Chapter 10. Facilities Design

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10.1. Facilities Design Definition

Facilities Design *is the planning and design of the physical environment of an activity to best support the execution of this activity.*

In other words, facilities design attempts to organize the tangible fixed assets of an activity in such way as to provide maximal support for the achievement of the activity's objectives at the present time and in the future at the lowest possible cost. This activity can take many different forms, e.g. manufacturing (plant layout), health care (hospital layout), transportation (airport layout) and services (bank layout).

Objectives of a Good Facilities Design

1. The facilities design should first and foremost enable and support the activity. This implies that it must enable the throughput requirements, storage requirements, and flow time requirements.
2. A secondary characteristic is that the activity can be executed at minimal cost for the given set of throughput, storage, response time requirements. Conflicting objectives at this level are increasing server utilization and decreasing the material handling cost, which consists of storage and transportation costs.
3. Finally, a good facility is flexible and robust enough so that it can accommodate server and material handling device breakdowns and that it can be adapted to a different product mix.

Cost Associated with a Facilities Design

A facilities design has associated fixed and variable costs. Fixed costs are incurred if an activity is executed at all. Examples are the server acquisition costs for the production function and the device acquisition costs and costs for buffer, inventory storage, aisles and transportation space for the material handling function.

Variable costs depend on the intensity of the executed activity. Examples are the unit production costs for the production function and the unit transportation costs for the material handling function.

Characteristics of a Facilities Design Project

Facilities design is a typical engineering design project and as such exhibits the main characteristics of any (large) engineering design project.

1. Facilities design is a ***complex problem***. The problem is ill defined, the objectives and constraints are fuzzy. Different people have different definitions and objectives of the project. Some constraints are implicitly assumed. Hence, there does not exist an optimal mathematical solution as in linear programming. Many, very different solutions can be equally good.
2. Facilities design is an ***interdisciplinary team effort***. No engineer can do all the work or has all the expertise. Many different groups will be using the facility and have different requirements for the facility. Communication between all the user groups and the design team is essential for the later acceptance of the facility.
3. Activities and their supporting facilities ***change constantly*** over time and the facilities design project will be redefined accordingly. Integration in a spatial and temporal master plan is essential for future efficient use of the facility.
4. The mathematical models for such a complex, fuzzy, and dynamic design problem are very hard to formulate and solve.
5. Most computer algorithms require a clear and precise statement of the problem, objectives, and constraints. The facilities design problem does not any of these, so there has been very limited success with the application of Computer Aided Layout (CAL) programs.
6. As a consequence, the design engineer is still very important in the facilities design process.

10.2. Main Facilities Design Principle

Optimize & Minimize the Material Flow

One of the major objectives of facilities design is to arrange the processing centers in such a way that the cost of material handling operations between the centers is minimized. A good facility design will always be characterized by a simple and intuitive material flow. In most instances, facilities design tries to minimize the distances traveled between processing operations.

10.3. Steps in the Facility Design Process

Facilities Design Process Steps

The facility design process follows the same steps as any engineering design process.

Most facilities design projects identify the following elements during the first two phases of the engineering design process:

1. ***Identify the major "material handling flows" in the project***. This "material flow" can be many different things depending on the facilities design application. In a hospital, patients, medical personnel, drugs, and medical supplies are all important material flows. In an airport, passengers (arriving and departing), crew, planes, and luggage are all important material flows. In a bank customer, personnel, documents, and money are examples of important material flows. Finally, in manufacturing, parts, personnel, and tools can be examples of the major material handling flows.
2. For each of the material handling flows in step 1, ***identify the major processing steps***. Again this includes a wide variety of task depending on the application. Examples are customer dining in a restaurant, luggage carousel in an airport, drug storage in the pharmacy of a hospital, etc.. The processing steps are executed in activity centers or departments.

3. Construct a graph with a column for each of the material handling flows and a row for each of the activity centers. For each of the material handling flow a line is drawn between the activity centers to indicate the order in which the centers are visited. An example of such a graph is a ***multiproduct process chart***.
4. Given the material handling flows and the activity centers ***determine the affinities between the activity centers*** in a common unit. If only material handling flows are present, then this is a relatively easy step. The material handling load such as a pallet of fork lift truck trip might be the common material handling unit. If other affinities are also present, then their size must be carefully determined to be consistent with the material flow units. Examples of positive affinities are the desirability of having windows in offices and cafeterias, which implies a location on the perimeter of the layout. Examples of negative affinities are welding (which produces sparks) and painting (which produces combustible vapors) departments, vibration pollution between a stamping and a measuring department and noise pollution between a sawing and an office department. Once a common handling unit has been defined, the flows in the above graph can now be quantified. All material handling flows and other affinities are then summarized in a relationship matrix also called a from-to matrix, which has as elements the sum of the affinities between two departments for all major material handling flows.
5. Given the material handling flows that need to be processed in each of the activity centers, compute the number of individual servers required in each activity center. Finally, based on the number of servers and the required area for each server and possible space for waiting area for the server, compute the required area for each activity center.

10.4. Characteristics of a Good Facilities Design

Growing Cost of Modifications

The cost of making changes to a design project grows exponentially over time. This can best be illustrated by Figure 10.1.

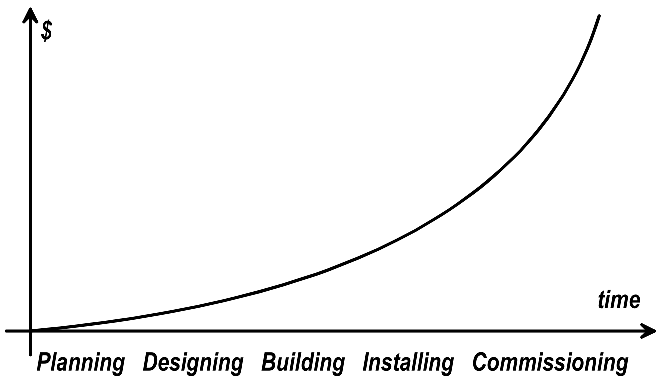

Figure 10.1. Exponential Cost of Design Changes

Design for Integration

Hence the current facilities design project should be integrated with the overall spatial and temporal master plan of the organization. Future expansions, contractions, and relocations of the material flow should be anticipated and planned for.

Design for Flexibility

To adapt to the constantly changing environment, business systems themselves must also change. The changes in product, production techniques and equipment have accelerated in the recent years. To minimize the long-term costs the facilities should accommodate this change. Hence facilities should be designed with flexibility and change in mind. One might call such easily reconfigurable facilities "agile facilities." Designing for future flexibility must be traded off with designing for maximal efficiency for the current system.

10.5. Product, Process, Schedule, and Facilities Design

Product Design

Product design involves both the determination of which products are to be produced and the detailed design of individual products. It answers the basic question ***WHAT*** will be produced.

Process Design

Process design involves the determination of required type and sequence of production steps to manufacture a product. This includes the classical "make-or-buy" decision. It answers the basic question ***HOW*** will be produced.

Schedule Design

Schedule design involves the determination of which quantities at what times will be produced. Schedule design philosophies such as "Material Requirements Planning" (MRP) and "Just In Time" (JIT) can help answer these questions. It answers the basic question ***HOW MUCH*** and ***WHEN*** will be produced.

Facilities Design

Facilities Design involves the determination of the design of the physical environment of an activity. It answers the basic question ***WHERE*** will be produced.

Integrated Design

To achieve the highest efficiency, the design of product, process, schedule and facilities should occur concurrently and in an integrated way. This principle is also partially expressed by "designing for manufacturability" concept. The principle is illustrated graphically by Figure 10.2.

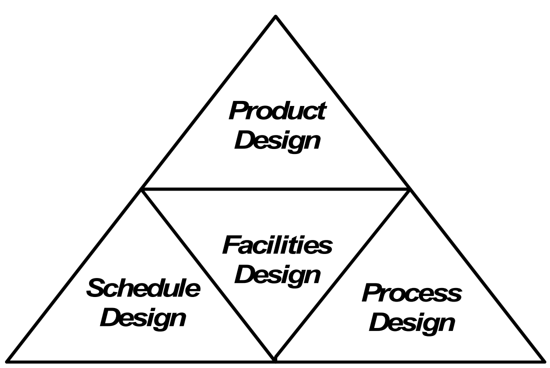

Figure 10.2. Integration of All Design Activities

The major manufacturing production system types and their associated layouts will be discussed in the next chapter on Manufacturing Systems.

10.6. Facilities Design Phases

Facility Location

Facility location determines the location of the production facility to be designed. This placement is important with respect to customers, suppliers, labor force, and other facilities with which it interfaces. Facilities location decisions are often made by the highest level of management and are based very often on political and financial considerations. A schematic illustration the facilities location problem is given in Figure 10.3. Facilities location will not be further discussed in this text.

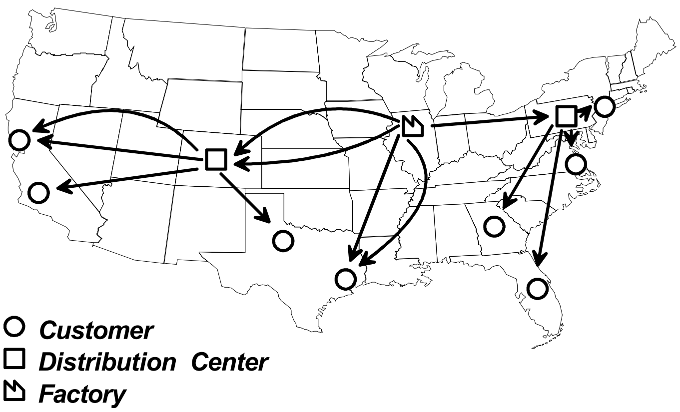

Figure 10.3. Facility Location

Conceptual Block Layout

Based upon the major flow patterns and the required areas, the general shape, relationships and location of each department are established. Each functional unit or department is represented by a simple block without any further details. An example of a conceptual block layout is given in Figure 10.4. The design of the conceptual block layout is the major task and opportunity for contribution of the industrial engineer.

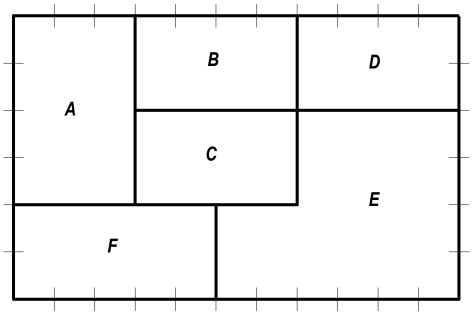

Figure 10.4. Conceptual Block Layout

Material Handling Layout

This layout shows the block layout of the departments and the major material handling areas such as aisles and storage systems, and the location of the interface points between the departments and the material handling system. An example of a material handling layout is given in Figure 10.5.

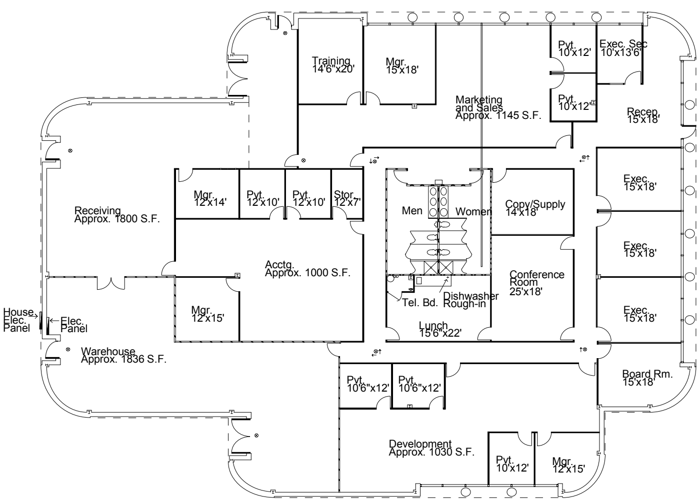

Figure 10.5. Office Material Handling Layout Example

Detailed Technical Layout

This layout is based on the material handling layout and includes all the details such as construction materials and details, exact position of production and material handling equipment, support networks such as electricity, water, sewer, local area networks, etc… The detailed technical layout is the result of a team effort of many engineering disciplines such as civil, electrical, industrial, mechanical, etc…

Layout Implementation

The layout is approved, scheduled and executed, i.e., the facility is constructed.

10.7. Facilities Design Types

Manufacturing Facilities

In this case the term ***Plant Layout*** is also frequently used instead of facilities design.

Main Manufacturing Systems Characteristics

Plant layouts for manufacturing operations can be divided into five general types depending on two main characteristics:

1. The ***number of different products*** manufactured. The larger the number of different products that can be manufactured, the more ***flexible*** the production system is.
2. The ***number of units manufactured*** of each product type. This is also called the batch or lot size. The more units manufactured of each product, the more ***efficient*** and specialized the production process can be.

Manufacturing Efficiency

Manufacturing efficiency is the percentage of the time a plant is actually producing, i.e. adding value to the products. This percentage is averaged over the whole year and includes vacation, weekends, nights, intermediate product storage, etc.. For example, a plant which operates a single shift of 8 hours during the regular workweek has a efficiency of approximately 22 %. This assumes continuous production on a part during the 8-hour shift, i.e. the products are never stored or waiting during this shift.

This number is arrived at by subtracting 104 days for weekends, 5 days for holidays, and 10 workdays for vacation from 365 days in a year to yield 246 work days. Each day is equivalent to 8 hours for a total of 1968 hours. The total number of available hours in a year is $365 \cdot 24 = 8760$. The ratio of 1968 hours worked over 8760 hours available yields 22 %. A first order approximation of this efficiency can be found by taking the number of working hours in a week (40 hours) and dividing it by the length of a week in hours (168 hours), which yields 24 %.

Point-Of-Use or POU denotes the warehousing philosophy where the parts, that are to be used in a manufacturing process, are not delivered to a central receiving department and then stored in a warehousing department but instead are delivered directly to the department where they will be assembled into the product. An example is the delivery of tires or seats to automotive assembly plants. Seats and tires have a low value to volume ratio and cost can be significantly reduced by not storing and handling the tires inside the assembly plant. The tires remain stored in the trailer, which is parked at a truck dock in the workstation area where the tires are put on the cars. Four tires are removed from the trailer and put directly on the car without ever having been stored in the assembly plant. From a layout perspective, this means that many departments now have a positive relationship or affinity with the outside and must be located on the perimeter of the building. It also means that the building will have many truck docks all around its perimeter instead of just in the shipping and receiving departments. This layout characteristic is also denoted by perimeter access.

Warehousing Facilities

Design of distribution centers, warehouses for raw materials and finished products. The warehousing function is responsible for storage, handling and control of the material. The design of container ports is also included with warehousing facilities.

Office and Service Facilities

Examples are office layouts, health care layouts such as hospitals, service layouts such as banks and airports. In this case the material flow can correspond to the flow of people or documents.

Military Facilities

Historically, military facilities have the added requirements that have to be easily defended and that access can be tightly controlled.

10.8. Layout Types

In most production operations there is always a tradeoff between the conflicting objectives of maximizing the utilizations of the production equipment versus maximizing the throughput and minimizing the flow time of the products. For example, the extremely expensive processing equipment in the manufacturing of printed circuit wafers focuses all the attention on its utilization and causes very long production flow times for the wafers and complex material flows. On other side of the spectrum, the overriding concern in the manufacturing of incandescent light bulbs is maintaining the high production volume, without product delays or detours.

Continuous Production Layout

In a continuous production system the products flow through a series of directly connected processes or operations, without intermediate storage or material movement. This type of operation is very common in the chemical industry, like refineries and chemical processing plants.

Continuous production is usually only applicable to bulk, gas, or liquid products, but it is the goal for many of the current day discrete part manufacturing philosophies. JIT (Just-In-Time), POU (Point-Of-Use) all attempts to produce a product in one smooth and uninterrupted sequence.

The material flow is very inflexible and there is no intermediate storage of products (i.e. all products are always being worked on or change status). The number of different products that can be manufactured is very limited and determined at the time the plant is build. One of the major cost and engineering design challenges occurs when a product with a slightly different processing sequence has to be manufactured in the plant, since there usually is not sufficient place to insert new processing equipment in the original layout. If a truly different product has to be manufactured, very often the facility has to be broken down and rebuild to suit the new product. Manufacturing efficiency is very high (96 %) since very large quantities of each product are manufactured 24 hours a day, 7 days a week.

Even though the layout of continuous production facilities in the chemical and petrochemical industry has a number of specific characteristics and constraints, the main objectives and methodologies of facilities design remain valid. See Georgiadis et al. (1997) for a discussion of layout in the chemical industry.

A continuous production layout involves directly connected processes without intermediate storage or revisiting a particular process. This type of layout is very specialized and mostly applies to the manufacturing of bulk, gas, and liquid products. The typical example is a chemical plant or oil refinery.

This type of layout is important to the discrete parts manufacturing because it represents the goal of discrete parts manufacturing, since inventory and system flow time are at their minimal levels. On the other hand, these facilities are highly specialized and changing the products usually involves fundamentally changing the facility.

The following layout types are used in discrete parts manufacturing and to illustrate their characteristics an example with seven products is used. The process sequences for the different products of the example are illustrated in the next figure. The graphical illustrations for this example were created Montreuil and are here used with permission.

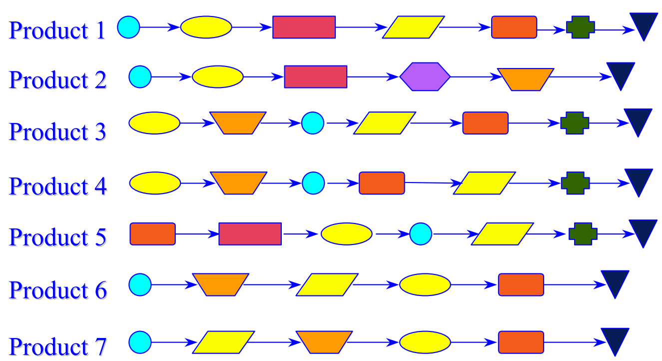

Figure 10.6. Processing Sequences for the Various Products

Product Layout

The overall production planning and layout is determined by the ***product***. Successive production units undergo the very similar sequences of operations and the processing equipment is arranged in the sequence required for producing the products. The manufacturing environment consists of large quantities manufactured on specialized machines for mass production. There is a limited number of different products with only minor variations.

The material flow diagram follows the production process and is very simple and linear in most cases. No back flow of products is allowed, i.e. units never visit the same machine twice during the production process and there is minimal distance between equipment that executes successive operations. Such a layout is called a product layout. An example is the transfer line in a car assembly line. Manufacturing efficiency is high for discrete parts manufacturing, up to 22 % for each shift. More than one shift is usually in operation.

In a product layout, all characteristics are dominated by the various products. Another name often used is flow shop. This production and layout type is mostly used for mass production of products. Examples are automotive assembly lines and manufacturing lines for consumer goods. The layouts are characterized by extremely simple material flows, either in a straight line or in simple line patterns such as U and L shapes.

The processing centers are organized following the sequence of processing steps for each of the products. One or more processing steps may be combined into a single processing center, but the sequence is never modified. The allocation of the processing steps to processing centers for the first product is illustrated in the next figure and the product layout for all products in Figure 10.8.

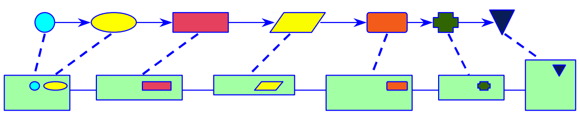

Figure 10.7. Processing Steps to Processing Center Allocation for Product 1

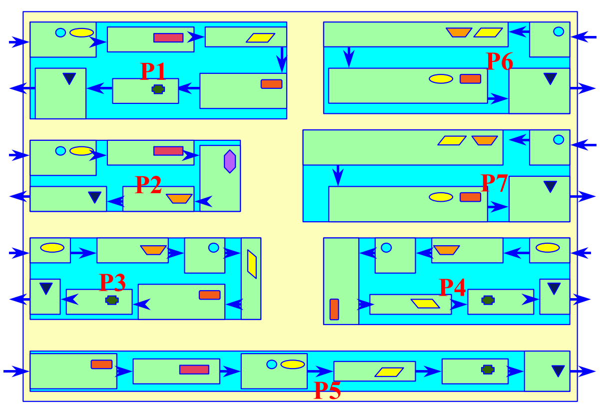

Figure 10.8. Product Layout

Process Layout

The overall layout is determined by the ***different processes***. Machines are grouped by function to produce a multitude of products and they are located without regard for the material movements of the products. The manufacturing environment consists of small order quantities with varying production routings. The number of units of each product is very small, typically less than a dozen. This layout is associated with a job shop and is called a process layout. A very large variety of products is being produced and most of the manufacturing experience is accumulated in the labor force. Hence, the objective is to keep all the workers familiar with a particular process concentrated in one area where they may control more than one machine. The material flow is very dense and complex and is sometimes called spaghetti flow. An example is a machining tool manufacturing shop.

The actual manufacturing efficiency is very low (around 6 % for each shift) and only one shift is usually used because of resistance of the higher labor grades.

In a process layout, all the characteristics are determined by the various processes. The activity centers consists of one or more servers that execute the same process. Another name for this production mode is job shop. Typical applications are small batch manufacturing. Examples are the wafer manufacturing for integrated circuits and microprocessors and a residential kitchen. The major disadvantage of the process layout is a very complex material flow all over the manufacturing facility.

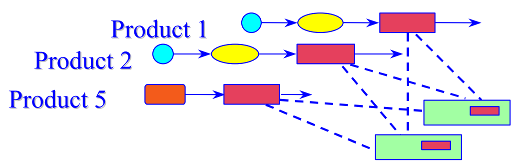

Figure 10.9. Processing Steps to Processing Center Allocation for a Process Layout

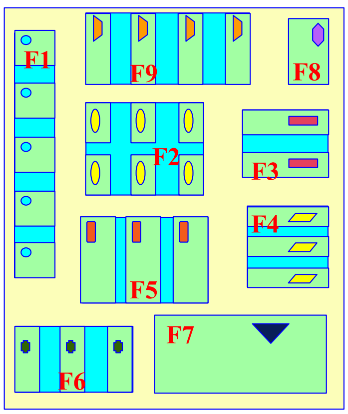

Figure 10.10. Process Layout

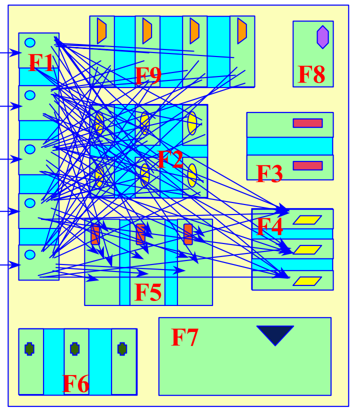

Figure 10.11. Product Flows In and Out of Activity Center F1

Cellular Layout

Clusters of machines are grouped together into machine cells to perform a specific group of operations on a specific group of similar products, which is called a product family. This operation is associated with batch production, where a limited number of similar products based on group technology is manufactured intermittently in limited quantities. The material flow has a two level, hierarchical structure. The material flow is very simple, almost linear, and sparse between the machining cells. The material flow inside the cell can be very complex and dense, but is usually handled by a single material handling device. The cells are usually circular or U-shaped. Because of the proximity of the machines in a cell, internal material transport can be executed very quickly and efficiently even with the dense and complex internal material flow.

The standard examples are small industrial machines or tools such as engine blocks and pumps.

The efficiency is the highest for discrete parts manufacturing, up to 25 % per shift (usually two to three shifts are in operation because of the large degree of automation). The key factor for efficiency is the correct identification of machine cells and product groups.

A cellular layout attempts to combine the advantages of the product and the process layout by creating groups of related products and cell of all the machines required for the production of a single group of products. The cells are heterogeneous since they contain different types of servers and machines. Typical application are batch production of related products. An example is the manufacturing of various models and sizes of industrial pumps. Clearly, the success or failure of the cellular layout depends on the quality of the group formation process. This is the topic of group technology. To remain efficient, the groups have to remain stable. The material flows between the different manufacturing cells are minimal and very simple, the material flows inside a cell are more dense but still linear because all products in the group have a similar or identical sequence of processes.

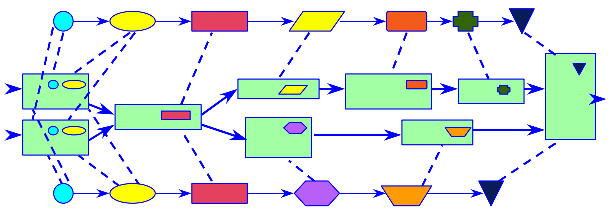

Figure 10.12. Processing Steps to Processing Center Allocation for a Cellular Layout

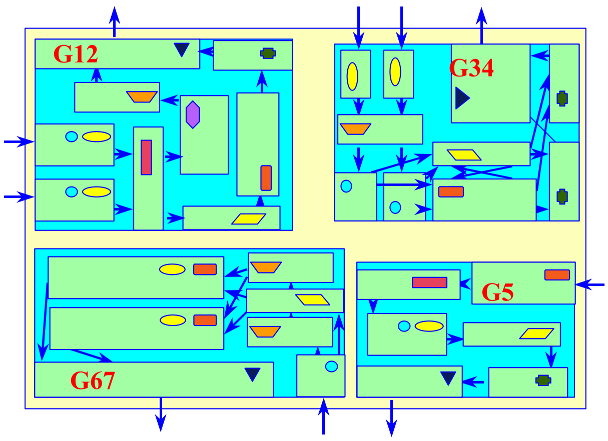

Figure 10.13. Cellular Layout

Fractal Layout

In a fractal layout near-identical and heterogeneous cells of machines are repeated in the manufacturing plant. Since each cell has nearly all of the machines, it can handle any product in the plant. A new product or a product with expanding volume can be assigned to a cell that is less utilized. The main advantage of a fractal layout is that it remains efficient when the product families change.

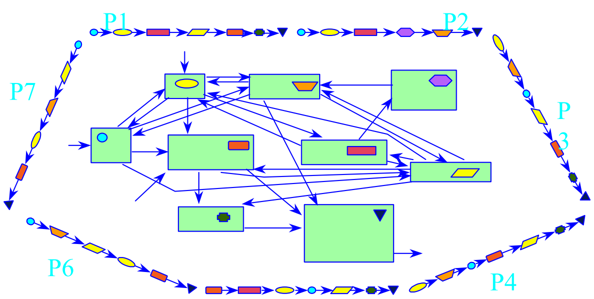

Figure 10.14. Processing Steps to Processing Center Assignment for a Fractal Layout

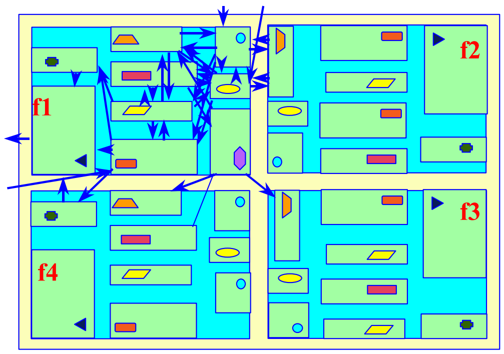

Figure 10.15. Fractal Layout

Holonic Layout

In the process layout the principle was to concentrate all servers of a particular type in one region of the layout. The holonic layout has exactly the opposite principle in that all servers of a particular type are uniformly distributed throughout the plant. When a particular product needs a server of a particular type, such a server is assignment based on its proximity and utilization. The main advantage of the holographic layout is that it can handle varying and unpredictable product mixes. The holonic layout also has been called a holographic layout by several authors.

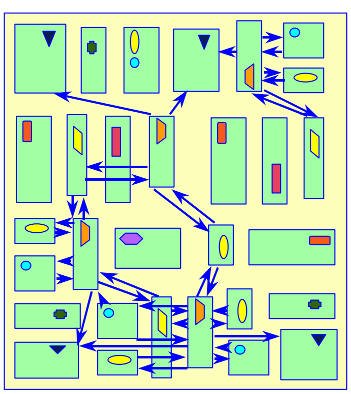

Figure 10.16. Holonic Layout

Up to this point we have only discussed cells that were assigned permanently to a particular product. The factory can also be organized in a set of virtual cells, that are responsible for the production of a group of products but the grouping of these cells is only at the logical level. No physical rearrangement is done. When those products are currently not produced, the cells are disbanded and the individual processors get assigned to another virtual cell. The main advantage of the holonic layout is that the virtual or temporary cells have a relative compact shape. If the same virtual cells were formed in a process layout, the cells would not have a compact shape.

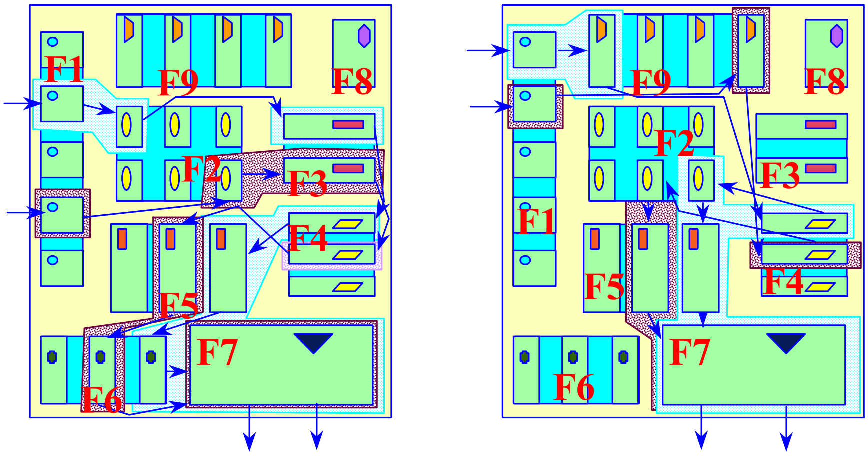

Figure 10.17. Two Possible Virtual Cells for Products 1 and 6 in a Process Layout

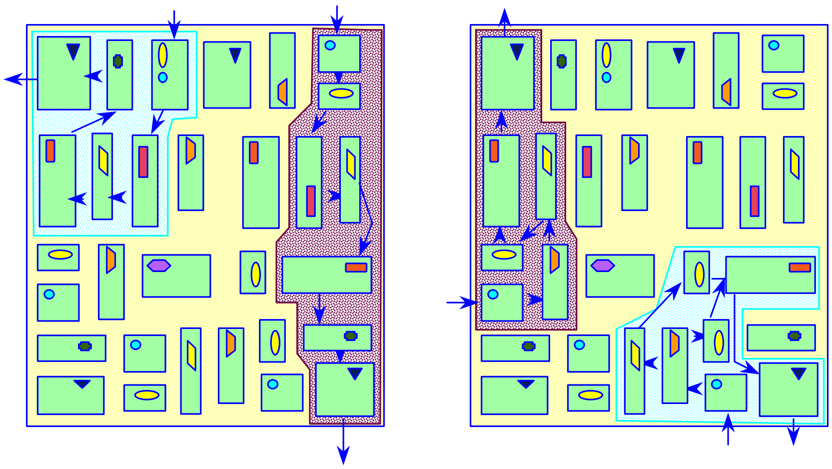

Figure 10.18. Two Possible Virtual Cells for Products 1 and 6 in a Holonic Layout

Project Layout

Manufacturing of a unique or immobile product. Instead of the product being transported to the machines, the machines are being transported to the product. The material flow is radial, i.e. like the spokes of wheel, towards the product that is located in the hub of the wheel. Typical examples are ship building, diesel engine assembly for locomotives, or satellite assembly. The lot size is almost always one or very small.

Efficiencies are very hard to measure, but are considered to be even lower than with process layouts.

In a project layout a unique or immobile product dominates all characteristics. Usually only a single type of product is produced in the plant. An example is satellite assembly or the assembly of heavy engines for rail transportation. The material flow has a radial pattern like the hub and spokes of a wheel, with the assembly site at the hub.

Comparison of Product and Process Layouts

Two main criteria for judging manufacturing operations are flexibility versus efficiency. Flexibility is ability to make many different products in different order quantities. Efficiency is the ability to make products at a low marginal cost and high throughput rates. In Table 10.1 the product and process manufacturing operations are compared with respect to several criteria.

Table 10.1. Comparison of Product and Process Manufacturing

Characteristic	Product	Process
Flexibility		
Efficiency		
Order Quantities		
Number Different Products		
Number Machine Types		
Machine Downtime Cost		
Material Flow Complexity		
Work in Process		
Product Flow Time		
Machine Utilization		
Unit Production Cost		
Quality Consistency		

10.9. Layout Methodology Definitions

Activity Centers or Departments

An ***activity center***, also commonly called a ***department***, is a compact area that has a homogeneous material flow with the rest of the facility so that it can be treated as a single unit (with respect to material flow).

Its area should not be too small, since otherwise it is not important enough to be considered separately. A rule of thumb is an area larger than 3 % of the total facility area. This means that the number of departments should be limited to 35. Its area should also not be too large, since the material flow might no longer be homogeneous over the area of this department.

Activity Relationships

The pairwise ***relationship*** between two departments expresses the affinity between these two departments, based on material flow and environmental considerations. Relationships can be numerical (quantitative) if accurate information is available, or symbolic (qualitative). The closer together one would like these departments to be, the more positive their relationship. A negative relationship means that it is desirable to keep the two departments separate, e.g. for noise or vibration pollution. The table of relationships is called a relationship chart or relationship matrix. An example of a qualitative relationship chart is shown in Figure 10.2. Possible representations of qualitative relationships are given in Table 10.3.

Table 10.2. Qualitative Relationship Chart

	A	B	C	D	E	F	G
A		E	O	I	O	U	U
B			U	E	I	I	U
C				U	U	O	U
D					I	U	U
E						A	I
F							E
G							

Table 10.3. Qualitative Relationships Representation

Closeness	Letter	Lines	Color
Absolute Necessary	A	4	Red
Especially Important	E	3	Orange
Important	I	2	Blue
Ordinary Closeness	O	1	Green
Unimportant	U	No	None
Undesirable	X	Wave	Brown

Conversion of a Multiproduct Process Chart to From-To Matrix

All the flows for the different products have to be expressed in a common unit. If the products are about the same size and weight, then these units can be the product flow, otherwise volume (cubic feet) or weight (pounds) can be used as common unit.

For each pair of origin and destination departments, the flow for all the products is added and placed in the corresponding cell of the from-to matrix.

Conversion Example

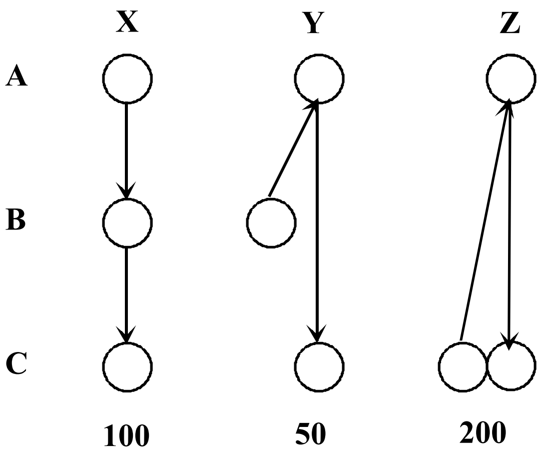

Figure 10.19. Multiproduct Process Chart

Table 10.4. From-To Matrix

	A	B	C
A	-	100	250
B	50	-	100
C	200	0	-

Layout Stages

Conceptual Block Layout

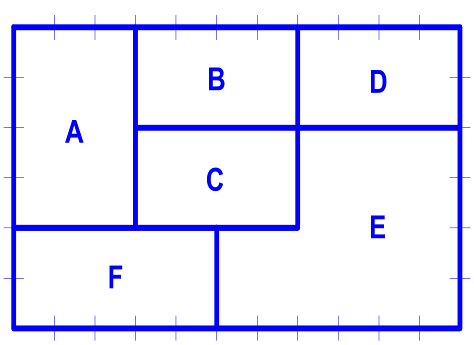

Figure 10.20. Conceptual Block Layout Example

Material Handling Layout

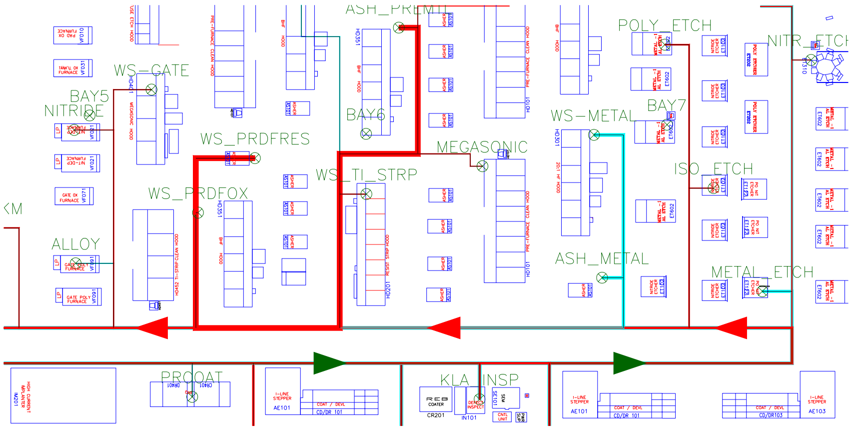

Figure 10.21. Material Handling Layout Example

Layout Algorithms

Construction versus Improvement Algorithms

There exist two major classes of algorithms. ***Construction*** algorithms design a layout from scratch, i.e. from raw numerical data such as the flow chart and area requirements. ***Improvement*** algorithms design a layout by modifying and improving an existing layout and hence require an initial feasible layout.

Area Based versus Graph Based Algorithms

There exist two major types of algorithms. Some algorithms are based on locating the areas of departments in a layout, these algorithms usually try to *minimize* the *distance score* of the layout. A second group of algorithms is based on determining the relative position of departments in a layout ignoring the area requirements of the departments. These algorithms try to *maximize* the *adjacency score* of a layout.

Discrete versus Continuous Layout Algorithms

Discrete layout algorithms divide the building and each department in a number of equal sized unit squares. The design decision is then to locate the unit squares of each department in the unit locations of the building. The coordinates of the vertices of the departments are integer multiples of the size of the unit square. Continuous layout algorithms allow the vertices of the departments to be located anywhere in the building area and thus the vertex coordinates can be fractional numbers.

Algorithm Components

Data Requirements

There are two major categories of required data.

The first category contains the *relationship data* between the departments (and the outside or building). These relationships can be given in qualitative form or in a quantitative form. The prime examples are the (qualitative) letter relationship chart and the (quantitative) flow chart.

The second category contains the *spatial requirements*. The departments areas are always required for area based algorithms. Sometimes the building area is required. Some of the programs also require the shape of each department and/or the building.

Department Selection Rule

A layout algorithm must specify at least two sets of rules or procedures for layout generation. The first set is called the *selection* procedure and it specifies in what order the departments will enter the layout (for a construction procedure) or will be considered for exchange (for an improvement procedure).

Department Location Rule

The second set is the *location* procedure and it specifies where the next department, as determined by the selection procedure, will located in the layout or where it will be located in the exchange. The department selection and department location rules can be combined into a single procedure.

Layout Evaluation Rule

The program must also specify a set of rules or evaluation procedure, which will assign a score to the obtained layout. For the *distance score* this usually is the product of the distance and the relationship matrices; for the *adjacency score* this usually is the product of the adjacency and relationship matrices. Further details on layout evaluation will discussed in the section on Layout Evaluation.

Special Functions

Facilities design algorithms can have several special characteristics such as

- the ability to fix departments in the building

- the ability to fix the building shape
- the ability to incorporate relationships with the outside
- the ability to handle multiple floors
- its user friendliness rating

Most facilities design algorithms are incorporated in computer programs. Three major categories of *user friendliness* of these programs can be distinguished. First generation programs require formatted batch input on punch cards and generate printed reports consisting of alphanumeric symbols. Their user friendliness is considered to be low. Second generation programs have interactive keyboard and CRT input and generate alphanumeric CRT output. Their user friendliness is considered to be medium. Third generation programs have interactive CRT and pointing devices (such as a mouse, a light pen and/or tablet) and generate color graphics CRT output. Their user friendliness is considered to be high.

10.10. Systematic Layout Planning or SLP

Steps in the SLP

Muther (1973) has developed a systematic way of constructing a layout. The steps are best illustrated by Figure 10.22. The SLP method attempts to create a good layout by introducing systematically more complicating factors in the design process.

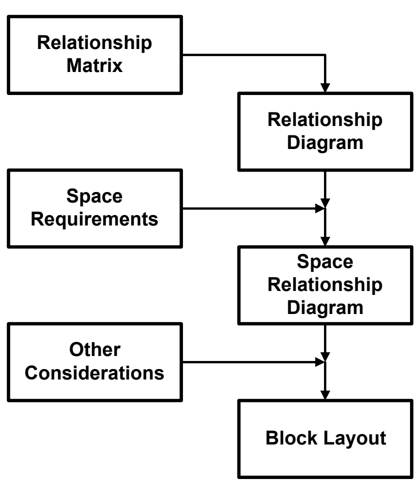

Figure 10.22. Systematic Layout Planning (SLP) Diagram

	A	B	C	D	E	F	G
A		45	15	25	10	5	
B				30	25	15	
C					5	10	
D		20			35		
E						65	35
F		5			25		65
G							

Figure 10.23. Relationship From-To Matrix

A relationship diagram positions departments in their relative position, while ignoring the space requirements of each department. A neutral symbol of the same size is used to represent departments. Relationships are shown with line coding or color coding. An illustration of a relationship diagram is given in Figure 10.24.

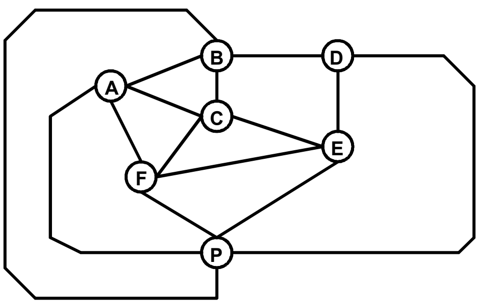

Figure 10.24. Relationship Diagram

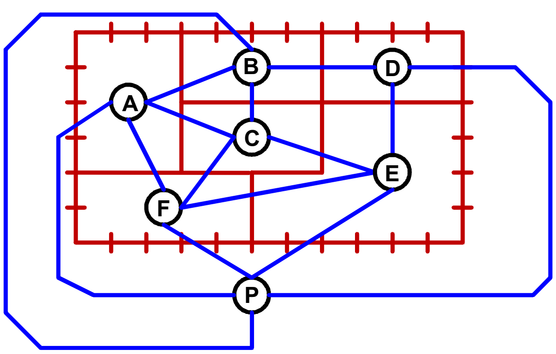

Figure 10.25. Relationship Diagram and Block Layout as Dual Graphs

A simple manual technique to generate a relationship diagram is the Spiral technique. The spiral algorithm can be executed on numerical or symbolic information. The Spiral algorithm is discussed in further detail in the Chapter on Computer Aided Layout.

Space Requirements

Space requirements are based on industry norms and health and safety rules.

The combination of the spatial relationship diagram and the space requirements is called the space relationship diagram. It is not yet a layout because it does not incorporate other considerations such as building shape.

Other Considerations

Other considerations include factors such as the building shape, department shapes, building supports, etc. After these considerations are incorporated, several alternative layouts can be generated.

10.11. Discrete Layout

Spacefilling Curves

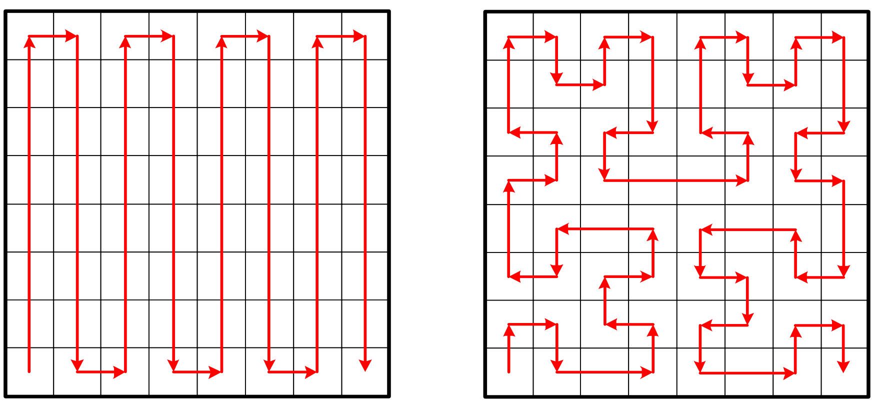

Figure 10.26. Spacefilling Curve Examples (Serpentine and Hilbert-19)

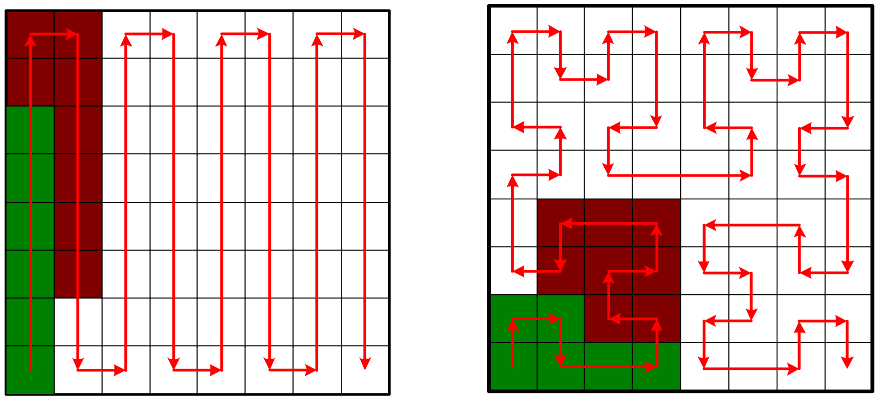

Figure 10.27. Department Locations Based on Spacefilling Curves (Serpentine and Hilbert-19)

10.12. Layout Evaluation

Adjacency Score

The adjacency score requires the information if corner adjacency is sufficient or if (regular) side to side adjacency is required. Corner adjacency requires only that the departments touch each other in one point, side to side adjacency requires that the departments have a common boundary of non zero length.

The adjacency score is the sum of the pairwise products of the relationship matrix with the adjacency matrix. The adjacency matrix has a one on the intersection of row and column if the two corresponding departments are adjacent, a zero otherwise. This measure is based on the notion that it is very cheap to pass products to an adjacent machine (requiring no external material handling), but that it is expensive to transport products between non-adjacent machines. The adjacency score is to be maximized by a good layout.

To score the graph, the sum of all **P**ositive relationships between **A**djacent departments will be denoted by PA. The sum of all **N**egative relationships between non-adjacent or **S**eparated departments will be denoted by NS. The sum of all **P**ositive relationships between non-adjacent or **S**eparated departments will be denote by PS, and the sum of all **N**egative relationships between **A**djacent department will be denoted by NA. The adjacency (A) and efficiency (e) are then computed as

$$A = PA + NA$$
$$e = \frac{PA - NS}{PA + PS - NS - NA} \cdot 100\ \% \qquad (10.1)$$

The efficiency has in its numerator all relationships that are desirable, namely positive adjacent and negative separated ones. It has in the denominator the sum of all relationships. The efficiency is thus a measure of the quality of the adjacency graph with values between 0 and 1 and invariant with respect to the magnitude of the relationships. An efficiency of 100 % indicates a perfect diagram. Ranking alternatives based on their adjacency score is equivalent to ranking them based on their efficiency. In other words, a diagram which maximizes the adjacency will also maximize the efficiency since the numerator of the efficiency is equal to adjacency minus the constant (NS + NA) and the denominator is constant.

Sometimes the inefficiency rating, denoted by i, is used to evaluate the relationships diagram. The inefficiency rating is equal to

$$i = 100\% - e \qquad (10.$$

Distance Score

Distances can be measured in many different ways, i.e. with many different norms. The most familiar is the straight-line distance or **E**uclidean norm, which is denoted by d_E. This norm is use in facilities location decisions, but not much facilities design decisions. In manufacturing facilities the **r**ectilinear distance is most predominantly used. It is denoted by d_R. This distance norm is based on the notion of material movement through a system of perpendicular aisle and cross aisles. The third commonly used distance measure is the **C**hebyshev norm, which is denoted by d_C. This norm is applicable when there is simultaneous travel in the x and y direction, such as travel of AS/RS cranes in the aisle and the travel of bridge cranes.

Given two points with coordinates (x_1, y_1) and (x_2, y_2), the respective distances are computed with the following formulas:

$$d_{ij}^E = L_2 = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \qquad (10.3)$$

$$d_{ij}^R = L_1 = |x_i - x_j| + |y_i - y_j| \qquad (10.4)$$

$$d_{ij}^C = L_\infty = \max\{|x_i - x_j|, |y_i - y_j|\} \qquad (10.5)$$

The distance computations require additional information such as which norm or distance measure should be used and where the start and end points of the material flows are located, i.e. are the distances centroid to centroid or boundary to boundary. The pairwise distances between departments are stored in the distance matrix. The distance score D is the sum of the pairwise products of the relationship matrix with the distance matrix. The most common measure is the centroid to centroid rectilinear distance, based on the notion of aisles and cross aisles. The centroid assumption is valid if no additional information is available, because the departments are defined as areas of homogeneous material flow. The distance score is to be minimized by a good layout. The distance score is composed of two elements: the internal distance score between each pair of departments and the external distance score between each department and the outside. The distance to the outside is the shortest distance of the centroid of the department to any of the four sides of the building.

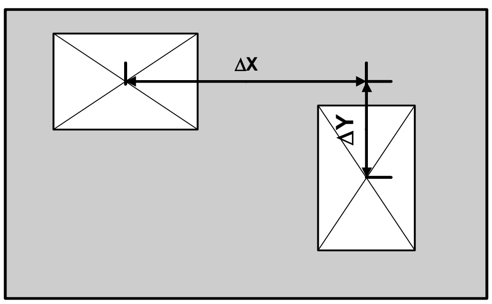

Figure 10.28. Internal Pairwise Department Distance Illustration

$$\begin{aligned} D_{int} &= \sum_i \sum_j rel_{ij} dist_{ij} \\ dist_{ij} &= \Delta x_{ij} + \Delta y_{ij} = \left| xc_i - xc_j \right| + \left| yc_i - yc_j \right| \end{aligned} \tag{10.6}$$

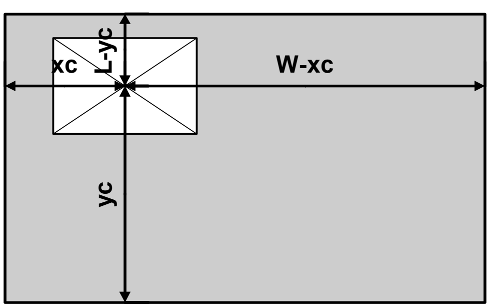

Figure 10.29. External Distance to the Outside Illustration

$$\begin{aligned} D_{ext} &= \sum_i rel_{io} dist_{io} \\ dist_{io} &= \min\left\{ xc_i, W - xc_i, yc_i, H - yc_i \right\} \end{aligned} \tag{10.7}$$

$$D = D_{int} + D_{ext} \tag{10.8}$$

The average distance d provides a measure of the distance traveled by a single load on a single trip, i.e., the expected length of a single trip. It yields a measure of layout quality irrespective of the magnitude of the material flows. The average distance is computed by dividing the distance score by the sum of the absolute values of all relationships.

$$d = \frac{D}{PA + PS - NS - NA} \cdot 100\ \% \tag{10.9}$$

Scoring Example

An example of the computation of the distance and adjacency score is given is next. Assume the layout is given in Figure 10.30, the associated adjacency matrix is given in Table 10.5 and the relationship values are given in Table 10.6. Assume further that all departments have either dimensions of 10 by 10 or 20 by 10 (as indicated in the layout) and that the distance score uses the rectilinear centroid to centroid distances. The interdepartmental distances are then given in Table 10.7.

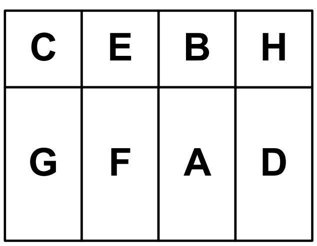

Figure 10.30. Small Layout Example

Table 10.5. Adjacency Matrix for Layout Example

	A	B	C	D	E	F	G	H
A		1	0	1	0	1	0	0
B			0	0	1	0	0	1
C				0	1	0	1	0
D					0	0	0	1
E						1	0	0
F							1	0
G								0
H								

Table 10.6. Relationship Values for Layout Example

	A	B	C	D	E	F	G	H
A		45	15	25	10	5		
B				50	25	20		
C					5	10		
D					35			
E						90	35	
F							65	
G								
H								

The adjacency score is then equal to 45 + 25 + 5 + 25 + 5 + 90 + 65 = 260. The efficiency of this layout is 260 / 435 = 60 %.

Table 10.7. Distance Matrix for Layout Example

	A	B	C	D	E	F	G	H
A		15	35	10	25	10	20	25
B			20	25	10	25	35	10
C				55	10	25	15	30
D					35	20	30	15
E						15	25	20
F							10	35
G								45
H								

The rectilinear distance score is then equal to $45 \cdot 15 + 15 \cdot 35 + 25 \cdot 10 + 10 \cdot 25 + 5 \cdot 10 + 50 \cdot 25 + 25 \cdot 10 + 20 \cdot 25 + 5 \cdot 10 + 10 \cdot 25 + 35 \cdot 35 + 90 \cdot 15 + 35 \cdot 25 + 65 \cdot 10 = 8{,}150$. The average distance traveled is then 8,150 / 435 = 18.74.

10.13. Material Handling Layout Algorithms

The SLP methodology developed by Muther can be extended to include the design of the material handling system in the facility. The material handling equipment and system design is based on the block layout and yields a material handling layout. The steps are illustrated by Figure 10.31.

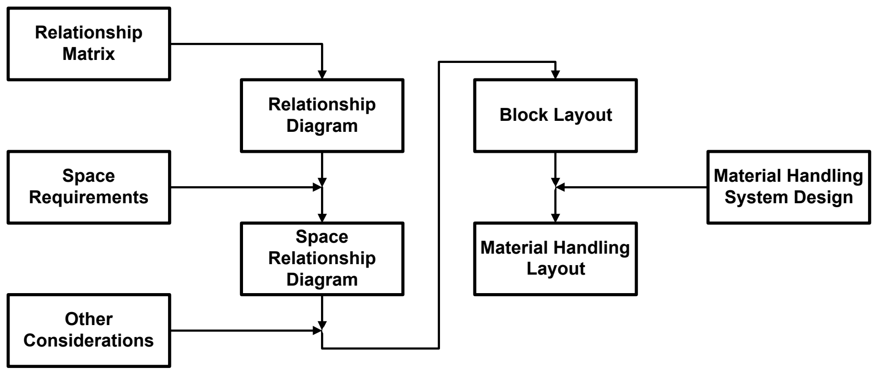

Figure 10.31. SLP Extension for Material Handling Layouts

10.14. Layout Selection

Ranking Method

Rank all evaluation methods or criteria by decreasing importance, i.e. the most important gets rank 1, and assign a column to each criteria in this order.

Construct a row for each layout alternative. In this row a one in a column indicates that this alternative layout satisfies the corresponding criteria.

Traverse columns from left to right and eliminate all criteria which have not a one in the current column, until only a single layout alternative is left.

Observe that the ranking method is not additive, i.e. any criterion is more important the sum of all following criteria.

Factoring Method

Assign a weight to each criterion. Usually the weights are normalized so that their sum adds up to 100 %. The criteria must be worded such that the alternatives that maximize the criteria are desirable.

For each alternative, fill in how much the alternative satisfies each criteria. Usually this value is normalized between zero and one.

Compute a score for each alternative by multiplying the criterion weight with the corresponding alternative value. The alternative with the highest score is selected.

Example

The criteria and their ranking for a layout evaluation are given in following Table 10.8.

Table 10.8. Selection Criteria with Their Ranking and Weight Factors

criterion	ranking	weight
D	4	8
C	2	25
A	1	60
E	5	10
B	2	30

Table 10.9 shows which alternative satisfies which criterion, which is indicated by a one in the satisfaction matrix.

Table 10.9. Satisfaction Matrix

Criterion	D	C	A	E	B
1	1	1	0	1	1
2	1	1	1	1	0
3	1	1	1	0	1
4	1	0	1	1	1
5	0	1	1	1	1

The results of the ranking method and factoring method are shown in Table 10.10 and Table 10.11, respectively.

Table 10.10. Ranking Method Example

Criterion	A	B	C	D	E	Selected
1	0	1	1	1	1	
2	1	0	1	1	1	
4	1	1	0	1	1	
5	1	1	1	0	1	
3	1	1	1	1	0	(*)

Table 10.11. Factoring Method Example

Criterion	D	C	A	E	B	Sum	Selected
1	1	1	0	1	1	73	
2	1	1	1	1	0	103	
3	1	1	1	0	1	123	
4	1	0	1	1	1	108	
5	0	1	1	1	1	125	(*)
weight	8	25	60	10	30		

Dominance Method

The weights in the factoring method are usually not known with great precision, so it is of interest to determine the range of weight values for which a particular layout is selected as the preferred one. The factoring method does not allow for such sensitivity analysis on the criteria weights. The dominance method allows this sensitivity analysis for a limited number of criteria. A graphical illustration of the sensitivity analysis of the weight of two criteria is given in Figure 10.32. Both criteria must either be minimized or maximized. In the example, the criteria are to be maximized. Six layout alternatives are considered. Their scores for criterion 1 are marked on the (left) vertical axis of criterion 1, their scores for criterion 2 are marked on the (right) vertical axis of criterion 2. For each layout alternative, those two points are then connected, corresponding to the continuous change of the weight of criterion 2. The weight of criterion 2 ranges from 0 at the criterion 1 axis to 100 at the criterion 2 axis. The weight of criterion 1 is equal to 100 minus the weight of criterion 2. The efficiency frontier or dominant alternative is then found by starting from the optimal side of the axes and moving in the direction for which the criteria values deteriorate until a line is encountered. The collection of these points for all possible weights is called the *efficiency frontier*. This efficiency frontier is marked in bold in the Figure 10.32. Observe that for a weight of criterion 2 less than 58, layout alternative five is preferred, and for a weight more than 58 the preference shifts to layout alternative one. When the weight of criterion 2 is exactly 58, then there exists a three-way tie between layout alternatives 5, 6, and 1. This range allows for sensitivity analysis. Layout alternative 2, 3, and 4 are never preferred and are said to be inefficient.

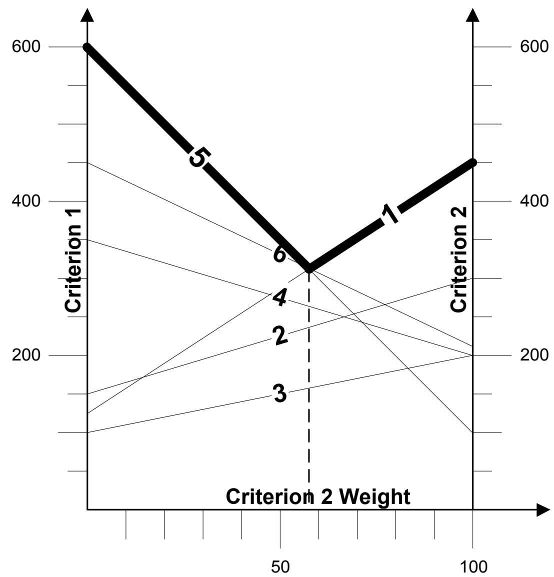

Figure 10.32. Sensitivity Analysis with Dominance Method

This analysis can be extended to a small number of criteria, but the graphics become very quickly hard to interpret.

10.15. Summary and Conclusions

Layout Algorithm Classification and Hierarchy

An overview of the algorithm hierarchy is provided in Figure 10.33.

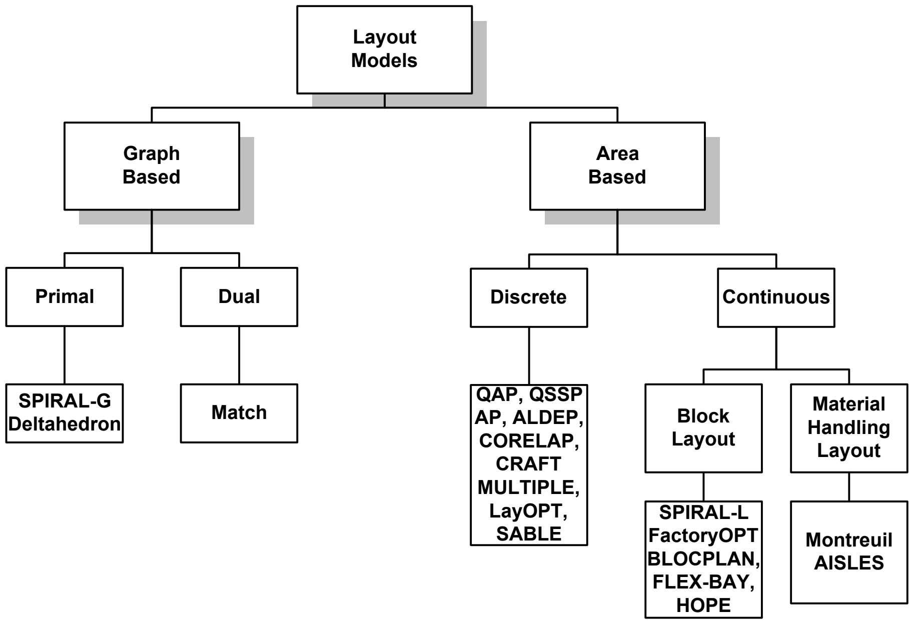

Figure 10.33. Layout Models, Algorithms, and Software Classification

Exercises

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