2

PRODUCT, PROCESS, AND SCHEDULE DESIGN

2.1 INTRODUCTION

Based on the presentation given in Chapter 1, the facilities planning process for manufacturing and assembly facilities can be listed as follows:

1. Define the products to be manufactured and/or assembled.
2. Specify the required manufacturing and/or assembly processes and related activities.
3. Determine the interrelationships among all activities.
4. Determine the space requirements for all activities.
5. Generate alternative facilities plans.
6. Evaluate the alternative facilities plans.
7. Select the preferred facilities plan.
8. Implement the facilities plan.
9. Maintain and adapt the facilities plan.
10. Update the products to be manufactured and/or assembled and redefine the objective of the facility.

The facilities planning process will be greatly impacted by the business strategic plan and the concepts, techniques, and technologies to be considered in the manufacturing and assembly strategy.

Before the 1980s, most American companies were not considering small lot purchasing and production, multiple receiving docks, deliveries to the points of use, decentralized storage, areas, cellular manufacturing, flat organizational structures, "pull" approaches with kanbans, team decision making, electronic data interchange, process quality, self-rework, multifunctional "associates," and many other concepts that are drastically changing the facilities planning process and the final facilities plan.

Among the questions to be answered before alternative facility plans can be generated are the following:

1. What is to be produced?
2. How are the products to be produced?
3. When are the products to be produced?
4. How much of each product will be produced?
5. For how long will the products be produced?
6. Where are the products to be produced?

The answers to the first five questions are obtained from product design, process design, and schedule design, respectively. The sixth question might be answered by facilities location determination or it might be answered by schedule design when production is to be allocated among several existing facilities.

Answering the sixth question has become much more complicated in recent years. Currently, many firms have global production strategies and utilize combinations of contract manufacturing and contract assembly. The textile industry, for example, has undergone tremendous change, with global sourcing occurring for yarn and textile production as well as for garment assembly. Few domestic sewing operations continue to exist in the United States.

The automobile is another example of global sourcing, resulting in the final product being called a *world car*; engines, powertrains, bodies, electronic assemblies, seating, and tires may well be manufactured in different countries. Similar conditions exist for the production of home appliances, computers, and televisions, with subassemblies and components being produced around the world.

Product designers specify what the end product is to be in terms of dimensions, material composition, and perhaps, packaging. The process planner determines how the product will be produced. The production planner specifies the production quantities and schedules the production equipment. The facilities planner is dependent on timely and accurate input from product, process, and schedule designers to carry out his task effectively.

In this chapter we focus on the product, process, and schedule (PP&S) design functions as they relate to facilities planning. The success of a firm is dependent on having an efficient production system. Hence, it is essential that product designs, process selections, production schedules, and facilities plans be mutually supportive. Figure 2.1 illustrates the need for close coordination among the four functions.

Frequently, organizations create teams with product, process, scheduling, and facilities design planners and with personnel from marketing, purchasing, and accounting to address the design process in an integrated, simultaneous, or concurrent way. Customer and supplier representatives are often involved in this process. These teams are referred to as *concurrent* or *simultaneous engineering* teams and reduce the design cycle time, improve the design process, and eliminate engineering changes. Companies implementing this integrated approach have reported impressive results in cost, quality, productivity, sales, customer satisfaction, delivery time, inventories, space and handling requirements, and building size, among others [14].

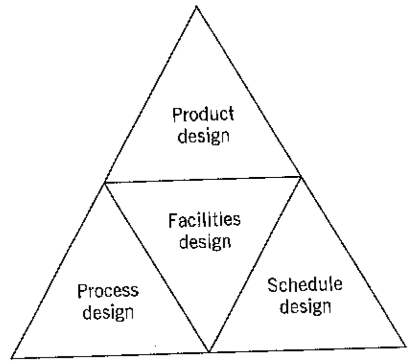

Figure 2.1 Relationship between product, process, and schedule (PP&S) design and facilities planning.

Product, process, schedule, and facilities design decisions are not made independently and sequentially. A clear vision is needed of what to do and how to do it (including concepts, techniques, and technologies to consider). For example, management commitment to the use of multiple receiving docks, smaller lot sizes, decentralized storage areas, open offices, decentralized cafeterias, self-managing teams, and focused factories will guide the design team in the generation of the best alternatives to satisfy business objectives and goals and make the organization more competitive.

In the case of an existing facility with ongoing production operations, a change in the design of a product, the introduction of a new product, changes in the processing of products, and modifications to the production schedule can occur without influencing the location or design of the facility.

In many cases, however, changes in product, process, and schedule design of current manufacturing facilities will require layout, handling, and/or storage modifications (especially if the design change requires more or less inventories, space, people, offices, and machines).

In this chapter, we are concerned with the interactions between facilities planning and PP&S design. Hence, we assume either a new facility or a major expansion/modification to an existing facility is being planned.

The *seven management and planning tools* methodology presented in Section 2.5 illustrates the integration of the facilities design process for a given scenario.

2.2 PRODUCT DESIGN

Product design involves both the determination of which products are to be produced and the detailed design of individual products. Decisions regarding the products to be produced are generally made by top management based on input from marketing, manufacturing, and finance concerning projected economic performance. In other instances, as illustrated in Chapter 1, the lead times to plan and build facilities, in the face of a dynamic product environment, might create a situation in which it is not possible to accurately specify the products to be produced in a given facility.

The facilities planner must be aware of the degree of uncertainty that exists concerning the mission of the facility being planned, the specific activities to be performed and the direction of those activities. As an illustration, a major electronics firm initially designed a facility for semiconductor manufacture. Before the facility was occupied, changes occurred in space requirements and another division of the company was assigned to the facility; the new occupant of the site used the space for manufacturing and assembling consumer electronic products. As the division grew in size, many of the manufacturing and assembly operations were off-loaded to newly developed sites and the original facility was converted to predominantly an administrative and engineering site.

Depending on the type of products being produced, the business philosophy concerning facilities, and such external factors as the economy, labor availability and attitudes, and competition, the occupants of a facility might change frequently or never change at all. Decisions must be made very early in the facilities planning process regarding the assumptions concerning the objectives of the facility.

If it is decided that the facility is to be designed to accommodate changes in occupants and mission, then a highly flexible design is required and very general space will be planned. On the other hand, if it is determined that the products to be produced can be stated with a high degree of confidence, then the facility can be designed to optimize the production of those particular products.[1]

The design of a product is influenced by aesthetics, function, materials, and manufacturing considerations. Marketing, purchasing, industrial engineering, manufacturing engineering, product engineering, and quality control, among others, will influence the design of the product. In the final analysis, the product must meet the needs of the customer.

This challenge can be accomplished through the use of Quality Function Deployment (QFD) [1]. QFD is an organized planning approach to identify customer needs and to translate the needs to product characteristics, process design, and tolerances required.

Benchmarking can also be used to identify what the competition is doing to satisfy the needs of your customer or to exceed the expectations of your customer [8]. It can also be used to identify best practices and the best of the best organizations.

Through QFD and benchmarking, product designers can focus their work on customer needs being met marginally or not at all (compared to the competition and to the best organizations).

Detailed operational specifications, pictorial representations, and prototypes of the product are important inputs for the facilities planner. Exploded assembly drawings, such as that given in Figure 2.2, are quite useful in designing the layout and handling system. These drawings generally omit specifications and dimensions, although they are drawn to scale.

As an alternative to the exploded assembly drawing, a photograph can be used to show the parts properly oriented. Such a photograph is given in Figure 2.3. Photographs and drawings allow the planner to visualize how the product is assembled, provide a reference for part numbers, and promote clearer communications during oral presentations.

[1]Minor changes in product design and the addition of similar products to the product family would be included in this scenario.

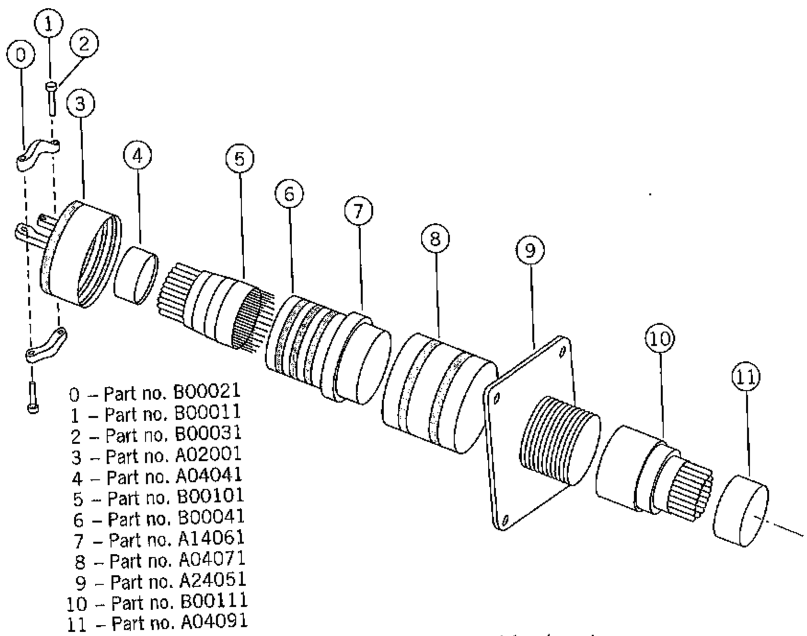

Figure 2.2 Exploded assembly drawing.

Detailed component part drawings are needed for each component part. The drawings should provide part specifications and dimensions in sufficient detail to allow part fabrication. Examples of component part drawings are given in Figures 2.4 and 2.5. The combination of exploded assembly drawings and component part drawings fully documents the design of the products.

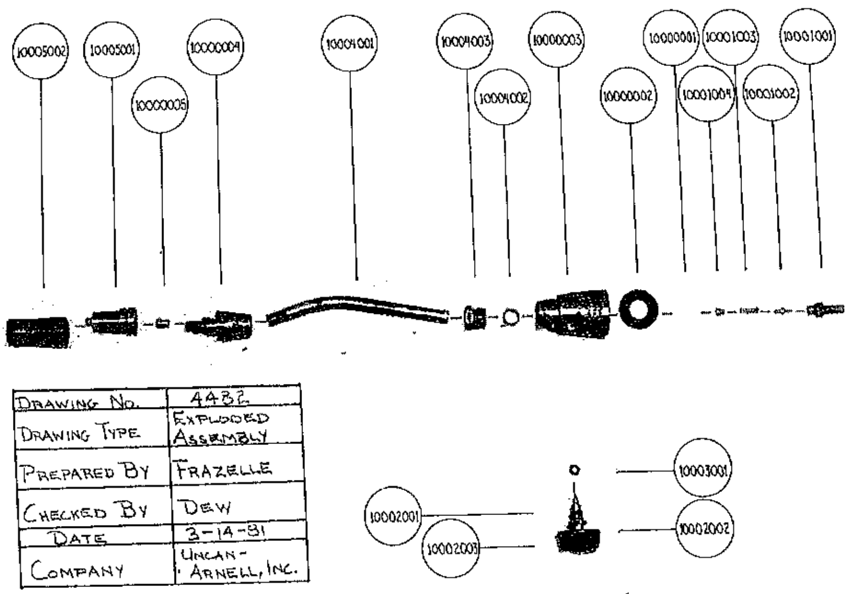

Figure 2.3 Exploded parts photograph.

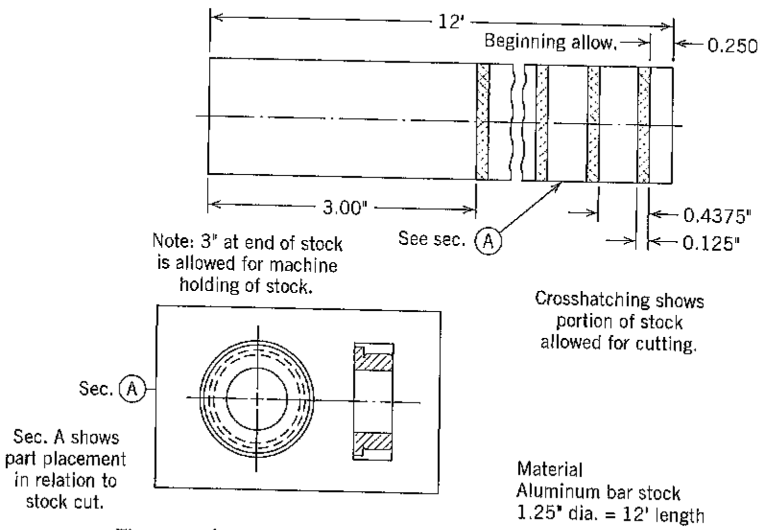

Figure 2.4 Component part drawing of a plunger.

The drawings can be prepared and analyzed with *computer aided design* (CAD) systems. CAD is the creation and manipulation of design prototypes on a computer to assist the design process of the product. A CAD system consists of a collection of many application modules under a common database and graphics editor. The blending of computers and the human ability to make decisions enable us to use CAD systems in design, analysis, and manufacturing [9].

During the facilities design process, the computer's graphics capability and computing power allow the planner to visualize and test ideas in a flexible manner. The CAD system also can be used for area measurement, building and interior design, layout of furniture and equipment, relationship diagramming, generation of block and detailed layouts, and interference checks for process oriented plants [2].

In addition to CAD, *concurrent engineering* (CE) can be used to improve the relationship between the function of a component or product and its cost. Concurrent engineering provides a simultaneous consideration in the design phase of life cycle factors such as product, function, design, materials, manufacturing processes,

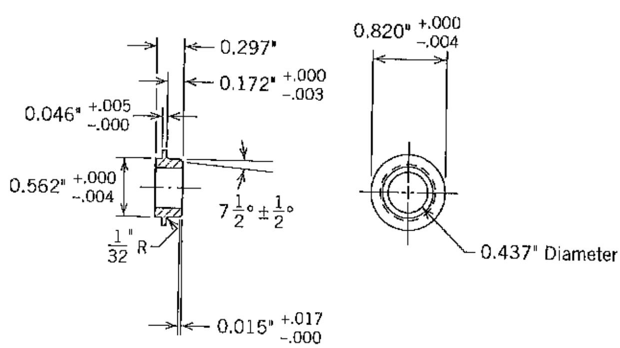

Figure 2.5 Component part drawing of a seat.

testability, serviceability, quality, and reliability. As a result of this analysis, a less expensive but functionally equivalent product design might be identified. Concurrent engineering is important because it is at the design stage that many of the costs of a product are specified. It has been estimated that more than 70% of a product's manufacturing cost is dictated by design decisions [14].

In addition to the design tools we have described, many other tools can be used to help the product-process designer in the evaluation and selection of the best product and process design combination [10, 21, 23].

2.3 PROCESS DESIGN

The process designer or process planner is responsible for determining *how* the product is to be produced. As a part of that determination, the process planner addresses *who* should do the processing; namely, should a particular product, subassembly, or part be produced in-house or subcontracted to an outside supplier or contractor? The "make-or-buy" decision is part of the process planning function.

In addition to determining whether a part will be purchased or produced, the process designer must determine how the part will be produced, which equipment will be used, and how long it will take to perform the operation. The final process design is quite dependent on input from both the product and schedule designs.

Identifying Required Processes

Determining the scope of a facility is a basic decision and must be made early in the facilities planning process. For a hospital whose objective is to serve the health needs of a community, it may be necessary to limit the scope of the facility by not including in the facility a burn-care clinic, specific types of diagnostic equipment, and/or a psychiatric ward. The excluded services, although needed by the community, may not be feasible for a particular hospital. Patients requiring care provided elsewhere would be referred to other hospitals. Similarly, the scope of a manufacturing facility must be established by determining the processes that are to be included within the facility. The extremes for a manufacturing facility may range from a vertically integrated firm that purchases raw materials and proceeds through a multitude of refining, processing, and assembly steps to obtain a finished product, to another firm that purchases components and assembles finished products. Therefore, it is obvious that the scope and magnitude of activities within a manufacturing facility are dependent on the decisions concerning the level of vertical integration. Such decisions are often referred to as "make-or-buy" decisions or "sourcing" decisions.

Large corporations have downsized large facilities and broken them into small business units that keep only processes that are economically feasible. Small business units operate with low overhead, low management levels, and frequently with self-managing operator teams. Buildings for this type of organization are smaller and management functions and offices are usually decentralized.

Make-or-buy decisions are typically managerial decisions requiring input from finance, industrial engineering, marketing, process engineering, purchasing, and perhaps human resources, among others. A brief overview of the succession of questions leading to make-or-buy decisions is given in Figure 2.6. The input to the facilities planner is a listing of the items to be made and the items to be purchased. The listing often takes the form of a parts list or a bill of materials.

The parts list provides a listing of the component parts of a product. In addition to make-or-buy decisions, a parts list includes at least the following:

1. Part numbers
2. Part name

Secondary Questions

1. Is the item available?
2. Will our union allow us to purchase the item?
3. Is the quality satisfactory?
4. Are the available sources reliable?

1. Is the manufacturing of this item consistent with our firm's objectives?
2. Do we possess the technical expertise?
3. Is the labor and manufacturing capacity available?
4. Is the manufacturing of this item required to utilize existing labor and production capacities?

1. What are the alternative methods of manufacturing this item?
2. What quantities of this item will be demanded in the future?
3. What are the fixed, variable, and investment costs of the alternative methods and of purchasing the item?
4. What are the product liability issues which impact the purchase or manufacture of this item?

1. What are the other opportunities for the utilization of our capital?
2. What are the future investment implications if this item is manufactured?
3. What are the costs of receiving external financing?

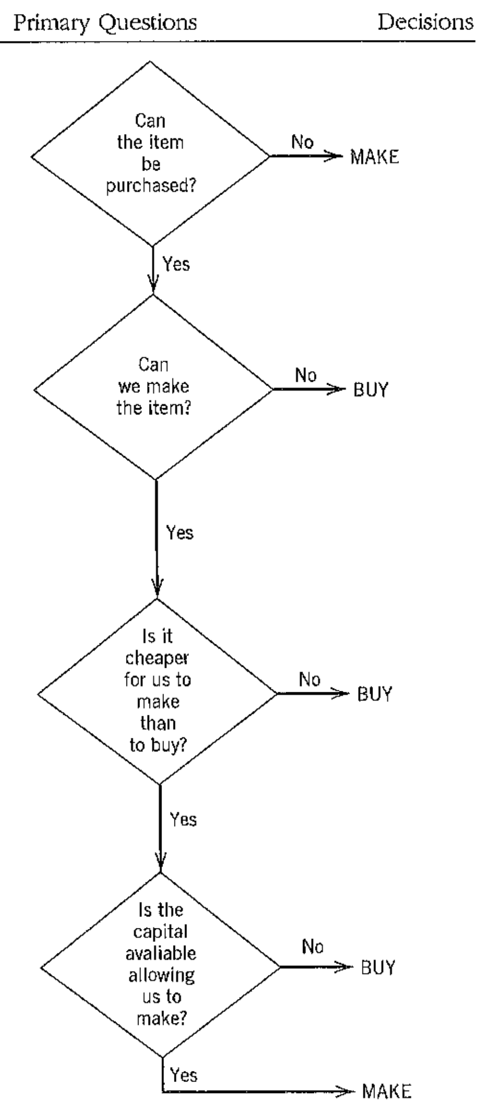

Figure 2.6 The make-or-buy decision process.

PARTS LIST

Company T. W., Inc. Prepared by J. A.
Product Air Flow Regulator Date

Part No.	Part Name	Drwg. No.	Quant./ Unit	Material	Size	Make or Buy
1050	Pipe plug	4006	1	Steel	.50″ × 1.00″	Buy
2200	Body	1003	1	Aluminum	2.75″ × 2.50″ × 1.50″	Make
3250	Seat ring	1005	1	Stainless steel	2.97″ × .87″	Make
3251	O-ring	—	1	Rubber	.75″ dia.	Buy
3252	Plunger	1007	1	Brass	.812″ × .715″	Make
3253	Spring	—	1	Steel	1.40″ × .225″	Buy
3254	Plunger housing	1009	1	Aluminum	1.60″ × .225″	Make
3255	O-ring	—	1	Rubber	.925″ dia.	Buy
4150	Plunger retainer	1011	1	Aluminum	.42″ × 1.20″	Make
4250	Lock nut	4007	1	Aluminum	.21″ × 1.00″	Buy

Figure 2.7 Parts list for an air flow regulator.

3. Number of parts per product
4. Drawing references

A typical parts list is given in Figure 2.7.

A bill of materials is often referred to as a structured parts list, as it contains the same information as a parts list plus information on the structure of the product. Typically, the product structure is a hierarchy referring to the level of product assembly. Level 0 usually indicates the final product; level 1 applies to subassemblies and components that feed directly into the final product; level 2 refers to the subassemblies and components that feed directly into the first level, and so on. A bill of materials is given in Figure 2.8 and is illustrated in Figure 2.9 for the product described in the parts list in Figure 2.7.

Selecting the Required Processes

Once a determination has been made concerning the products to be made "inhouse," decisions are needed as to how the products will be made. Such decisions are based on previous experiences, related requirements, available equipment, production rates, and future expectations. Therefore, it is not uncommon for different processes to be selected in different facilities to perform identical operations. However, the selection procedure used should be the same. In Figure 2.10, the procedure for process selection is given.

BILL OF MATERIALS

Company T. W., Inc. Prepared by J. A.
Product Air Flow Regulator Date

Level	Part No.	Part Name	Drwg. No.	Quant./ Unit	Make or Buy	Comments
0	0021	Air flow regulator	0999	1	Make	
1	1050	Pipe plug	4006	1	Buy	
1	6023	Main assembly	—	1	Make	
2	4250	Lock nut	4007	1	Buy	
2	6022	Body assembly	—	1	Make	
3	2200	Body	1003	1	Make	
3	6021	Plunger assembly	—	1	Make	
4	3250	Seat ring	1005	1	Make	
4	3251	O-ring	—	1	Buy	
4	3252	Plunger	1007	1	Make	
4	3253	Spring	—	1	Buy	
4	3254	Plunger housing	1009	1	Make	
4	3255	O-ring	—	1	Buy	
4	4150	Plunger retainer	1011	1	Make	

Figure 2.8 Bill of materials for an air flow regulator.

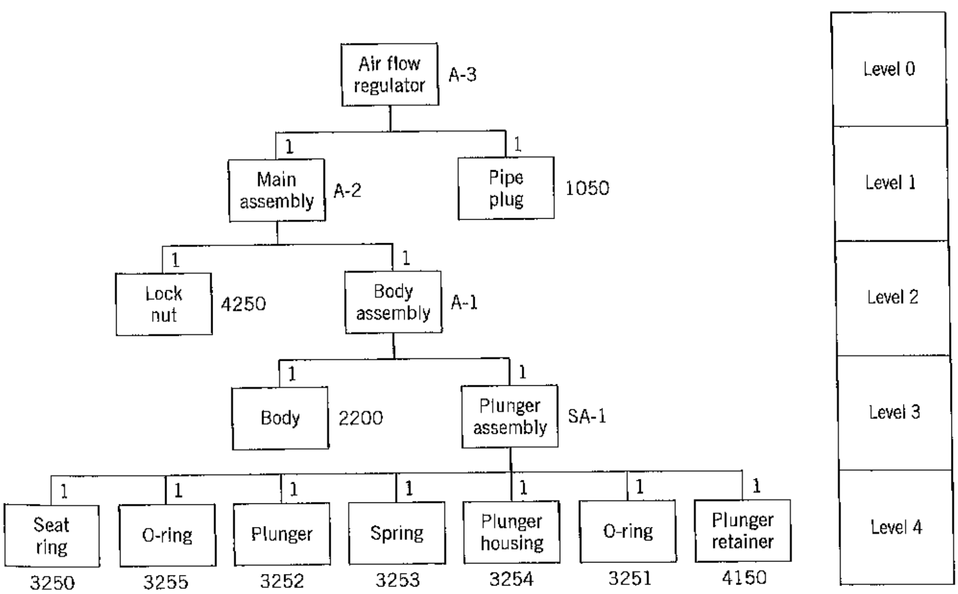

Figure 2.9 Bill of materials for an air flow regulator.

PROCESS IDENTIFICATION	
Define elemental operations	Step 1
Identify alternative process for each operation	Step 2
Analyze alternative processes	Step 3
Standardize processes	Step 4
Evaluate alternative processes	Step 5
Select processes	Step 6

Figure 2.10 Process selection procedure.

Input into the process selection procedure is called **process identification.** Process identification consists of a description of what is to be accomplished. For a manufactured product, process identification consists of a parts list indicating what is to be manufactured, component part drawings describing each component, and the quantities to be produced.

Computer aided process planning (CAPP) can be used to automate the manual planning process. There are two types of CAPP Systems: *variant and generative*. In a variant CAPP, standard process plans for each part family are stored within the computer and called up whenever required. In generative process planning, process plans are generated automatically for new components without requiring the existing plans. Selection of these systems basically depends on product structure and cost considerations. Typically, variant process planning is less expensive and easier to implement.

Since process planning is a critical bridge between design and manufacturing, CAPP systems can be used to test the different alternative routes and interact with the facility design process. The input of a CAPP system is commonly a three dimensional model from a CAD database including information related to tolerances and special features. Based on these inputs, manufacturing leadtime and resource requirements can also be determined [2].

The facilities planner will not typically perform process selection. However, an understanding of the overall procedure provides the foundation for the facilities plan. Step 1 of the procedure involves the determination of the operations required to produce each component. In order to make this determination, alternative forms of raw materials and types of elemental operations must be considered. Step 2 involves the identification of various equipment types capable of performing elemental operations. Manual, mechanized, and automated alternatives should be considered. Step 3 includes the determination of unit production times and equipment utilizations for various elemental operations and alternative equipment types. The utilizations are inputs into step 4 of the procedure. Step 5 involves an economic evaluation of alternative equipment types. The results of the economic evaluation along with intangible factors such as flexibility, versatility, reliability, maintainability, and safety serve as the basis for step 6.

Computer programs that perform time and cost evaluations of different process combinations have also been developed to aid process planners [10, 21].

The outputs from the process selection procedure are the processes, equipment, and raw materials required for the in-house production of products. Output is generally given in the form of a **route sheet.** A route sheet should contain at least the data given in Table 2.1. Figure 2.11 is a route sheet for the production given in part in Table 2.1.

Table 2.1 *Route Sheet Data Requirements*

Data	Production Example
Component name and number	Plunger housing—3254
Operation description and number	Shape, drill, and cut off—0104
Equipment requirements	Automatic screw machine and appropriate tooling
Unit times	Setup time—5 hr operation time—.0057 hr per component
Raw material requirements	1 in. dia. × 12 ft. aluminum bar per 80 components

Sequencing the Required Processes

The only process selection information not yet documented is the method of assembling the product. An **assembly chart,** given in Figure 2.12, provides such documentation. The easiest method of constructing an assembly chart is to begin with the completed product and to trace the product disassembly back to its basic components. For example, the assembly chart given in Figure 2.12 would be constructed by beginning in the lower right-hand corner of the chart with a finished air flow regulator. The first disassembly operation would be to unpackage the air flow regulator (operation A-4). The operation that precedes packaging is the inspection of the air flow regulator. Circles denote assembly operation; inspections are indicated on assembly charts as squares. Therefore, in Figure 2.12, a square labeled I-1 immediately precedes operation A-4. The first component to be disassembled from the air flow regulator is part number 1050, the pipe plug, indicated by operation A-3. The lock nut is then disassembled, followed by the disassembly of the body assembly (the subassembly made during subassembly operation SA-1) and the body. The only remaining steps required to complete the assembly chart are the labeling of the circles and lines of the seven components flowing into SA-1.

Although route sheets provide information on production methods and assembly charts indicate how components are combined, neither provides an overall understanding of the flow within the facility. However, by superimposing the route sheets on the assembly chart, a chart results that does give an overview of the flow within the facility. This chart is an **operation process chart.** An example of an operation process chart is given in Figure 2.13.

To construct an operation process chart, begin at the upper right side of the chart with the components included in the first assembly operation. If the components are purchased, they should be shown as feeding horizontally into the appropriate assembly operation. If the components are manufactured, the production methods should be extracted from the route sheets and shown as feeding vertically into the appropriate assembly operation. The operation process chart may be completed by continuing in this manner through all required steps until the product is ready for release to the warehouse.

The operation process chart can also include materials needed for the fabricated components. This information can be placed below the name of the component. Additionally, operation times can be included in this chart and placed to the left of

ROUTE SHEET

ompany A.R.C., Inc. Part Name Plunger Housing Prepared by J. A.

oduce Air Flow Regulator Part No. 3254 Date

per. No.	Operation Description	Machine Type	Tooling	Dept.	Set-up Time (hr.)	Operation Time (hr.)	Materials or Parts Description
104	Shape, drill, cut off	Automatic screw machine	.50 in. dia. coller, feed fingers, cir. form tool, .45 in. dia. center drill, .129 in. twist drill, finish spiral drill, cut off blade		5	.0057	Aluminum 1.0 in. dia. × 12 ft.
204	Machine slot and thread	Chucker	.045 in. slot saw, turret slot attach. 3/8–32 thread chaser		2.25	.0067	
304	Drill 8 holes	Auto. dr. unit (chucker)	.078 in. dia. twist drill		1.25	.0038	
404	Deburr and blow out	Drill press	Deburring tool with pilot		.5	.0031	
A1	Enclose subassembly	Dennison hyd. press	None		.25	.0100	

Figure 2.11 Route sheet for one component of the air flow regulator.

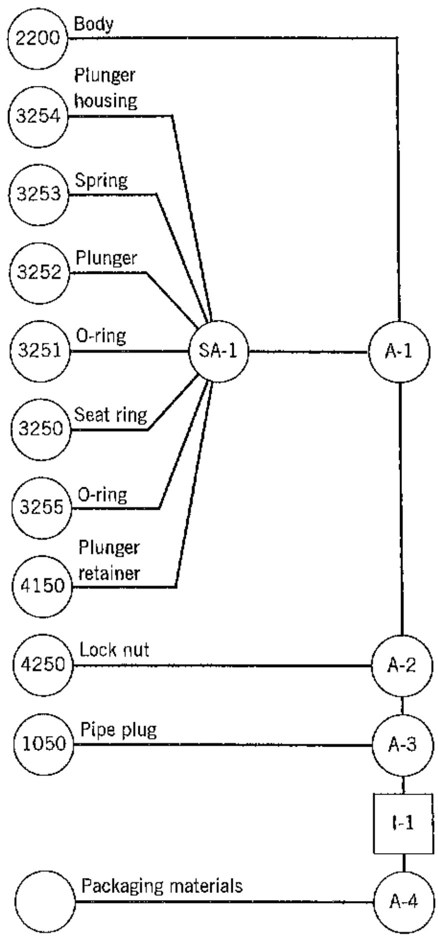

Figure 2.12 Assembly chart for an air flow regulator.

operations and inspections. A summary of the number of operations and inspections and operation times can be provided below the chart.

The operation process chart can be complemented with transportations, storages, and delays (including distances and times) when the information is available. Such a chart is referred to as a **flow process chart** by some and a **process chart** by others [3].

Assembly charts and operation process charts may be viewed as analog models of the assembly process and the overall production process, respectively. As noted previously, circles and squares represent time and horizontal connections represent sequential steps in the assembly of the product.

Notice in the assembly chart that components have been identified with a four-digit code starting with 1, 2, 3, and 4. Furthermore, subassemblies (SA) and assemblies (A) have been identified with letters and numbers. The same identification approach has been used in the operation process chart. Additionally, fabrication operations have been represented with a four-digit code starting with 0.

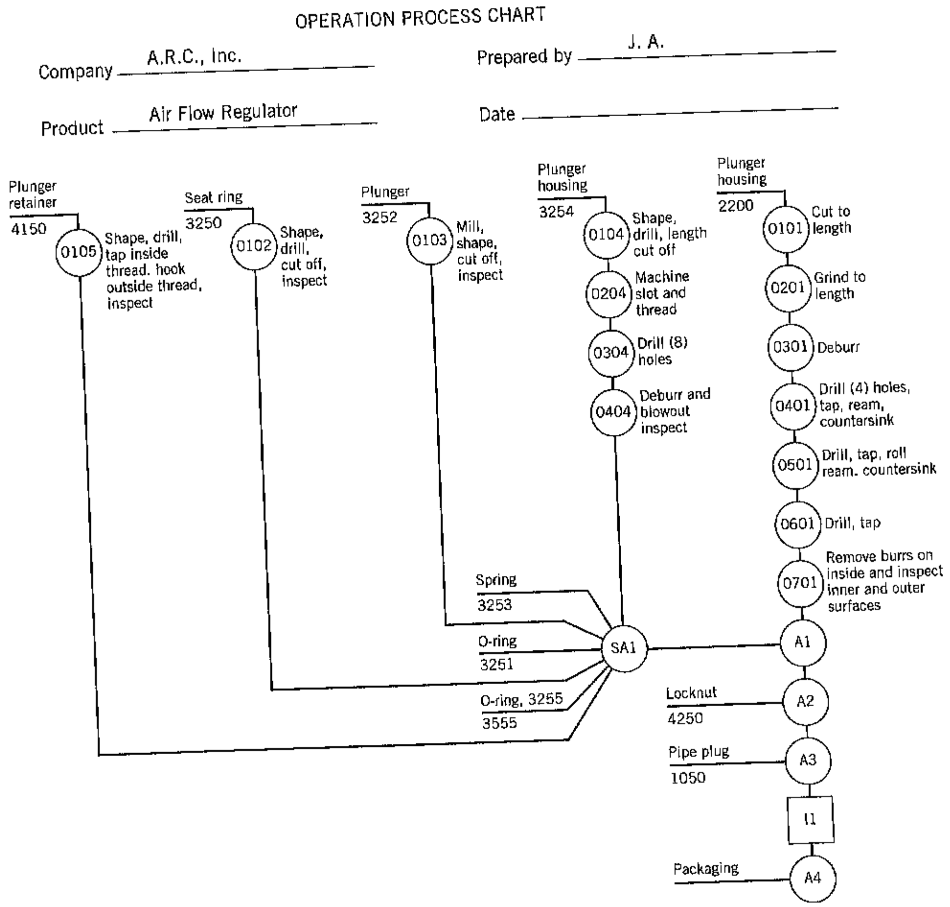

Figure 2.13 Operation process chart for the air flow regulator.

A second viewpoint (from graph and network theory) is to interpret the charts as network representations, or more accurately, tree representations of a production process. A variation of the network viewpoint is to treat the assembly chart and the operation process chart as special cases of a more general graphical model, the **precedence diagram.** The precedence diagram is a directed network and is used in project planning; critical path diagrams and PERT charts are examples of precedence diagrams.

A precedence diagram for the air flow regulator is given in Figure 2.14. The precedence diagram shows part numbers on the arcs and denotes operations and inspections by circles and squares, respectively. A procurement operation, 0100, is used in Figure 2.14 to initiate the process.

Notice in the precedence diagram that purchased parts and materials that do not require modifications are placed on the top and bottom part of the diagram so that they can be inserted in the center part of the diagram when needed (packaging materials, pipe plug, lock nut, spring, and O-rings). The center part of the diagram is then used to include purchased materials and/or components that require some work before being assembled (body, plunger housing, plunger, seat ring, and

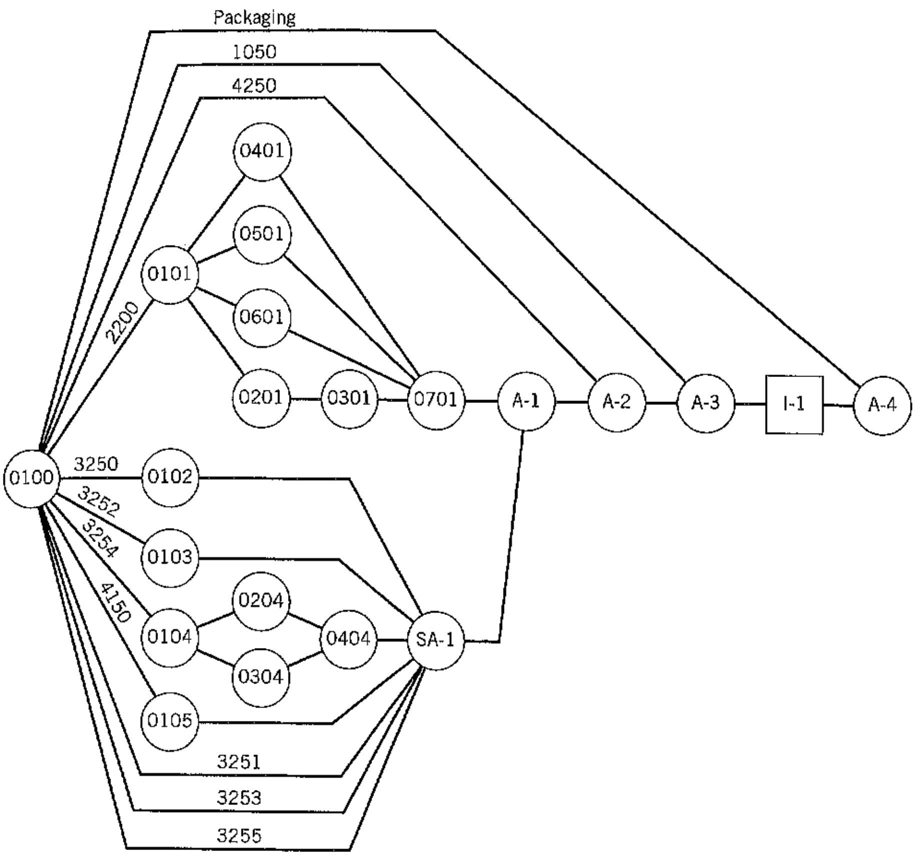

Figure 2.14 Precedence diagram for the air flow regulator.

plunger retainer). Fabrication and assembly operations are placed in the center part of the diagram.

The precedence diagram representation of the operations and inspections involved in a process can be of significant benefit to the facilities planner. It establishes the precedence relationships that must be maintained in manufacturing and assembling a product. No additional constraints are implicitly imposed; no assumptions are made concerning which parts move to which parts; no material handling or layout decisions are implicit in the way the precedence diagram is constructed. Unfortunately, the same claims cannot be made for the assembly chart and operation process chart.

Recall the instructions we gave for constructing the assembly chart: "The easiest method of constructing an assembly chart is to begin with the completed product and to trace the product disassembly back to its basic components." Implicit in such an instruction is that *the sequence used to disassemble the product should be reversed to obtain the sequence to be used to assemble the product.* Just as there are alternative disassembly sequences that can be used, there are also alternative assembly sequences. *The assembly chart and the operation process chart depict a single sequence.* The particular sequence used can have a major impact on space and handling system requirements.

Notice operations 0101, 0201, 0301, 0401, 0501, 0601, and 0701 are not shown in series in Figure 2.14, even though they were so represented on the operation process chart. Hence, there exists some latitude in how the product is assembled.

Unfortunately, there doesn't exist a mechanism to show the possibility of alternative processing sequences on the operation process chart.

In order to motivate further our concerns regarding the misuse of the operation process chart in layout planning, consider the processes involved in manufacturing an axle for an over-the-road tractor. Using the advice typically provided in texts that describe the construction of operation process charts, the axle itself should be shown at the extreme right side of the chart. Subassemblies, components, and purchased parts would be shown sequentially feeding into the axle until a finished assembly was produced.

By observing the operation process chart one might be tempted to develop an assembly line for the axle (assuming sufficient quantities are to be produced). The axle would be moved along the assembly line and subassemblies, components, and purchased parts would be attached to it. Using such an approach, *space and handling equipment requirements for the line would be based on the largest component part in the assembly.*

As an alternative, after performing the last processing operation on the axle it could remain stationary and all subassemblies could flow to it. No further movement of the axle would have to occur.

Because of the limitations of the assembly chart and the operation process chart, we recommend a precedence diagram be constructed first. Based on the precedence diagram, alternative assembly charts and operation process charts should then be constructed.

Other techniques to generate and evaluate assembly sequences have been explored. These techniques consider the assembly according to the relationship among parts instead of the order in which parts will be assembled. With these approaches, liaison sequences are generated instead of assembly sequences.

The original *Liaison Sequence Analysis* (LSA) method for assembly sequencing was proposed by Bourjault [4]. Bourjault's method is an algorithmic approach that uses the relationships between parts to generate all possible assembly sequences.

The second LSA method is a modification of Bourjault's technique developed by Whitney and DeFazio [22]. It reduces the number of questions while keeping the algorithmic nature of the original approach.

Improvements to LSA are currently being addressed. For example, Silva [20] developed the assembly sequences generator system (ASGS) to produce all the physically possible assembly sequences for a given functional product design. ASGS also considers the factors affecting the decision-making process to select the best assembly sequence.

Group technology is having an impact on product and process design. Group technology refers to the grouping of parts into families and then making design decisions based on family characteristics. Groupings are typically based on part shapes, part sizes, material types, and processing requirements. In those cases where there are thousands of individual parts, the number of families might be less than 100. Group technology is an aggregation process that has been found to be quite useful in achieving standardized part numbers, standard specifications of purchased parts, for example, fasteners and standardized process selection.

The importance of the process design or process plan in developing the facilities plan cannot be overemphasized. Furthermore, it is necessary that the process planner understands the impact of process design decisions on the facilities plan. Our experience indicates that process planning decisions are frequently made without such an understanding. As an example, it is often the case that alternatives exist in both the selection of the processes to be used and their sequence of usage. The final choice should be based on interaction between schedule design and facilities planning. Unfortunately, the choice is often based on "We've always done it this way" or "The computer indicated this was the best way."

In many companies the process selection procedure has become sufficiently routine that CAPP systems have been developed. The resulting standardization of process selection has yielded considerable labor savings and reductions in production lead times. At the same time, standardization in process selection might create disadvantages for schedule and facility design. If such a situation occurs, a mechanism should exist to allow exceptions.

The facilities planner must take the initiative and participate in the process selection decision process to ensure that "route decisions" are not unduly constraining the facilities plan. Many of the degrees of freedom available to the facilities planner can be affected by process selection decisions.

2.4 SCHEDULE DESIGN

Schedule design decisions provide answers to questions involving how much to produce and when to produce. Production quantity decisions are referred to as lot size decisions; determining when to produce is referred to as production scheduling. In addition to how much and when, it is important to know how long production will continue; such a determination is obtained from market forecasts.

Schedule design decisions impact machine selection, number of machines, number of shifts, number of employees, space requirements, storage equipment, material handling equipment, personnel requirements, storage policies, unit load design, building size, and so on. Consequently, schedule planners need to interface continuously with marketing and sales personnel and with the largest customers to provide the best information possible to facilities design planners.

To plan a facility, information is needed concerning production volumes, trends, and the predictability of future demands for the products to be produced. The less specificity provided regarding product, process, and schedule designs, the more general purpose will be the facility plan. The more specific the inputs from product, process, and schedule designs, the greater the likelihood of optimizing the facility and meeting the needs of manufacturing.

Marketing Information

A facility that produces 10,000 television sets per month should differ from a facility that produces 1000 television sets per month. Likewise, a facility that produces

Table 2.2 ***Minimum Market Information Required for Facilities Planning***

Product or Service	First Year Volume	Second Year Volume	Fifth Year Volume	Tenth Year Volume
A	5000	5000	8000	10,000
B	8000	7500	3000	0
C	3500	3500	3500	4,000
D	0	2000	3000	8,000

10,000 television sets for the first month and increases production 10% per month thereafter should not be considered the same as a facility that produces 10,000 television sets per month for the foreseeable future. Lastly, consider a facility that produces 10,000 television sets per month for the next 10 years versus one that produces 10,000 television sets per month for 3 months and is unable to predict what product or volume will be produced thereafter; they too should differ.

As a minimum, the market information given in Table 2.2 is needed. Preferably, information regarding the dynamic value of demands to be placed on the facility is desired. Ideally, information of the type shown in Table 2.3 would be provided. If such information is available, a facilities plan can be developed for each demand state and a facility designed with sufficient flexibility to meet the yearly fluctuations in product mix. By developing facilities plans annually and noting the alterations to the plan, a facilities master plan may be established [16]. Unfortunately, information of the type given in Table 2.3 is generally unavailable. Therefore, facilities typically are planned using deterministic data. The assumptions of deterministic data and known demands must be dealt with when evaluating alternative facilities plans.

In addition to the volume, trend, and predictability of future demands for various products, the qualitative information listed in Table 2.4 should be obtained. Additionally, the facilities planner should solicit input from marketing as to why market trends are occuring. Such information may provide valuable insight to the facilities planner.

An Italian economist, Pareto, observed that 85% of the wealth of the world is held by 15% of the people. Surprisingly, his observations apply to several aspects of facilities planning. For example, *Pareto's law* often applies to the product mix of a facility. That is, 85% of the production volume is attributed to 15% of the product line. Such a situation is depicted by the **volume-variety chart** or **Pareto chart** given in Figure 2.15. This chart suggests that the facilities plan should consist of a mass production area for the 15% of high-volume items and a job shop arrangement for the remaining 85% of the product mix. By knowing this at the outset, development of the facilities plan may be significantly simplified.

This volume-variety information is very important in determining the layout type to use. As described in Chapter 3, identifying the layout type will impact among others the type of material handling alternatives, storage policies, unit loads, building configuration, and the location of receiving/shipping docks.

Pareto's law may not always describe the product mix of a facility. Figure 2.16 represents the product mix for a facility where 15% of the product line represents approximately 25% of the production volume; Pateto's law clearly does not apply. However, knowing that Pareto's law does not apply is valuable information; because if no product dominates the production flow, a general job shop facility is suggested.

Table 2.3 *Market Analysis Indicating the Stochastic Nature of Future Requirements for Facilities Planning*

		First Year		Second Year		Fifth Year		Tenth Year	
Product or Service	Demand State	Probability	Volume	Probability	Volume	Probability	Volume	Probability	Volume
A	Pessimistic	.3	3000	.2	3500	.1	5500	.1	7,000
	Most likely	.5	5000	.6	5500	.8	8000	.9	10,000
	Optimistic	.2	6000	.2	6500	.1	9500		
B	Pessimistic	.1	7000						
	Most likely	.6	8000	.7	7000	.9	3000	1.0	0
	Optimistic	.3	8500	.3	8000	.1	3500		
C	Pessimistic	.2	2000	.2	2000	.2	2000	.2	2,000
	Most likely	.7	4000	.7	4000	.7	4000	.6	4,000
	Optimistic	.1	4500	.1	4500	.1	4500	.2	5,000
D	Pessimistic			.1	1500	.1	2500	.2	7,000
	Most likely	1.0	0	.9	2000	.8	3000	.6	8,000
	Optimistic					.1	3500	.2	9,000
Confidence level or degree of certainty		90%		85%		70%		59%	

Table 2.4 *Valuable Information that Should Be Obtained from Marketing and Used by a Facilities Planner*

Information to Be Obtained from Marketing	Facilities Planning Issues Impacted by the Information
Who are the consumers of the product?	1. Packaging 2. Susceptibility to product changes 3. Susceptibility to changes in marketing strategies
Where are the consumers located?	1. Facilities location 2. Method of shipping 3. Warehousing systems design
Why will the consumer purchase the product?	1. Seasonability 2. Variability in sales 3. Packaging
Where will the consumer purchase the product?	1. Unit load sizes 2. Order processing 3. Packaging
What percentage of the market does the product attract and who is the competition?	1. Future trends 2. Growth potential 3. Need for flexibility
What is the trend in product changes?	1. Space allocations 2. Materials handling methods 3. Need for flexibility

Process Requirements

Process design determines the specific equipment types required to produce the product. Schedule design determines the number of each equipment type required to meet the production schedule.

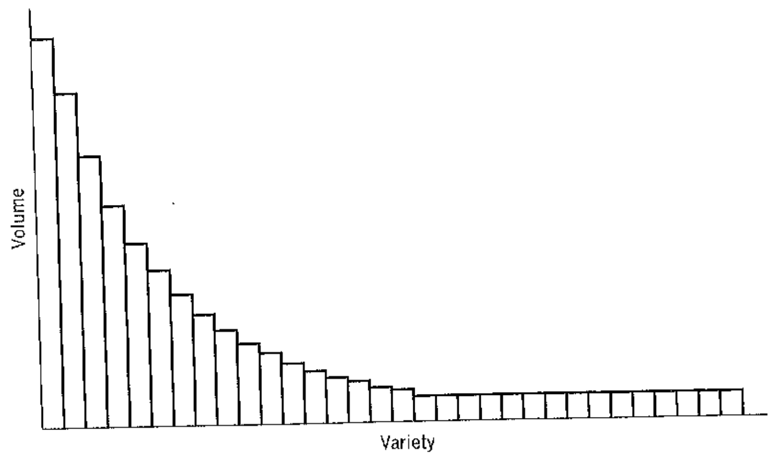

Figure 2.15 Volume-variety chart for a facility where Pareto's law is applicable.

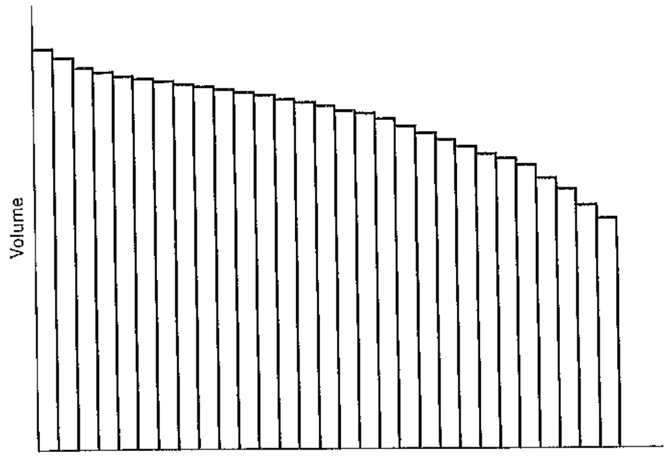

Figure 2.16 Volume-variety chart for a facility where Pareto's law is not applicable.

Specification of process requirements typically occurs in three phases. The first phase determines the quantity of components that must be produced, including scrap allowance, in order to meet the market estimate. The second phase determines the equipment requirements for each operation, and the third phase combines the operation requirements to obtain overall equipment requirements.

Scrap Estimates

The market estimate specifies the annual volume to be produced for each product. To produce the required amount of product, the number of units scheduled through production must equal the market estimate plus a scrap estimate. Hence, production capacity must be planned for the production of scrap. Otherwise, when scrap is produced the market estimate will not be met. Scrap is the material waste generated in the manufacturing process due to geometric or quality considerations. For example, scrap due to geometry is generated when a rectangular steel plate is used to create circular components or when rolls of fabric are used to make shirts. Scrap due to bad quality might be caused by mistakes in machining or assembly operations. Ideally, a company should strive for continuous improvement to achieve zero scrap. An estimate of the percentage of scrap to be incurred from each operation must be made. This may be based on historical data or estimated from similar operations. In general, the more automated a process, the less scrap is produced; the looser the part tolerance, the less scrap is produced; the bigger the number of certified suppliers, the less scrap is generated; the more quality at the source and prevention techniques are applied, the less scrap is generated; and the higher the grade of material, the less scrap is produced.

Let P_k represent the percentage of scrap produced on the k^{th} operation, O_k the desired output of nondefective product from operation k, and I_k the production input to operation k. It follows that, on the average

$$O_k = I_k - P_k I_k \tag{2.1}$$

or

$$O_k = I_k(1 - P_k)$$

Hence,

$$I_k = \frac{O_k}{1 - P_k} \tag{2.2}$$

Thus, the expected number of units to start into production for a part having n operations is

$$I_1 = \frac{O_n}{(1 - P_1)(1 - P_2)\cdots(1 - P_n)} \tag{2.3}$$

where in this case O_n is the market estimate.

Example 2.1

A product has a market estimate of 97,000 components and requires three processing steps (turning, milling, and drilling) having scrap estimates of $P_1 = 0.04$, $P_2 = 0.01$, and $P_3 = 0.03$. The market estimate is the output required from step 3. Therefore,

$$I_3 = \frac{97{,}000}{1 - 0.03} = 100{,}000$$

Assuming no damage between operations 2 and 3 and an inspection operation to remove all rejects, the output of good components from operation 2 (O_2) may be equated to the input to operation 3 (I_3). Therefore, the number of components to start into operation 2 (I_2) is

$$I_2 = \frac{100{,}000}{1 - 0.01} = 101{,}000$$

Likewise, for operation 1:

$$I_1 = \frac{101{,}010}{1 - 0.04} = 105{,}219$$

The calculations are identical to:

$$I_1 = \frac{97{,}000}{(1 - 0.03)(1 - 0.01)(1 - 0.04)} = 105{,}219$$

The amout of raw material and processing on operation 1 is not to be based on the market estimate of 97,000 components, but on 105,219 components, as summarized in Table 2.5.

Table 2.5 *Summary of Production Requirements for Example 2.1*

Operation	Production Quantity Scheduled (units)	Expected Number of Good Units Produced
Turning	105,219	101,010
Milling	101,010	100,000
Drilling	100,000	97,000

Reject Allowance Problem

As suggested by the previous analysis, random events influence the number of acceptable units produced. The calculations performed using Equations 2.1 through 2.3 are reasonable when high-volume production is occurring. However, when producing small batches the use of average values is less appropriate. As an example, consider a foundry that produces small numbers of custom-designed castings. If conditions are such that the foundry has only one chance to produce the number of castings required, then the probability of a casting being good should be considered when determining the batch size to be produced.

In determining how many castings to produce, the following questions come to mind:

1. How much does it cost to produce a good casting? How much for a bad casting?
2. How much revenue is generated from a good casting? How much from a bad casting?
3. What is the probability distribution for the number of good castings resulting from a production lot?

If answers are available for these questions, then a determination can be made regarding the number of castings to schedule in order to, say, maximize the expected profit or achieve a desired confidence level of not producing fewer good castings than are needed. Determining the number of additional units to allow when scheduling low-volume production where rejects randomly occur is called the *reject allowance problem* [22].

To facilitate a formulation of the reject allowance problem, let

X = random variable representing the number of good units produced
$p(x)$ = probability of producing exactly x good units
Q = quantity of units to produce
$C(Q, x)$ = cost of producing Q units, of which exactly x are good units
$R(Q, x)$ = revenue from producing Q units, of which exactly x are good units
$P(Q, x)$ = profit from producing Q units, of which exactly x are good units $= R(Q, x) - C(Q, x)$
$E[P(Q)]$ = expected profit from producing Q units $= \sum_{x=0}^{Q} P(Q, x)\, p(x)$

The expected profit from producing Q units can be determined as follows:

$$E[P(Q)] = \sum_{x=0}^{Q} \{R(Q, x) - C(Q, x)\}\, p(x)$$

If it is desired to maximize expected profit, the value of Q that maximizes Equation 2.4 can be determined by enumerating over various values of Q. For most cost and revenue formulations, Equation 2.4 is a concave function; therefore, unimodal search routines can be used. See [22] for necessary and sufficient conditions for Q to be the optimum production quantity when X is binomially distributed.

Table 2.6 ***Probability Distributions for the Number of Good Castings (x) Out of Q***

# Good Castings (x)	Number of Castings Produced (Q)										
	20	21	22	23	24	25	26	27	28	29	30
12	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.10	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00
17	0.10	0.10	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00
18	0.15	0.10	0.10	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00
19	0.20	0.15	0.10	0.10	0.05	0.05	0.05	0.05	0.00	0.00	0.00
20	0.25	0.20	0.15	0.10	0.10	0.05	0.05	0.05	0.05	0.00	0.00
21	0.00	0.25	0.20	0.15	0.10	0.10	0.05	0.05	0.05	0.05	0.00
22	0.00	0.00	0.25	0.20	0.15	0.10	0.10	0.05	0.05	0.05	0.05
23	0.00	0.00	0.00	0.25	0.20	0.15	0.10	0.10	0.05	0.05	0.05
24	0.00	0.00	0.00	0.00	0.25	0.20	0.15	0.10	0.10	0.05	0.05
25	0.00	0.00	0.00	0.00	0.00	0.25	0.20	0.15	0.10	0.10	0.05
26	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.20	0.15	0.10	0.10
27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.20	0.15	0.10
28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.20	0.15
29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.20
30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25

Example 2.2

A foundry produces castings to order. An order for 20 custom-designed castings has been received. The casting process costs \$1,100 per unit scheduled. If a casting is not sold, it has a recycle value of \$200. The customer has indicated a willingness to pay \$2,500 per casting for 20 acceptable castings—no more, no less! Based on historical records, the probability distributions given in Table 2.6 have been estimated. How many castings should be scheduled for production to maximize expected profit? What is the probability of losing money at this production level?

The revenue and cost functions can be given as follows:

$$R(Q, x) = \begin{cases} \$200Q & x < 20 \\ \$2{,}500(20) + \$200(Q - 20) & 20 \le x \le Q \end{cases}$$

$$C(Q, x) = \$1{,}100Q \qquad 0 \le x \le Q$$

$$P(Q, x) = \begin{cases} -\$900Q & x < 20 \\ \$46{,}000 - \$700Q & 20 \le x \le Q \end{cases}$$

Therefore, the expected profit can be given as follows:

$$E[p(Q)] = -\sum_{x=0}^{19} 900Q\, p(x) + \sum_{x=20}^{Q} (46{,}000 - 700Q)\, p(x)$$

The expected profit expression can be shown to reduce to

$$E[p(Q)] = \sum_{x=20}^{Q} (46{,}000 + 200Q)\, p(x) - 900Q$$

Table 2.7 *Profit from Producing Q Castings, with Exactly x Being Good*

# Good Castings	Number of Castings Scheduled										
	20	21	22	23	24	25	26	27	28	29	30
12	−$18,000	−$18,900	−$19,800	−$20,700	−$21,600	−$22,500	−$23,400	−$24,300	−$25,200	−$26,100	−$27,000
13	−$18,000	−$18,900	−$19,800	−$20,700	−$21,600	−$22,500	−$23,400	−$24,300	−$25,200	−$26,100	−$27,000
14	−$18,000	−$18,900	−$19,800	−$20,700	−$21,600	−$22,500	−$23,400	−$24,300	−$25,200	−$26,100	−$27,000
15	−$18,000	−$18,900	−$19,800	−$20,700	−$21,600	−$22,500	−$23,400	−$24,300	−$25,200	−$26,100	−$27,000
16	−$18,000	−$18,900	−$19,800	−$20,700	−$21,600	−$22,500	−$23,400	−$24,300	−$25,200	−$26,100	−$27,000
17	−$18,000	−$18,900	−$19,800	−$20,700	−$21,600	−$22,500	−$23,400	−$24,300	−$25,200	−$26,100	−$27,000
18	−$18,000	−$18,900	−$19,800	−$20,700	−$21,600	−$22,500	−$23,400	−$24,300	−$25,200	−$26,100	−$27,000
19	−$18,000	−$18,900	−$19,800	−$20,700	−$21,600	−$22,500	−$23,400	−$24,300	−$25,200	−$26,100	−$27,000
20	$32,000	$31,300	$30,600	$29,900	$29,200	$28,500	$27,800	$27,100	$26,400	$25,700	$25,000
21	$0	$31,300	$30,600	$29,900	$29,200	$28,500	$27,800	$27,100	$26,400	$25,700	$25,000
22	$0	$0	$30,600	$29,900	$29,200	$28,500	$27,800	$27,100	$26,400	$25,700	$25,000
23	$0	$0	$0	$29,900	$29,200	$28,500	$27,800	$27,100	$26,400	$25,700	$25,000
24	$0	$0	$0	$0	$29,200	$28,500	$27,800	$27,100	$26,400	$25,700	$25,000
25	$0	$0	$0	$0	$0	$28,500	$27,800	$27,100	$26,400	$25,700	$25,000
26	$0	$0	$0	$0	$0	$0	$27,800	$27,100	$26,400	$25,700	$25,000
27	$0	$0	$0	$0	$0	$0	$0	$27,100	$26,400	$25,700	$25,000
28	$0	$0	$0	$0	$0	$0	$0	$0	$26,400	$25,700	$25,000
29	$0	$0	$0	$0	$0	$0	$0	$0	$0	$25,700	$25,000
30	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$25,000

The profits resulting from various combinations of Q and x are shown in Table 2.7. (Zero profit values are shown for infeasible combinations of Q and x to simplify the calculation of expected profit using Excel's SUMPRODUCT function.) The vector products of columns from Tables 2.6 and 2.7 are obtained using the SUMPRODUCT function and yield the expected profit values in Table 2.8. The maximum expected profit ($26,400) results from scheduling 28 castings to be produced. From Table 2.6, when 28 castings are produced there is a zero probability of losing money; the penalty for not producing at least 20 good units is so severe that the minimum number of units having a zero probability of producing less than 20 good units is optimum.

Equipment Fractions

The quantity of equipment required for an operation is referred to as the equipment fraction. The equipment fraction may be determined for an operation by dividing the total time required to perform the operation by the time available to complete the operation. The total time required to perform an operation is the product of the standard time for the operation and the number of times the operation is to be performed. For example, if it takes ½ hr to duplicate a paper and if six papers are to be duplicated in 2 hr, it clearly follows that 1.5 duplicating machines are needed to complete the operation. Whether or not 1.5 duplicating machines are actually adequate to duplicate the required papers depends on the following questions.

1. Are the papers actually being duplicated according to the 1/2 hr per paper standard?
2. Is the duplicating machine available when needed during the 2-hr period?
3. Are the standard time, the number of papers, and the time the equipment is actually available known with certainty and fixed over time?

The first question may be handled by dividing the standard time by the historical efficiency of performing the operation. The second question may be handled by multiplying the time the equipment is available to complete an operation by the historical reliability factor for the equipment. The reliability factor is the percentage of time the equipment is actually producing and is not down because of malfunctioning or planned maintenance.

The third question dealing with the uncertainty and time-varying nature of machine fraction variables can be an important factor in determining process requirements. If considerable uncertainty and variation over time exists, it may be useful to consider using probability distributions, instead of point estimates for the parameters, and utilize a probabilistic machine fraction model. Typically, such models are not utilized and the approach taken is to use a deterministic model and plan the facility to provide sufficient flexibility to handle changes in machine fraction variables.

Table 2.8 ***Expected Profit from Producing Q Castings***

Number of Castings Scheduled (Q)										
20	21	22	23	24	25	26	27	28	29	30
−$5,500	$3,690	$10,440	$14,720	$19,040	$20,850	$22,680	$24,530	$26,400	$25,700	$25,000

The following deterministic model can be used to estimate the equipment fraction required:

$$F = \frac{SQ}{EHR} \tag{2.5}$$

where

F = number of machines required per shift
S = standard time (minutes) per unit produced
Q = number of units to be produced per shift
E = actual performance, expressed as a percentage of standard time
H = amount of time (minutes) available per machine
R = reliability of machine, expressed as percent "uptime"

Additionally, equipment requirements are a function of the following factors:

- Number of shifts (the same machine can work in more than one shift).
- Setup times (if machines are not dedicated, the longer the setup, the more machines needed).
- Degree of flexibility (customers may require small lot sizes of different products delivered frequently—extra machine capacity will be required to handle these requests).
- Layout type (dedicating manufacturing cells or focused factories to the production of product families may require more machines).
- Total productive maintenance (will increase machine up time and improve quality, thus fewer machines will be needed).

Example 2.3

A machined part has a standard machinery time of 2.8 min per part on a milling machine. During an 8-hr shift 200 units are to be produced. Of the 480 min available for production, the milling machine will be operational 80% of the time. During the time the machine is operational, parts are produced at a rate equal to 95% of the standard rate. How many milling machines are required?

For the example, S = 2.8 min per part, Q = 200 units per shift, H = 480 min per shift, E = 0.95, and R = 0.80. Thus,

$$F = \frac{2.8(200)}{0.95(480)(0.80)} = 1.535 \text{ machines per shift}$$

Specifying Total Equipment Requirements

The next step in determining process requirements is to combine the equipment fractions for identical equipment types. Such a determination is not necessarily straightforward. Even if only one operation is to be performed on a particular equipment type, overtime and subcontracting must be considered. If more than one operation is to be run on a particular equipment type, several alternatives must be considered.

Table 2.9 *Total Equipment Requirement Specification Example*

Operation Number	Equipment Fraction	Next Highest Whole Number
109	1.1	2
206	2.3	3
274	0.6	1

Example 2.4

The machine fractions for an ABC drill press are given in Table 2.9. No drill press operator, overtime, or subcontracting is available for any operation on the ABC drill press. It may be seen that a minimum o four and a maximum of six machines are required. How many should be purchased? The answer is either four, five, or six. With no further information, a specific recommendation cannot be made. Information on the cost of the equipment, the length of machine setups, the cost of in-process inventories, the cost and feasibility of over-time, production, and/or setups, the expected future growth of demand, and several other qualitative factors must be analyzed to reach a decision.

Machine Assignment Problem

Chapter 4 addresses facility requirements for personnel, including employee parking, locker rooms, restrooms, food services, and so forth. It is assumed that a determination of the number of people to be employed in the facility already has been made. Typically, such decisions are not a part of the facilities planning process. However, the combination of product, process, and schedule design decisions significantly influences the number of employees involved in producing the product. In this section, we consider how decisons regarding the assignment of machines to operators can affect the number of employees. Specifically, we consider a situation involving the assignment of operators to semiautomatic production equipment. For purposes of this discussion, it is assumed the machines are identical. In contrast to the reject allowance problem, it is assumed that the times required to load and unload each machine are constant, the automatic machining time is constant, and the "independent" time required for the operator to travel between machines, prepare parts for maching, and inspect and pack parts are constant.

To illustrate the situation under consideration, see Figure 2.17, which depicts the activities of an operator and three machines. The chart is called a **human-machine chart** or a **multiple activity chart,** since it shows the activities of one or more poeple and one or more machines. Such charts can be used to analyze multiple activity relationships when nonidentical machines are being tended by one or more operators. The multiple activity chart can prove useful in analyzing the activities or each operator and each machine during "transient" and "steady-state" conditions.

Example 2.5

For the situation illustrated in Figure 2.17, it takes 0.5 minute to travel between machines, 1.0 minute to load a machine, 1.0 minute to unload a machine, 6 minutes of automatic machine time, and 0.5 minute to inspect and pack a finished part. As shown, the analysis

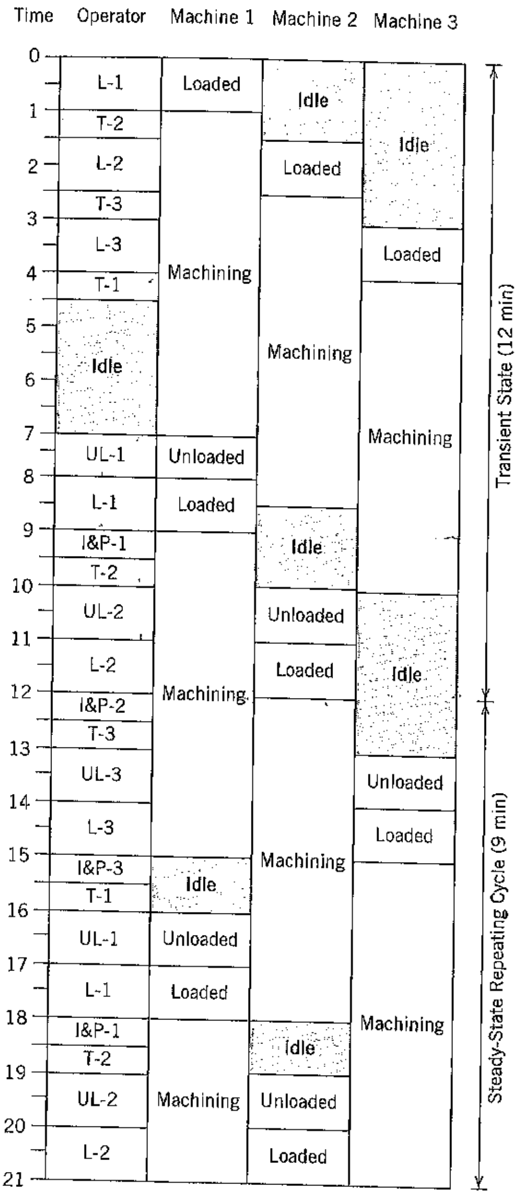

Figure 2.17 Multiple Activity Chart for Example 2.5.

begins with each machine empty and the operator standing in front of Machine 1 (M-1). The operator loads M-1, walks to M-2, loads M-2, walks to M-3, loads M-3, walks to M-1, unloads M-1, loads M-1, inspects and packs the part removed from M-1, travels to M-2, and so forth. As shown in Figure 2.18, it takes 12 minutes for the operator and 3 machines to achieve a steady-state condition; thereafter, a repeating cycle of 9 minutes in duration occurs. (In other words, if nothing interrupts the activities of the operator and the three machines, the 9-minute cycle will repeat indefinitely.)

Under conditions similar to those depicted by Figure 2.17, a deterministic model can be developed to determine the optimum number of machines to assign to an individual

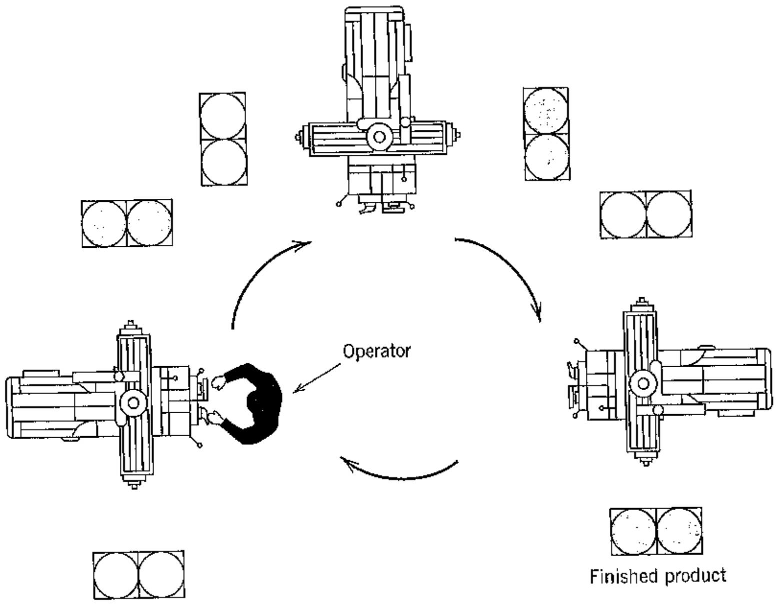

Figure 2.18 Assignment of three machines to one operator. (Reprinted with permission from [23].)

operator. To facilitate the development of the model, let

a = concurrent activity time (e.g., loading and unloading a machine)
b = independent operator activity time (e.g., walking, inspecting, packing)
t = independent machine activity time (e.g., automatic machining time)
n' = ideal number of identical machines to assign an operator
m = number of identical machines assigned an operator
T_c = repeating cycle time
I_o = idle operator time during a repeating cycle
I_m = idle time for each machine during a repeating cycle

Excluding idle time, each machine cycle requires $a + t$ minutes to complete a cycle. Likewise, the operator devotes $a + b$ minutes to each machine during a cycle. Hence, an ideal assignment is

$$n' = (a + t)/(a + b) \tag{2.6}$$

For the example, a equals 2 minutes, b equals 1 minute, and t equals 6 minutes. Therefore, n' equals 2.67 machines. Since a fractional number of machines cannot be assigned to an operator, consider what will happen if some integer number of machines, m, is assigned. The work content for the operator will total $m(a + b)$, while a machine cycle will be $(a + t)$ in duration. The repeating cycle will be the larger of the two and the difference in the two will be idle time. If $m > n'$, then the repeating cycle will be $m(a + b)$ in duration; if $m < n'$, then the repeating cycle will be $(a + t)$ in duration. Therefore,

$$T_c = \begin{matrix} (a + t) & \quad m \le n' \\ m(a + b) & \quad m > n' \end{matrix} \tag{2.7}$$

$$I_m = \begin{matrix} 0 & m \le n' \\ T_c - (a + t) & m > n' \end{matrix} \tag{2.8}$$

$$I_o = \begin{matrix} T_c - m(a + b) & m \le n' \\ 0 & m > n' \end{matrix} \tag{2.9}$$

For the example, with $m = 3$ and $n' = 2.67$, the repeating cycle is $3(2 + 1)$, or 9 minutes as observed in Figure 2.17. The idle time for each machine during a repeating cycle equals $9 - (2 + 6)$, or 1 minute, again as observed in Figure 2.17. As shown in Figure 2.18, the work cell must be designed carefully to provide adequate access for incoming and outgoing material, machine maintenance, and operator movement.

If we wish to determine the cost per unit produced by an m machine assignment, the following notation will be helpful

C_o = cost per operator-hour
C_m = cost per machine-hour
ϵ = C_o/C_m
$TC(m)$ = cost per unit produced based on an assignment of m machines per operator

The cost per hour of a combination of m machines and an operator totals $C_o + mC_m$. Assuming each machine produces one unit during a repeating cycle, the cost per unit produced during a repeating cycle can be determined as follows:

$$TC(m) = \begin{matrix} (C_o + mC_m)(a + t)/m & m \le n' \\ (C_o + mC_m)(a + b) & m > n' \end{matrix} \tag{2.10}$$

To minimize $TC(m)$ when $m \le n'$, m should be made a large as possible; to minimize $TC(m)$ when $m > n'$, m should be made as small as possible. If n' is integer valued, n' will minimize $TC(m)$. If n' is not integer valued then either n or $n + 1$ will minimize $TC(m)$ where n is defined to be the integer portion of n'.

To facilitate the determination, let Φ represent the ratio of $TC(n)$ to $TC(n + 1)$. Hence, from Equation 2.10,

$$\begin{aligned} \Phi &= TC(n)/TC(n + 1) \\ &= \frac{(C_o + nC_m)(a + t)}{n[C_o + (n + 1)C_m](a + b)} \end{aligned} \tag{2.11}$$

which reduces to

$$\Phi = \frac{\epsilon + n}{\epsilon + n + 1} \frac{n'}{n} \tag{2.12}$$

If $\Phi < 1$, then $TC(n) < TC(n + 1)$ and n machines should be assigned; if $\Phi > 1$, then $TC(n + 1) < TC(n)$ and $n + 1$ machines should be assigned; if $\Phi = 1$, then either n or $n + 1$ machines should be assigned.

For the example, suppose C_o equals \$15 per hour and C_m equals \$50 per hour. Therefore, ϵ equals 0.30 and Φ equals 0.929. Since $\Phi < 1$, then 2 machines should be assigned to an operator. The problems at the end of the chapter explore various aspects of the machine assignment problem, such as assigning machines to operators if, say, a total of 11 machines are required to meet the daily production schedule or there is uncertainty regarding the value of C_m.