators

(d) Handicapped Users

- Walkways
- Parking lots
- Ramps
- Doors and doorways
- Toilets, fountains, telephones
- Elevators

(e) Ventilation System

- Required number of air changes per hour
- Type of air flow
- Number of room occupants

(f) Plumbing and Sanitary Systems

- Toilets/sinks
- Urinals
- Water fountains

(g) Building Codes

- Health, safety, and welfare
- Egress

Codes are primarily concerned with fire prevention, structural safety, and the necessary means of access and egress for building occupants. In many cases, the feasibility of meeting code requirements will be premised on the sensitivity and common-sense of the code officials. Updating an existing facility to meet current building codes can be a major factor in the cost-benefit analysis of renovation vs. new construction.

12.4 Heating, Ventilating, and Air-Conditioning

Among the most important elements of a building are its building systems: heating, ventilating, air-conditioning, electrical, plumbing, fire protection, and vertical transportation. Whether it be a new or existing building, these systems represent its lifeblood and nervous system. The cost of a new facility or a renovation is highly dependent on the type and extent of building systems added. Complex heating, ventilating, and air-conditioning systems and fire extinguisher systems can represent significant cost items.

Buildings are basically leaky heat containers; heat is generated both inside and outside the structure and flows through the roof, walls, windows, air ducts, corridors, and other spaces.

Exploration of new systems for existing buildings is also important from the viewpoint of reusing previously uninhabitable spaces, such as attics or basements, or taking advantage of these spaces for the placement of mechanical equipment. A positive feature of existing buildings is that they had to rely predominately on natural means of ventilation and lighting, which, if properly balanced by the addition of new supplemental mechanical systems, can become a cost-effective means of conserving energy resources.

Existing buildings were usually not designed to effectively distribute heat throughout the building, which results in an uneven distribution of heat energy. Roof and wall insulation of an existing building is usually a first step in improving the use of energy for thermal comfort. Also, the addition of new heating, ventilating, and air-conditioning (HVAC) systems can be carried out in existing structures, because there are often high ceilings or leftover spaces that can accommodate the necessary ductwork and mechanical equipment.

12.4.1 *Electrical/Lighting*

HVAC systems can be broken down into two basic types: centralized and decentralized. Among their various advantages and disadvantages are the following:

Centralized systems: Generally, centralized systems use 10–15% less energy, require fewer control devices, and can accommodate high-velocity ducts in existing crowded chases and shafts. Disadvantages are that centralized systems are not very flexible operationally unless they have elaborate control systems; they require increased initial capital expenditures and can be severely limited by existing structural and architectural barriers and obstacles.

Decentralized systems: These systems allow more operational flexibility, reduced initial capital expenditures, can be relatively unconstrained by structural and architectural barriers, and are more appropriate where the value or length of stay in the building is not great. Disadvantages occur because these systems have higher operating and maintenance costs than centralized systems, they are not energy conserving, and they are usually much noisier.

Ultimately the cost and extent of remodeling an existing building will depend on the existing thermal comfort systems, the type of insulation that can be applied, and the type of additional mechanical systems necessary to bring the building and its spaces up to acceptable thermal comfort conditions for the uses it is to serve.

The use of electrical energy, especially for facility activities, has increased considerably over recent years. The addition of networked computer systems, elevators, sophisticated copying equipment, communication systems, personal computers, and so on puts new demands on the electrical system of a building. The electrical system of existing buildings is usually incapable of accommodating this increased demand.

Coupled with the increased demand is the inevitable deterioration, the myriad of piecemeal changes made to the existing system over the years, and the potential fire hazards. Depending on its condition, it is often best to replace the service and completely redo the system to accommodate its present and future needs. This must be coordinated with the power company, which will likely replace the feed to the building.

Along with the deficient electrical system, the lighting system in existing buildings is usually inadequate and must be supplemented with new lighting fixtures and systems. Every space in the existing building should be measured for its lighting level and compared with the standard foot-candle requirements for the activity that will occupy that space.

12.4.2 Plumbing

Layout of plumbing and sanitary systems will often closely follow the layout of other HVAC mechanical systems in the building, since the space for these systems is rather expensive and combining the chase spaces can be cost effective.

An existing building's plumbing system needs to be carefully examined for leaks, corrosion, and the quality of the fixtures. The building's hot water system needs should also be assessed, not only for present use but for future use as well. When new activities previously not accommodated occur in an existing building, the

provision of necessary washroom facilities becomes an expensive proposition in a remodeling project, on the order of tens of thousands of dollars per fixture.

Again, the high-ceilinged spaces many existing buildings offer can accommodate new plumbing systems without these severely protruding into or obstructing the use or beauty of the existing space. With careful and sensitive handling, the new plumbing systems can be accommodated without destroying the architectural beauty of historic buildings. Unused attic and basement spaces can be used to house boilers, generators, and hot water heaters.

Fire extinguishing systems are important considerations where valuable records or equipment must be stored. They should be carefully integrated with modifications to other parts of the plumbing system.

12.4.3 Vertical Transportation

The use of elevators in buildings is becoming recognized more as a necessity than a mere convenience for users. Americans with Disabilities Act (ADA) requirements will often necessitate employment of elevators in multistory buildings to bring the facility up to code. Freight elevators will be a necessity if multiple stories occur in the manufacturing building. As a means of transporting customers, visitors, staff, and the general public in a building, an elevator is often critically important. Even in nonmetropolitan areas with low-rise structures of three or four stories, the employment of elevators can significantly increase the efficiency, safety, and security of the movement system.

The careful placement and integration of elevators is important. The average cost of adding one elevator for a two-story building (2000 lb.) is around \$100,000–300,000, with about \$30,000–50,000 for each additional floor. The shaft and the structure are the critical cost elements, not the elevator itself. Elevator size, hoistway or shaftway, pit, and machine-room dimensions are critical variables in determining the feasibility of accommodating an elevator in an existing building.

12.5 Functional Adaptation of Existing Buildings

Even if a facility is renovated and restored, will it still meet the present needs of the client? This is a difficult question and one that would usually have to be answered in the negative unless some physical, operational, and technological changes are made in the physical plant and operation of the building. Most existing facilities were not designed to accommodate the increased product demands, customer needs, and operational complexity that modern manufacturing and service sector facilities now face. Moreover, even if a facility is brought up to today's standards, what will happen in 10 or 20 years? How much will the current system continue to change, and consequently what response must the physical environment make to

accommodate these future needs? This latter question is an especially difficult one to resolve and can affect the entire renovation and remodeling question.

Two criteria are basic to assessing the functional quality of a building being considered for remodeling: adaptability and flexibility.

12.5.1 Adaptability

Adaptability refers to whether an existing building, whether a facility or not, can be converted to present and future facility needs. Flexibility measures whether a structure can respond to and accommodate the changing manufacturing operations, staff, and equipment needs that inevitably develop with building use over time. These concepts are somewhat complementary.

While retaining existing facilities with lavish decor and grandeur may be desirable, other spaces may be undesirable and difficult to adapt to modern needs. High ceilings, compartmentalized spaces, old record vaults, and similar characteristics of existing buildings do not lend themselves to today's manufacturing and office needs and operations. On the other hand, there are often spaces in attics or basements that have remained relatively unused and that, with the addition of appropriate mechanical systems, could be converted for facility use. Other inventive ways of adding mezzanine floors or reusing these extra spaces in a building can be found by sensitive architects and engineers.

Finally, the adaptability of a building for facility use depends on its environmental quality and character—that is, its ability to absorb and transmit noises, the quality of natural light and views, and aesthetic considerations of materials, textures, colors, and patterns. A factory or warehouse that was built with industrial-type materials and finishes, without any interior windows, and with highly reverberant spaces may not be easily or inexpensively changed to another manufacturing or service sector use. Even if such a building is converted, will the predominant image still be that of a factory and not that of the service sector activity?

What impact will this image have on the quality of service? Once a building is brought up to present needs and operations, how will it perform over time? Will it be able to respond to changes in work operations, staffing needs, and changes in equipment and technologies?

12.5.2 Flexibility

Flexibility and adaptability are complementary concepts but are not necessarily always present together. Something that is adaptable to present uses may be highly inflexible to changes in these uses over time. For instance, a building with highly compartmentalized spaces may be adaptable to present-day uses but hopelessly fail to accommodate future changes in operational, staffing, and equipment needs. On

the other hand, a loft-space building may be quite flexible yet difficult to adapt to specific needs and requirements of present operations. Usually, some middle ground must be established in balancing the need for meeting these two criteria in a building.

Some types of changes that may be expected over time include the following:

Manufacturing operations: Changes in manufacturing operations such as going from a flexible to a cellular layout can have a significant impact on the overall plant and facility layout. Changes in manufacturing operations can significantly affect the product volumes and ultimately have a resounding effect on the facility's physical environment. Changes of this type can have a significant effect on service sector facilities as well.

Staffing operations: Increased staff needs are among the important measures for assessing the flexibility of a building's environment. In one sense, staffing fluctuations can be localized to areas of the facility most likely to expand and change, and this can be helpful in assessing where building flexibility is needed; however, it is not always that simple. Other functional areas in the facility may hire summer interns or make use of volunteer organizations, and these areas may then require flexible space use.

Equipment needs: In the last decade, new technologies have been applied to facility management and operations. Computers, DVD, CD, and video tape systems, microfilm and microfiche, and electronic alarm systems are among the recent technologies. To accommodate the new types of electronic equipment necessary in modern facility operations, an existing building may have to provide special power requirements, certain types of security precautions, and special considerations for protection against fire, vandalism, or natural destruction. A building not capable of providing these features, or at least not at reasonable cost, has questionable flexibility value.

Many existing facilities can be updated to meet current technologies, with which the functional efficiency of activities can be immensely improved. Remote computer systems with satellite terminals, personal computers, and the like are possible. These technologies usually conserve staff and add space and are therefore cost effective in accommodating increased caseloads for the facility without requiring major physical plant changes.

12.6 Building Economics

Since the facility is a leased one, the problem of construction-cost estimation will not be treated; however, the issue of new construction vs. remodeling costs to determine project feasibility will be addressed. Also, we will not delve into the problem of building maintenance, since the leasing arrangement will include these costs. The factory project has concerned itself with many other cost components, and to address construction-cost estimation and building maintenance in any detail takes the project beyond the scope of its intended use. (Of course, an instructor with an interest in cost-estimation and building-maintenance issues may wish to address these issues.)

A major reason for considering the reuse of existing buildings for new and continued uses has been and continues to be building economics. Reusing existing buildings has been shown to be a cost-effective alternative to new construction for a number of reasons, including:

- Less initial capital may be needed to start the retrofitting process.
- It may take less time to complete the project.
- Less money may be tied up for a shorter period of time.
- There are social benefits as well as monetary benefits through the conservation of material resources and acknowledgment of historical and architectural values.

Recycling existing buildings can be a cost-effective alternative to the actual operating and maintenance cost output, which normally escalates as a building reaches 40 years of age. In one study, architects found that the cash necessary for operating and maintenance costs could be applied to a modernization program, and, if prorated over a period of 30 years, the benefits of the modernization would balance out the remaining costs involved.

Recycling existing buildings may not always be cheaper than new construction, but it does present itself as a viable alternative. The actual costs involved in retrofitting a building can be examined in three major categories:

I. Site and acquisition costs

II. Construction costs

- Demolition (asbestos, lead and chemical contamination, and so on)
- Structural
- Architectural
- Mechanical (electrical and plumbing)

III. Administrative costs

Site and acquisition costs will probably not be a major expense item in retrofitting buildings. In fact, they will probably be among the initial reasons for carrying out the retrofitting process, either because the client already owns the land and buildings or because they can be obtained at minimum expense.

Construction costs, however, do vary between new and recycled facilities, and they seem to vary according to the specific type of construction-cost item. These costs can be examined in terms of four subcategories: demolition, structural, architectural, and mechanical. As is shown, architectural and mechanical system costs can be significant percentages of the total project cost of a remodeling project, and they seem to vary the most when comparing new construction costs and retrofit costs.

In one survey of the costs involved in retrofitting buildings, the interior demolition costs for removal of unwanted partitions, structure, and equipment amounted only to 1–4% of the total project costs. While demolition does not appear to be a significant variable in resolving the decision of remodeling vs. new construction, care must be taken if there is asbestos, lead, or chemical contamination due to prior occupants.

12.6.1 Structural System

In this same survey, structural costs, which included reinforcement of the existing system and structural members, accounted for only 5–12% of total project costs. Thus, as in the previous category, structural costs apparently do not vary significantly between new and retrofit construction.

12.6.2 Architectural Costs

Architectural costs include new interior partitions, new vertical circulation equipment, and all treatments and finishes except furnishings. Again, the same survey showed that these costs vary considerably, often exceeding the average architectural costs required in new construction. Where significant architectural work is required, as may be the case when retrofitting a building that was gutted, the architectural costs will probably be significant percentages of the total project cost. Where retrofitting a building amounts to little more than shuffling new uses into existing spaces, architectural costs will probably be insignificant. Therefore, this category of costs is a critical variable to watch for in determining the economic feasibility of retrofit construction.

12.6.3 Mechanical Systems

Mechanical costs are also subject to wide variation above and below the normal percentages occurring in new construction. Where complex climate control systems and extensive fire extinguishing systems are necessary, mechanical construction costs will become significant percentages of the total construction budget. Mechanical costs together with architectural costs are therefore the two key variables to examine in assessing the economic feasibility of retrofit construction, while demolition and structural costs seem not to differ significantly between new and retrofit construction.

12.6.4 Administrative Costs

Administrative costs, including all licensing fees, architectural fees, financing costs, and developer and real estate fees, do not seem to vary whether the project is new construction or a retrofit. Therefore, these costs should not be a lever to favor new construction over remodeling or vice versa.

Table 12.2 Example percent cost-estimation procedure

Cost items	APTP (%)	PAB (%)	APTP $\times$ PAB (%)
I. ARCHITECTURAL ITEMS			
Exterior walls	10	70	7.0
Roofing	3	100	3.0
Flooring	4	0	0.0
Ceilings	3	20	0.6
Partitioning	9	10	0.9
Wall finishes	2	0	0.0
Total	40%		11.5%
II. STRUCTURAL ITEMS			
Excavation and substructure	5	100	5.0
Vertical frame	2	100	2.0
Horizontal frame	18	90	16.2
Total	25%		23.2%
III. MECHANICAL ITEMS			
HVAC	20	50	10.0
Plumbing	5	75	3.8
Electrical	10	65	6.5
Total	35%		20.3%
TOTAL	100%		55.0%

When 20–30 years are to be added to the life of a facility, a general rule of thumb is that if the remodeling costs are more than 50% of the costs to replace the facility, remodeling is not really justified. Of course, this general rule of thumb can be ignored, but it does provide a rough measure of economic feasibility.

A way to systematically arrive at this percentage is the following:

1. Itemize the expected construction costs into three categories: architectural, structural, and mechanical system costs. (The example that follows will illustrate this.)
2. Estimate the average percentage that each item should account for in the total project cost. Call this variable APTP—average percentage of total project cost.
3. Estimate the percentage amount of existing architectural, structural, and mechanical system that is reusable or acceptable. Call this variable PAB—percentage acceptable in the building.
4. Multiply for each cost item and scan overall cost items to get the total percentage value of the existing structure that is reusable.

Table 12.2 illustrates this procedure [1]. For the illustrated example in this table, the value of the existing building represents 55% of the total cost of remodeling the building. From our rule of thumb, it would be cost effective to remodel the building, since the remodeling costs would be only 45% of the total cost of construction. Finally, to arrive at the estimates of the actual costs of remodeling, the following set of steps is suggested [3]:

- Step 1.** Estimate the amount of interior work including demolition (actual square footage estimated cost per square foot).
- Step 2.** Estimate the cost of any new construction (actual square cost per square foot).
- Step 3.** Estimate the cost of any special equipment (computer, communication system, special security devices, and so on).
- Step 4.** Estimate the square-footage cost for mechanical systems—heating, ventilating, air-conditioning.
- Step 5.** Estimate the square-footage costs for plumbing and emergency fire extinguishing systems.
- Step 6.** Estimate the square-footage cost for electrical work (air-conditioning should be figured in Step 4, not in this step).
- Step 7.** Estimate the cost of site work (landscaping, lighting, vegetation, walks); some planners suggest that this be 10–25% of total modernization costs.

12.6.5 Cultural

The cultural legacy and value of existing buildings for the environment and the community of users is a difficult but important determinant in the evaluation process. Certain buildings, for example, are especially valuable for their physical presence, their pedestrian parks or squares, and the infectious vitality they give to the buildings and environment near them. What makes this problem of renovation design and evaluation even more difficult is that these buildings often cannot be economically replaced exactly as they were originally constructed.

There are two basic dimensions upon which the cultural value of the building can be measured: historical and architectural.

Without a certain amount of scholarly research, it is somewhat difficult to estimate the historical worth of any building. One major source of US government funding requires that a property or building be listed on the National Register of Historic Places before matching grants and aid can be allocated to help preserve it. The National Register for Historic Places is America's official listing of historic districts, sites, buildings, and objects worthy of preservation in American history, architecture, archeology, and culture.

A statewide survey of historic resources conducted by each state, together with a review by a state review committee, precedes the nomination of a resource for inclusion on the National Register. The National Park Service, based on a state's nomination, decides whether to include the resource on the National Register.

Three major criteria should be examined in assessing the historic value of a building:

- Historic events
- Historic persons
- Community interest

A building's historic importance is largely measured by the historic events that have occurred there. Well-known products, inventions, or discoveries are major indicators of historic importance. In another sense, the building may be part of a historic district where a series of related events have occurred that affect the historic value of the building. To gather information about these events will usually require in-depth research into old public records, old newspapers, historical society collections, wills, deeds, and so on. Such research is vital to documenting historical events and how the building played an important role in their development.

Often, a building will be identified with a famous person (or persons) such as lawyers, judges, witnesses, or defendants. It is important to realize that the "George Washington slept here" syndrome is seldom valid or important enough to alone justify the preservation of a building. The famous person's association with the building should be a meaningful one; the building should be directly related to the person's life and work.

Finally, the historical value of a facility is highly dependent on the interest of the community in its upkeep and maintenance. If this element in the equation is missing, then it is likely that the facility will fall into serious disrepair over time and eventually become a blight in the community. While someone outside the community may feel the building is worthwhile, unless the local community shares this view, it may be futile to spend time and money in restoration.

12.6.6 Factory Renovation Project

Figures 12.10 and 12.11 are drawings of the plans for the factory renovation project first shown in Fig. 12.3 of Sect. 12.1. As indicated there, this layout represents a two-story building where manufacturing operations are located on the first floor and the mezzanine part of the second floor.

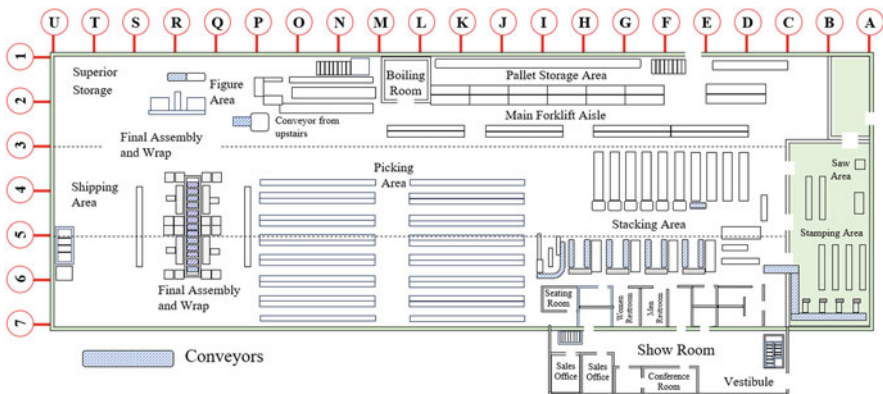


Fig. 12.10 First floor factory project

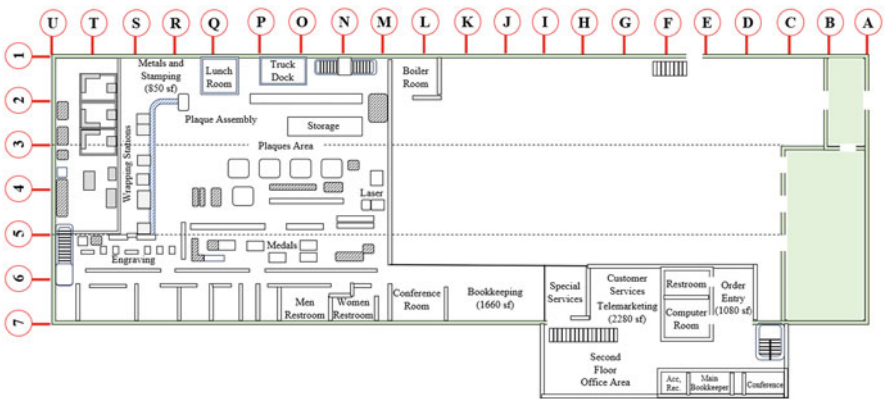


Fig. 12.11 Second floor factory project

Most factory renovation undertakings aim at restoring space in an existing building to a good state of repair. Some components in existing buildings are replaced with new or modernized construction that changes the appearance, structure, or shape of a space to reengineer a factory layout.

Figure 12.10 illustrates the factory accommodation on the first floor. Notice that certain equipment has to be designed and arranged to be integrated with the structural column system of the building. The layout is placed on a rectangular area containing a 20×7 grid. Each cell has dimensions of 20'×20'.

Figure 12.11 illustrates the accommodation of factory activities on the mezzanine floor. The material handling system connecting the two floors consists of a belt conveyor. The layout is placed on a rectangular area exactly the same in dimensions as the layout of Fig. 12.10.

12.7 Factory Design Project: Section VI. Recommended Layout

At this point in the development of the factory design project, the objectives listed below have been achieved and documented. Each team has submitted a project section report, which has been graded and returned along with a checklist documenting the grade and recommendations for corrections, additions, deletions, and improvements.

1. The product has been designed. Parts to be purchased and those to be manufactured have been identified. Furthermore, a tentative production volume has been determined.

2. The process to fabricate the product has been planned. Specific manufacturing processes have been selected, and the appropriate order for implementing this process has been determined.
3. The initial factory layout and material handling system have been determined. Production departments have been created and production volumes along with the route sheets have been consolidated into a from-to chart. Computerized procedures have been used for this purpose.
4. The personnel requirements in terms of number and types of management and plant positions, as well as personnel facilities, have been determined.
5. The office layout has been designed. The main input for this activity has been the creation of a relationship chart. Computerized procedures have been used for this purpose.

The overall purpose of Section VI is to review, enhance, and integrate the existing layouts for both the plant (Section III) and the offices (Section V). A critical approach is required from each team to identify possible shortcomings, deficiencies, and errors in all previous work. All improvements and modifications recommended for each project section report are implemented. The specific objectives of Section VI are listed below:

1. Improve existing layouts (plant and office).
2. Consolidate layouts.
3. AutoCAD drawings of final layouts.
4. Material flow for selected parts (on plant layout).
5. Computer outputs for plant layout (document first and last layouts at least).
6. One application of any of the analytical procedures described in class. The purpose of this is to show the ability of the students to apply their knowledge of analytical procedures to a specific relevant area of the factory design project.

12.7.1 Factory Report Organization

The final report of the project should include all the recommended changes for Sections I through V, along with the selection of a final layout for factory and offices. All figures, formulas, tables, and bibliographical references must be numbered and referred to in the main body of the report in terms of their numbers.

The following organization is suggested for the final project report. The specific organization of Sections I through V has been detailed in Chaps. 3, 7, and 11.

Title Page

Table of Contents

Introduction

- (a) Overview and Scope of Report
- (b) Organization

Section I. Product Design
Section II. Process Design
Section III. Layout Planning
Section IV. Personnel Requirements
Section V. Office Layout
Section VI. Recommended Plant and Office Layout

Summary, Conclusions, and Recommendations

Appendices

The organization of the documentation report for Section VI is outlined below:

Introduction

- (a) Relevant Background
- (b) Scope of Report
- (c) Organization of Report

Summary of Enhancements (Refer to Sections I through V)

Computerized Approach

- (a) Initial Layout (Section III)
- (b) Proposed Modifications
- (c) Computer Input
- (d) Computer Output

Proposed Layout

- (a) Plant and Office (Section IV)
- (b) Material Flows for Selected Parts
- (c) Discussion

Plant Layout Summary Sheet

Summary, Conclusions, and Recommendations

Appendix with Illustration of Analytical Procedure

Bibliographical References

12.7.2 Plant Layout Summary Sheet

The purpose of the plant layout summary sheet is to document all components of the total cost per unit of product. The format of the sheet is shown in Fig. 12.12.

PLANT LAYOUT SUMMARY			
Names of Team Members			
Company Name			
Description of Product			
Market Selling Price			
Number of Parts in Product (by type)			
PRODUCTION VOLUME			
Per Day _____		Per Week _____	Per Year _____
1	NUMBER OF MACHINES BY TYPE		
	Total Number of Machines		
	Annual cost of Equipment		\$
2	MATERIAL COST		
	Cost per Unit of Manufactured Parts	\$	
	Cost per Unit of Purchased Parts	\$	
	Total Cost per Unit	\$	
	Annual Material Cost		\$
3	MATERIAL HANDLING COST		
	Annual Cost		\$
4	PERSONNEL REQUIREMENTS AND COSTS		
	Number of Factory Direct Workers		
	Number of Factory Indirect Workers		
	Number of Supervisors		
	Annual Cost (Direct, Indirect, Supervisors)		\$
	Annual Cost (Office Management)	\$	
	Annual Cost (support Personnel)	\$	
	Annual Cost (Management, Support)		\$
5	DIRECT LABOR COST PER MANUFACTURED UNIT		
	Manufacturing	\$	
	Assembly	\$	
	Total Unit Cost		\$
6	ANNUAL FACILITY COSTS (LEASE)		
	Square Feet	Manufacturing Area at	\$
	Square Feet	Warehouse Area at	\$
	Square Feet	Office Area at	\$
	Annual Facility Costs		\$
	Cost Total Operations		\$
	Unit Cost		\$

Fig. 12.12 Plant layout summary sheet

12.7.3 Checklist for Final Report

The final report will be graded according to the requirements specified in the grading sheet shown in Fig. 12.13. The checklist emphasizes four requirements: (1) organization and style, (2) worth of proposed layout, (3) plant layout summary documenting all relevant components of the product unit cost, and (4) the relevance and suitability of the analytical procedure chosen to illustrate its applicability to the project.

Group No _____	Product Description	Grade _____	Date _____
Names 1. 2. 3. 4.			
Organization and style			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Introduction of report is lacking ☐ Technical English style can be improved ☐ Organization can be improved			
Proposed Layout			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Minimum requirements are inadequate ☐ Alternative layouts are not meaningful or show little creativity ☐ Discussion of alternative layouts is not included or is not sufficient ☐ Selection of final layout is not documented			
Plant Layout Summary Sheet			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Sheet is not included ☐ Sheet is incomplete ☐ Unreasonable costs ☐ Unreasonable areas			
Illustration of Analytical Procedure			
Excellent ☐	Good ☐	Average ☐	Fair ☐
☐ Model chosen is not appropriate ☐ Minimal or no discussion of illustration			
Comments			

Fig. 12.13 Grading sheet for final report

12.7.4 Final Layout [1]

The final step in the design of the USA Wood Corporation facility is to complete the recommended plant layout by combining information from all previous sections to integrate the entire facility layout (office and plant). The three most important factors considered are flow, space, and activity relationships. The layout planning charts help to determine necessary quantities of machines, as well as flow between departments.

After incorporating the shipping and receiving departments in the from-to chart, the computerized programs CRAFT (computerized relative allocation of facilities technique) and FLAP (facilities layout program) were used. The output generated by these programs allow the choice of flow paths that best fit the facility's needs. All team members completed a proposed plan individually. These were then analyzed and the arrangement that maximized both effectiveness and efficiency was chosen.

The recommended layout is a product layout consistent with USA Wood Corporation's projections of a high volume of sales. Furthermore, it is anticipated that the revolving desktop organizer will be the most important product to be manufactured, with the possibility of very few secondary products. The overall flow through the factory has a U-shaped pattern. It is simplistic and allows the use of docks on one side of the plant, instead of putting shipping on one side and receiving on another.

The machining areas of the layouts have been provided with 4-foot aisle widths, according to the guidelines given in Chap. 4. These aisles should be sufficient to allow the traffic of the material handling equipment chosen in Section III of the factory design project. The plant also has spacious areas for the forklift to move from packaging, to storage, and to shipping.

First aid stations are conveniently placed in two locations of the plant. There is also a break room that accommodates 36 persons and it is furnished with micro-waves and a refrigerator. Restrooms are located at both ends of the facility. Several features have been incorporated in the final layout to enhance the safety and level of satisfaction of the employees. The facility layout planning process was finished with the addition of all necessary amenities. A parking lot was the primary addition, designed according to the recommended sizes.

The final plant layout shown in Fig. 12.14 [1] was selected based on the evaluation of all available alternatives (one per student) using the following essential factors: (a) flow, (b) space, and (c) activity relationships.

12.7.4.1 Flow Considerations

The selected layout has a U-shaped pattern around the factory floor, starting at the receiving area, proceeding to shipping, and returning to the receiving area. This flow of material is simplistic in nature and contributes to significant space and activity relationships.

The aisles are wide enough to allow the effective flow of material handling equipment. Some aisles have been designed to cut through the various departments enabling flow along shorter routes.

12.7.4.2 Space Considerations

The layout was designed in such a way that the required space will be significantly minimized, using the following three guiding principles:



Fig. 12.14 Final plant layout

1. Having shipping and receiving next to each other will enable the forklift to work both areas without having to travel across the facility. This will save aisle space and create a safe work area.
2. Most of the machine areas are facing each other with the machines in the front of the workstations. This greatly facilitates the supply of power to machine areas.
3. The layout will effectively integrate inventory, storage, equipment, and building as a working unit.

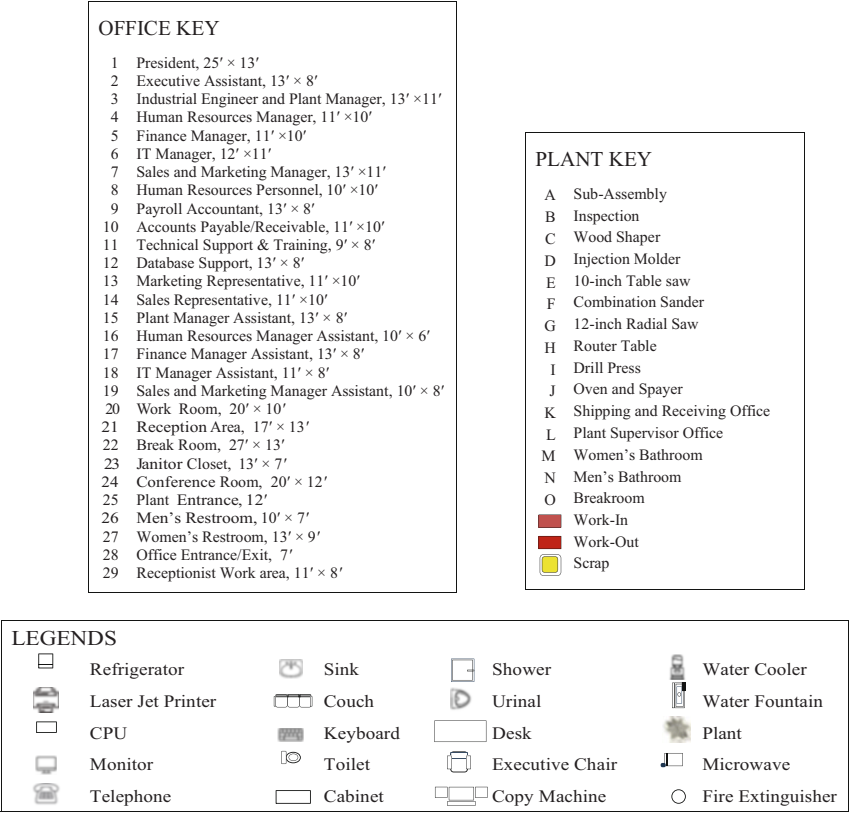


Fig. 12.14 (continued)

12.7.4.3 Activity Relationships

The chosen layout is influenced by activity relationships that positively impact the flow of materials, people, and equipment. In particular, the flow of parts through the facility allows the concept of product or part family to be implemented in moving materials. More specifically, all the material designated for a certain part will be moved from one workstation to the next.

12.7.5 Break-Even Point Analysis [1]

It was decided that, for the facility being used, a maximum of 225,000 units per year could be manufactured. The costs associated with the manufacture of the revolving desktop organizer can be divided into both fixed and variable costs. The fixed cost includes the annual lease payment on the actual facility, \$213,537 per year.

The variable costs came from a number of sources—equipment costs, labor costs, material costs, and material handling costs. The machine cost was determined to be \$0.074 per unit. The labor cost, including all direct, indirect, and management and office personnel, was found to be \$14.17 per unit, around 70% of the total cost. Furthermore, the material costs amounted to \$3.32 per unit. The fourth and final variable cost considered in this break-even analysis was the material handling cost, determined to be \$0.011 per unit. Adding all these components, a total variable cost of \$17.575 per unit was determined.

In order to account for costs not previously considered, a 10% markup was added to both the fixed and variable costs. This brought the total fixed costs to \$234,891, and the total variable costs to \$19.33 per unit. Now, if P represents the selling price and Q the break-even quantity, then $PQ = \$234,891 + \$19.33 Q$. The selling price was set equal to \$20, \$21, \$22, \$23, \$24, and \$25 and the corresponding break-even points were found to be 350,584, 140,653, 87,945, 64,003, 50,298, and 41,427, respectively. After considering these results, a selling price equal to \$22.50 was chosen. This price corresponds to a break-even point of 74,099 units per year and a 10.4% markup. The projected production level of 225,000 units per year will yield an annual profit of \$478,359.

12.7.6 Factory Design Project Presentation Guidelines

Each team will make a project presentation with specific areas presented by designated members of the group. The guidelines shown below are for project teams consisting of four members. For teams consisting of a different number of members, sections should be properly redistributed.

1. The presentation will take approximately 25 minutes per team, including questions (about 5 minutes).
2. First presenter will do introduction to project and Section I.
3. Second one presents Sections II and III.
4. Third one presents Sections IV and V.
5. Fourth one presents Section VI, summary, conclusions, recommendations, and final remarks.
6. Each project presentation will be graded according to the requirements indicated in Fig. 12.15. Shaded areas represent portions of the table not allowed for scoring.

A significant skill required of all engineers is the ability to communicate. The purpose of this final part of the project is to allow the team members to exercise their abilities to present in a clear, brief, and organized fashion the results of their work. When properly followed, the general recommendations listed below can effectively aid in presenting the results.

PROJECT PRESENTATION													
NAMES		Grade _____											
1		Group No. _____											
2		Product Description _____											
3													
4													
No.	SUBJECT	1	2	3	4	5	6	7	8	9	10	Total	
1	Presentation Organization												
2	Delivery of Presentation												
3	Product Description & Model												
4	Overall Project Development Approach												
5	Detailed Results (by Section)												
6	Material Flow for Selected Parts												
7	Computerized Procedure (Input & Output)												
8	Illustration of Analytical Procedure												
9	Quality of Slides and Presentation Materials												
COMMENTS													

Fig. 12.15 Project presentation grading sheet

- Thinking on your feet is 99% being prepared:
 - Clarify your goal in advance.
 - Know your message.
 - Develop skills in verbal bridging.
 - Rehearse verbally and physically.
- Remember that people do things (and listen to you) for *their own reason*, not yours.
- Thank the questioner (“*Bob, that’s a good question. . .*”).
- Your best confidence tools are:
 - Knowledge
 - Energy
 - A smile
 - A pause
 - Direct eye contact

5. Never overreact:
 - “Under” react.
 - Show surprise in your words, *not* your face or voice.
6. Remember to breathe!
 - Tension is blocked energy.
 - Send oxygen to your brain to help unfreeze it.
7. If you have “brain freeze”:
 - Go to your central message.
 - Ask for help (“Please remind me. . .”).
 - Tell a familiar story.
 - Pause and go directly to your “wrap-up.”
 - Use the “two key points” bail out.
8. Remember the face-to-face communication statistics can be in your favor!
 - Voice 38%
 - Body 55%
 - Words 7%

Appendix 12.1 Renovation Versus New Construction Planning Issues

Structural

- When was the building constructed? What type of structural framing system was used? Have there been any recent studies of the structural system of the building?
- Have there been any major repairs to the structure in the past? What changes or additions were made and what repairs are being planned?
- Are there static or dynamic cracks in the structure? If so, where are they located and has an architect or structural engineer been called in to examine the extent of the damage?
- Are there any sagging floors, extensive moisture penetration, sticking windows or doors, or other noticeable indicators of potential structural settlement or damage?
- What building codes, if any, are currently being violated by the structure? Is there a special code especially developed for historic buildings that affects the facility?

Mechanical/Electrical

- What types of building insulation (roof and walls) and storm window protection should be added to the building to reduce heat loss and heat gain to the building interior?
- Have there been any recent alterations or studies made of the heating, ventilating, air-conditioning, electrical, plumbing, fire protection, and vertical transportation systems of the building?
- Is there a sufficient amount of unused or leftover spaces to accommodate any new building equipment that might be necessary?
- Would a centralized heating, ventilating, and air-conditioning system be more appropriate than decentralized system for the building under consideration? What are the costs and benefits of these two alternative systems?
- Will there be any sophisticated new equipment technologies added to the building?
- How will the air-conditioning and power system requirements be accommodated within the structure?

Functional

- Will the remodeled structure be capable of responding to changes in work operations, staffing needs and reorganization, and changes in equipment and technologies?
- What will be the eventual impact on the quality of service once the renovation is complete?
- What are the expected product demands and staff needs of the facility over the next 20 years?
- If the facility is restored as it is presently situated, will it be capable of accommodating the increased use of product demand forecasted over the next 20 years?

Financial

- What is the total expected remodeling cost for bringing the existing building up to current standards of the facility operations?
- What existing vacant or unused buildings are available in the vicinity that are prime candidates for remodeling for the client's use?
- What are the economic and social benefits and costs of remodeling as opposed to new construction? When is new construction economically more feasible than remodeling?

- What is the approximate current outlay of monies for the operating and maintenance costs per square foot of the existing building?
- If the existing facility cannot be recycled for the client's use, can it be recycled for some other institutional or commercial use?
- What funding programs are available from the federal or state government to fund the rehabilitation process? Are there any special requirements, such as placing the structure on the National Register of Historic Places, that must be met prior to obtaining the funds?
- Which private businesses or industries have programs for providing funds for the remodeling of historic or existing buildings?
- Is there need for a fire protection system within the building (smoke detectors, alarms, fire extinguishers, etc.). If so, what is the most appropriate type of extinguishing system (fog, water, etc.)?

Cultural

- What historic events or persons are associated with the existence of the building being evaluated for its historic worth? How significant are these events or persons to the continued existence of the building(s) under consideration?
- What is the level of interest in the preservation of the building(s) by the local community? How important is their level of interest in the continued maintenance and preservation of the project?
- Is the building under study architecturally significant? Are there any unique design concepts, architectural treatments, engineering solutions, or urban design features associated with the building that underlie its architectural importance?
- Is the building unique because of its age or because of the architect who designed it?
- How important is this to the overall preservation question?
- What if the existing facility or building were to be removed from its existing location?
- What consequences would result to the ambience and character of the environment?
- What additional values would accrue to the environment and setting of the existing building if the structure were enhanced with additional exterior planting, landscaping, boundary definitions, and a general renewal of its appearance?

References

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Appendix: Decision Support Methodology (DSM)

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Master's Degree Report, Industrial and Systems Engineering Department

Texas A&M University, 2004

Introduction

A conceptual overview of the decision-support methodology (DSM) is shown in Fig. A.1. This application, coded in Visual Basic, enables the user to determine the unit cost of the product. It interfaces with an MS Access application containing two databases, one for production equipment and a second one for material handling equipment. The DSM is included in a web-based repository for all the software, easily accessible to students and instructors through the following link: <https://facilitiesplanning.wixsite.com/my-site>

It is noted that Chap. 11 provides an alternative simplified excel spread sheet procedure that can be used to calculate the unit cost of the product.

Modules

The DSM computerized procedure consists of seven modules, each one designed to calculate a component of the total cost:

- Material
- Machinery
- Material handling
- Direct labor

Machine Selection and Cost Determination

A separate database application (**MC.mdb**) has been created in Microsoft Access. It has a wide range of machines for each of the commonly used manufacturing processes. Each record in the database provides specific information about the type of the machine, its dimensions, other relevant attributes, capacity, and cost. This database application provides the user with necessary information and helps the user in the selection of appropriate machinery.

The cost associated with a particular type of machine depends on the number of individual machines to be used. To determine this number, it is essential to have reliable data on machine availability, percentage of nondefective product after the machine operation, and standard operational times per unit of product. The **Turning**, **Milling**, and **Drilling** forms are specifically designed to calculate standard times for turning, milling, and drilling machine operations. Once the number of machines and the cost per machine are established, the total machine cost can be calculated for each type of machine.

Material Handling Equipment Selection and Cost Determination

A separate Visual Basic application (**DSS-MHE**) has been created to select appropriate Material Handling Equipment, based on user input provided for the following items:

- Primary function of material handling Equipment
- Size of the material (part) to be moved
- Frequency of the movement of material (parts)
- Path the material follows during transportation

Another set of user inputs is obtained to further classify the chosen type of material handling equipment. Cost information pertaining to specific equipment is obtained from a MS Access database (**PicSource.mdb**).

Labor Cost Determination

The labor cost component includes the costs associated with three classes of labor—direct labor (operators), indirect labor, and administrative personnel. This application obtains user-provided input regarding the number of types of workers in each labor class, number of workers of each type, and the corresponding salaries to determine the total labor cost.

Enter the number of types of parts to be produced	2
Working days per year	300
Working hours per day	8
Cost of all parts purchased	300
Fringe Benefit of Employees (%)	23
Number of classes of administrative personnel	2
Number of classes of operators/workers used	2
Number of classes of indirect workers used	2

ExitHelpNext

Fig. A.2 Sample of general question form

General Question Form

The first form in the application is the **General Question** form, as shown in Fig. A.2 (with hypothetical sample data). This form documents the number of parts to be manufactured, the number of working days per year, working hours per day, the total cost of parts to be purchased instead of manufactured, and required information associated with labor costs. The application checks the validity of the input after each piece of data is provided by the user.

Part Details Form

After completing the General Question form, the user is required to provide specific information about the parts to be produced using the **Part Details** form shown in Fig. A.3. The form is designed to document information such as the average number of units of a specific part to be manufactured, types of manufacturing operations involved, types of material used, and types of material handling equipment utilized. Furthermore, the form calculates standard times for turning, milling, and drilling operations. For each other type of operation, the form stores a user-provided

Part_Details

Details for Part 1

Number of units to be produced per year

10000

Number of units to be produced per day

34

Number of Machines Required

Turning

1

Calculate standard time

0.523

Milling

1

Calculate standard time

0.157

Drilling

1

Calculate standard time

0.126

Others

1

Cost Calculation

Unit cost of material

6.69

Decision Support for Material Cost

Amount of scrap estimated (ln)/100 unit of part

2

Cost of scrap/lb

80

Types of Material Handling Equipment

1

Cost Calculation

Cost of Material Handling Equipment

10000

Back

Help

Next

Fig. A.3 Sample of part details form

standard time. On another form to be introduced later in this appendix, these standard times will be used as partial inputs to calculate the number of machines required. The form also interfaces with the materials cost module of the decision-support methodology.

Button 1 (Standard time calculation): The button next to the turning label takes the user to a separate form where the standard time for a turning operation is calculated. This is the **Turning Standard Time** form. A sample is shown in Fig. A.4. The number of turning operations in a specific part can be entered in the box adjacent to the turning label. For each turning operation, the turning standard time form is repeated as many times as the number of turning operations indicated by the user.

Buttons 2 and 3 (Standard time calculation): Similarly, these buttons allow the user to access the standard time calculation forms for milling and drilling operations. These forms are similar to that shown in Fig. A.4 for turning operations.

Button 4 (Cost calculation): Apart from the basic operations of turning, milling, and drilling, a part may require other operations—grinding, shaping, boring, broaching, and so on. Button 4 takes the user to a separate form, here called the **Other Machines** form. A sample of this form is shown in Fig. A.5. For each machine type, the form determines the number of machines, provides guidelines

Turning

STANDARD TIME CALCULATION FOR TURNING OPERATION

TURNING 1

Description	Steps of Calculation	Formula	Variables
Cutting time for turning	Workpiece RPM	$N = \frac{12V}{314D}$	N = RPM of the rotating workpiece V = Cutting velocity (Sfm) D = Diameter of workpiece (inches)
	Cutting Time	$C.T. = \frac{L + A}{F_r * N}$	CT = Cutting time (min.) L = Length of cut (inches) F _r = Feed (inches per revolution) N = RPM A = Overrun allowance (inches)

Enter the values

V

1.5

D

3

L

1.5

A

0.05

F_r

0.5

Calculate Cutting Time

1.622

Back

Next

Fig. A.4 Sample of turning standard time form

Other_Machines

Machine 1

Enter standard time in minutes

11

Availability factor in percentage

80

Probability of producing non-defective item

0.98

Number of Machines required

☒ Integer value of No of machines

☐ Fractional value of No of machines

Calculate

2

Unit cost of machine

Help on machine cost

20000

Service life of the machine in years

10

Salvage value after service life

2000

(This application assumes Linear Depreciation)

Back

Next

Fig. A.5 Sample of other machines form

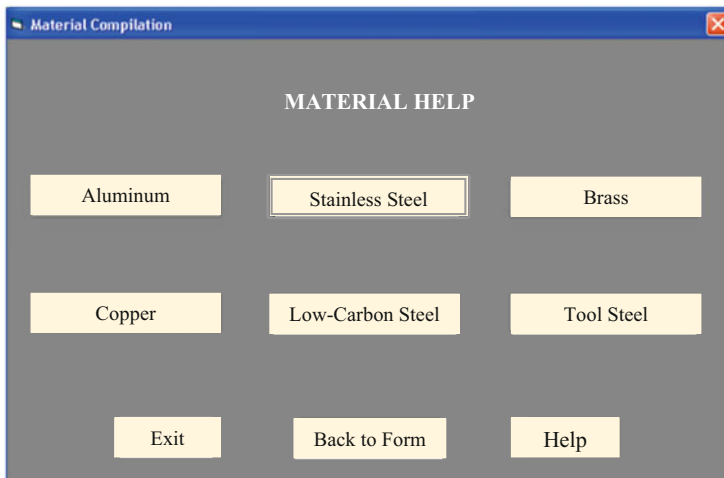


Fig. A.6 Sample of the material help form

on the cost per machine, and requests information concerning service life and salvage value for each machine.

Button 5 (Decision support for material cost): This button leads the user to the **Material Help** form shown in Fig. A.6. The form provides the user with several options from which to select the material for a part to be produced.

For each type of material chosen, the user is provided with a form with options from which to select the material size. Fig. A.7 shows a sample of this form (here named the **Stainless Steel** form) when stainless steel is chosen as the material needed.

Button 6 (Material handling cost calculation): This button switches the control to another application, wherein, based on user-provided inputs, appropriate material handling equipment is chosen. Its cost is retrieved from an MS Access database, which is a major component of the decision-support methodology.

Machine Form

After the user enters the details about the various parts which make up the product, the application leads to a **Machine** form designed for calculating the number and cost of machines. A sample form is shown in Fig. A.8 for turning operations. Similar forms are available for milling and drilling operations.

Steel

STAINLESS STEEL DETAILS

Types	Dimension	Thickness (inches)	Diameter (inches)	Price
Flat Sheet	36×96	0.06		\$180.61
	36×96	0.048		\$145.61
	48×96	0.048		\$194.04
	30×96	0.036		\$92.73
	36×96	0.036		\$109.48
Solid Round Bar	12" long		1/8	\$3.90
			1/4	\$8.48
			3/8	\$20.32
			1/2	\$35.29
			3/4	\$72.22
			1	\$117.87

Expected number of units (Flat Sheet or SRB)

29

Price

194,04

Back

Calculate

Fig. A.7 Sample of the stainless steel form

Turning Machine details

Turning

Availability factor in percentage

80

Probability of producing non-defective items

.95

Number of turning machines required

☐ Integer value of No of machines

☒ Fractional value of No of machines

Calculate

View Equation

0.615

Unit cost of machine

Help on machine cost

7000

Service life of the machine in years

6

Salvage value after service life

1500

(This application assumes Linear Depreciation)

Close

Fig. A.8 Sample of machine form

The *View Equation* button allows to view the equation to calculate the number of machines required. The *Help on Machine Cost* button indicates the availability of an MS Access database populated with machines details and their costs. The *Calculate* button determines the number of machines required, after the user clicks either of two radio buttons, *Fractional value or Integer value*, depending on the specified type of the number of machines needed. The standard times calculated in the Part Details forms are used with other inputs in this form to determine the machine cost to manufacture a unit of the product.

Personnel Form

The next cost component to be determined is that of labor, which is divided into three categories: administrative personnel, direct labor, and indirect labor. There is a form for each category: the **Administrative Personnel Class** form, the **Operator Class** Form, and the **Indirect Worker Class** form. Number of individuals and corresponding salaries are provided by the user on each form. Fig. A.9 shows a sample of the Administrative Personnel Class form. The other two types of forms are similar to this one.

Administrative Personnel Cost

Administrative Personnel – Class 1

Number of personnel 3

Annual Salary (per head) 60000

Back Exit Next

Fig. A.9 Sample administrative personnel class form

Part Cost Results Form

The **Part Cost Results** form, shown in Fig. A.10, gives a distribution of the total cost for producing a unit of a product across all cost components associated with the manufacturing of each part. The total cost includes the cost incurred in-house to manufacture the part plus the cost of the parts which are purchased from outside. The *Print button* is for printing the form. The *Back button* and *Next button* are for navigating back and forth within the application. The *Exit button* is for ending the application.

The screenshot shows a window titled "Results" with a blue title bar. Inside, the heading "Results for Part 1" is centered. To the right of the heading is a yellow "Print" button. Below the heading is a table with two columns: the left column lists cost components, and the right column shows their corresponding values in white text boxes. The components and values are: "Cost of machines per unit (part)" (2.039), "Cost of materials per unit (part)" (0.89), "Cost of administrative personnel per unit (part)" (35.67), "Cost of direct operators per unit (part)" (38.13), "Cost of indirect workers per unit (part)" (9.963), "Cost of material handling per unit (part)" (4), "Estimated Unit Cost" (90.692), and "Additional cost" (9.069). Below the table, a text label states: "Additional cost includes: Building cost, Maintenance cost, Utility cost, etc. (10% of estimated cos)". At the bottom of the window, there are three yellow buttons: "Back", "Exit", and "Next".

Results for Part 1	
Cost of machines per unit (part)	2.039
Cost of materials per unit (part)	0.89
Cost of administrative personnel per unit (part)	35.67
Cost of direct operators per unit (part)	38.13
Cost of indirect workers per unit (part)	9.963
Cost of material handling per unit (part)	4
Estimated Unit Cost	90.692
Additional cost	9.069
Additional cost includes: Building cost, Maintenance cost, Utility cost, etc. (10% of estimated cos)	
Total unit cost of part	99.761

Back Exit Next

Fig. A.10 Sample part cost results form

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