# Industrial Automation

Course Notes

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Syllabus

Automation technologies; Manufacturing operations; Industrial control systems; Hardware components for automation; Numerical control; Industrial robotics; Programmable logic controllers; Material transport systems; Automated storage systems; Automatic identification and data capture; Inspection technologies; Automated manufacturing systems; Automated production lines; Automated assembly systems; Flexible manufacturing systems; CAD/CAM.

Suggested Reading
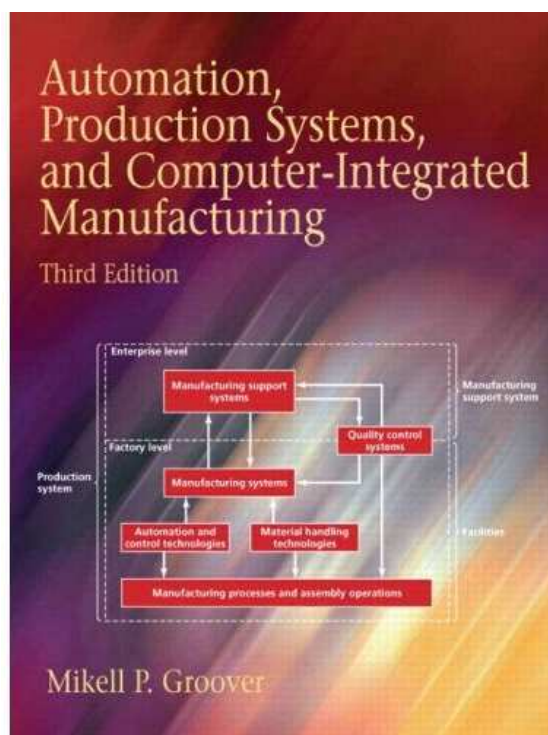
Online Resources

A complete copy of all slides used on the course will be available at www.owl.ie. Sample questions and answers are also available at www.owl.ie.

Visit www.youtube.com for video clips of all of the technology discussed in this course. Also visit various technology supplier web sites.

Introduction

CHAPTER CONTENTS

This book is about production systems that are used to manufacture products and the parts assembled into those products. The *production system* is the collection of people, equipment, and procedures, organized to accomplish the manufacturing operations of a company (or other organization). Production systems can be divided into two categories or levels as indicated in Figure 1.1:
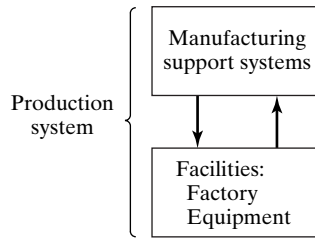
Figure 1.1 The production system consists of facilities and manufacturing support systems.

1. *Facilities*. The facilities of the production system consist of the factory, the equipment in the factory, and the way the equipment is organized.
2. *Manufacturing support systems*. This is the set of procedures used by the company to manage production and to solve the technical and logistics problems encountered in ordering materials, moving work through the factory, and ensuring that products meet quality standards. Product design and certain business functions are included among the manufacturing support systems.

In modern manufacturing operations, portions of the production system are automated and/or computerized. However, production systems include people. People make these systems work. In general, direct labor people *(blue collar workers)* are responsible for operating the facilities, and professional staff people *(white collar workers)* are responsible for the manufacturing support systems.

In this introductory chapter, we consider these two aspects of production systems and how they are sometimes automated and/or computerized in modern industrial practice. In Chapter 2, we examine the manufacturing operations that the production systems are intended to accomplish.

1.1 PRODUCTION SYSTEM FACILITIES[1]

The *facilities* in the production system are the factory, production machines and tooling, material handling equipment, inspection equipment, and the computer systems that control the manufacturing operations. Facilities also include the *plant layout*, which is the way the equipment is physically arranged in the factory. The equipment is usually arranged into logical groupings, and we refer to these equipment arrangements and the workers who operate them as the *manufacturing systems* in the factory. Manufacturing systems can be individual work cells, consisting of a single production machine and worker assigned to that machine. We more commonly think of manufacturing systems as groups of machines and workers, for example, a production line. The manufacturing systems come in direct physical contact with the parts and/or assemblies being made. They "touch" the product.

A manufacturing company attempts to organize its facilities in the most efficient way to serve the particular mission of that plant. Over the years, certain types of production facilities have come to be recognized as the most appropriate way to organize for a given type of manufacturing. Of course, one of the most important factors that determine the type of manufacturing is the type of products that are made. Our book is concerned primarily with

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[1] Portions of this section are based on M. P. Groover, *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems* [2].

the production of discrete parts and products, compared with products that are in liquid or bulk form, such as chemicals (we examine the distinction in Section 2.1).

If we limit our discussion to discrete products, the quantity produced by a factory has a very significant influence on its facilities and the way manufacturing is organized. *Production quantity* refers to the number of units of a given part or product produced annually by the plant. The annual part or product quantities produced in a given factory can be classified into three ranges:

1. *Low production*: Quantities in the range of 1 to 100 units per year.
2. *Medium production*: Quantities in the range of 100 to 10,000 units annually.
3. *High production*: Production quantities are 10,000 to millions of units.

The boundaries between the three ranges are somewhat arbitrary (author's judgment). Depending on the types of products we are dealing with, these boundaries may shift by an order of magnitude or so.

Some plants produce a variety of different product types, each type being made in low or medium quantities. Other plants specialize in high production of only one product type. It is instructive to identify product variety as a parameter distinct from production quantity. *Product variety* refers to the different product designs or types that are produced in a plant. Different products have different shapes and sizes and styles; they perform different functions; they are sometimes intended for different markets; some have more components than others; and so forth. The number of different product types made each year can be counted. When the number of product types made in a factory is high, this indicates high product variety.

There is an inverse correlation between product variety and production quantity in terms of factory operations. When product variety is high, production quantity tends to be low; and vice versa. This relationship is depicted in Figure 1.2. Manufacturing plants tend to specialize in a combination of production quantity and product variety that lies somewhere inside the diagonal band in Figure 1.2. In general, a given factory tends to be limited to the product variety value that is correlated with that production quantity.
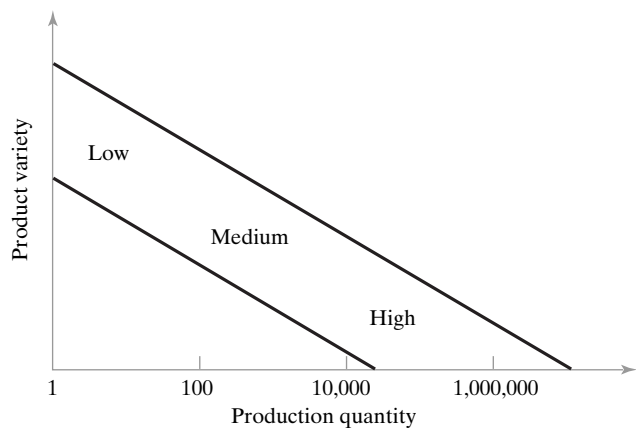

Figure 1.2 Relationship between product variety and production quantity in discrete product manufacturing.

   Although we have identified product variety as a quantitative parameter (the number of different product types made by the plant or company), this parameter is much less exact than production quantity is because details on how much the designs differ is not captured simply by the number of different designs. The differences between an automobile and an air conditioner are far greater than between an air conditioner and a heat pump. Products can be different, but the extent of the differences may be small or great. The automotive industry provides some examples to illustrate this point. Each of the U.S. automotive companies produces cars with two or three different nameplates in the same assembly plant, although the body styles and other design features are nearly the same. In different plants, the same auto company builds heavy trucks. Let us use the terms "hard" and "soft" to describe these differences in product variety. *Hard product variety* is when the products differ substantially. In an assembled product, hard variety is characterized by a low proportion of common parts among the products; in many cases, there are no common parts. The difference between a car and a truck is hard. *Soft product variety* is when there are only small differences between products, such as the differences between car models made on the same production line. There is a high proportion of common parts among assembled products whose variety is soft. The variety between different product categories tends to be hard; the variety between different models within the same product category tends to be soft.

   We can use the three production quantity ranges to identify three basic categories of production plants. Although there are variations in the work organization within each category, usually depending on the amount of product variety, this is nevertheless a reasonable way to classify factories for the purpose of our discussion.

1.1.1   Low Quantity Production

The type of production facility usually associated with the quantity range of 1 to 100 units/year is the *job shop*, which makes low quantities of specialized and customized products. The products are typically complex, such as space capsules, aircraft, and special machinery. Job shop production can also include fabricating the component parts for the products. Customer orders for these kinds of items are often special, and repeat orders may never occur. Equipment in a job shop is general purpose and the labor force is highly skilled.

   A job shop must be designed for maximum flexibility to deal with the wide part and product variations encountered (hard product variety). If the product is large and heavy, and therefore difficult to move in the factory, it typically remains in a single location, at least during its final assembly. Workers and processing equipment are brought to the product, rather than moving the product to the equipment. This type of layout is referred to as a *fixed–position layout*, shown in Figure 1.3(a). In the pure situation, the product remains in a single location during its entire fabrication. Examples of such products include ships, aircraft, railway locomotives, and heavy machinery. In actual practice, these items are usually built in large modules at single locations, and then the completed modules are brought together for final assembly using large-capacity cranes.

   The individual parts that comprise these large products are often made in factories that have a *process layout*, in which the equipment is arranged according to function or type. The lathes are in one department, the milling machines are in another department, and so on, as in Figure 1.3(b). Different parts, each requiring a different operation sequence,
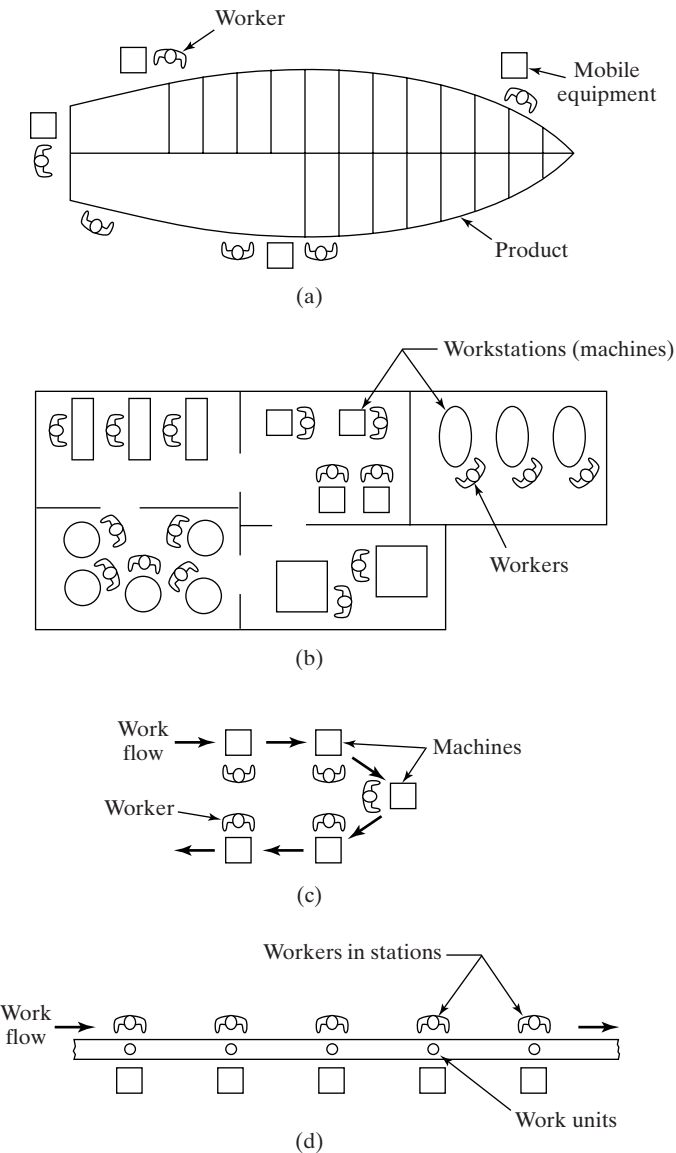
Figure 1.3 Various types of plant layout: (a) fixed-position layout, (b) process layout, (c) cellular layout, and (d) product layout.

are routed through the departments in the particular order needed for their processing, usually in batches. The process layout is noted for its flexibility; it can accommodate a great variety of alternative operation sequences for different part configurations. Its disadvantage is that the machinery and methods to produce a part are not designed for high efficiency. Much material handling is required to move parts between departments, so in-process inventory can be high.

1.1.2   Medium Quantity Production

In the medium quantity range (100–10,000 units annually), we distinguish between two different types of facility, depending on product variety. When product variety is hard, the traditional approach is *batch production*, in which a batch of one product is made, after which the facility is changed over to produce a batch of the next product, and so on. Orders for each product are frequently repeated. The production rate of the equipment is greater than the demand rate for any single product type, and so the same equipment can be shared among multiple products. The changeover between production runs takes time. Called the *setup time* or *changeover time*, it is the time to change tooling and to set up and reprogram the machinery. This is lost production time, which is a disadvantage of batch manufacturing. Batch production is commonly used in make-to-stock situations, in which items are manufactured to replenish inventory that has been gradually depleted by demand. The equipment is usually arranged in a process layout, Figure 1.3(b).

An alternative approach to medium range production is possible if product variety is soft. In this case, extensive changeovers between one product style and the next may not be required. It is often possible to configure the equipment so that groups of similar parts or products can be made on the same equipment without significant lost time for changeovers. The processing or assembly of different parts or products is accomplished in cells consisting of several workstations or machines. The term *cellular manufacturing* is often associated with this type of production. Each cell is designed to produce a limited variety of part configurations; that is, the cell specializes in the production of a given set of similar parts or products, according to the principles of *group technology* (Chapter 15). The layout is called a *cellular layout*, depicted in Figure 1.3(c).

1.1.3   High Production

The high quantity range (10,000 to millions of units per year) is often referred to as *mass production*. The situation is characterized by a high demand rate for the product, and the production facility is dedicated to the manufacture of that product. Two categories of mass production can be distinguished: (1) quantity production and (2) flow line production. *Quantity production* involves the mass production of single parts on single pieces of equipment. The method of production typically involves standard machines (such as stamping presses) equipped with special tooling (e.g., dies and material handling devices), in effect dedicating the equipment to the production of one part type. The typical layout used in quantity production is the process layout, Figure 1.3(b).

Flow line production involves multiple workstations arranged in sequence, and the parts or assemblies are physically moved through the sequence to complete the product. The workstations consist of production machines and/or workers equipped with specialized tools. The collection of stations is designed specifically for the product to maximize efficiency. The layout is called a *product layout*, and the workstations are arranged into one long line, as in Figure 1.3(d), or into a series of connected line segments. The work is usually moved between stations by powered conveyor. At each station, a small amount of the total work is completed on each unit of product.

The most familiar example of flow line production is the assembly line, associated with products such as cars and household appliances. The pure case of flow line production is where there is no variation in the products made on the line. Every product is identical, and the line is referred to as a *single model production line*. However, to successfully market a
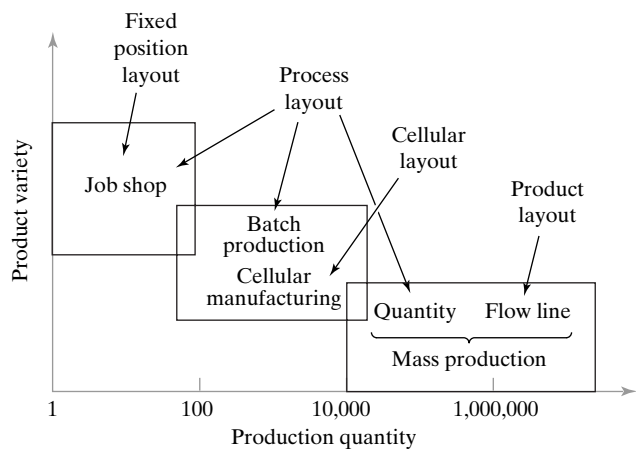
Figure 1.4 Types of facilities and layouts used for different levels of production quantity and product variety.

given product, it is often necessary to introduce model variations so that individual customers can choose the exact style and options that appeal to them. From a production viewpoint, the model differences represent a case of soft product variety. The term *mixed–model production line* applies to those situations where there is soft variety in the products made on the line. Modern automobile assembly is an example. Cars coming off the assembly line have variations in options and trim representing different models (and, in many cases, different nameplates) of the same basic car design.

Much of our discussion of the types of production facilities is summarized in Figure 1.4, which adds detail to Figure 1.2 by identifying the types of production facilities and plant layouts used. As the figure shows, some overlap exists among the different facility types.

1.2 MANUFACTURING SUPPORT SYSTEMS

To operate the production facilities efficiently, a company must organize itself to design the processes and equipment, plan and control the production orders, and satisfy product quality requirements. These functions are accomplished by manufacturing support systems – people and procedures by which a company manages its production operations. Most of these support systems do not directly contact the product, but they plan and control its progress through the factory.

Manufacturing support involves a cycle of information-processing activities, as illustrated in Figure 1.5. The production system facilities described in Section 1.1 are pictured in the center of the figure. The information-processing cycle, represented by the outer ring, can be described as consisting of four functions: (1) business functions, (2) product design, (3) manufacturing planning, and (4) manufacturing control.

Business Functions.   The business functions are the principal means of communicating with the customer. They are, therefore, the beginning and the end of the information-processing cycle. Included in this category are sales and marketing, sales forecasting, order entry, cost accounting, and customer billing.
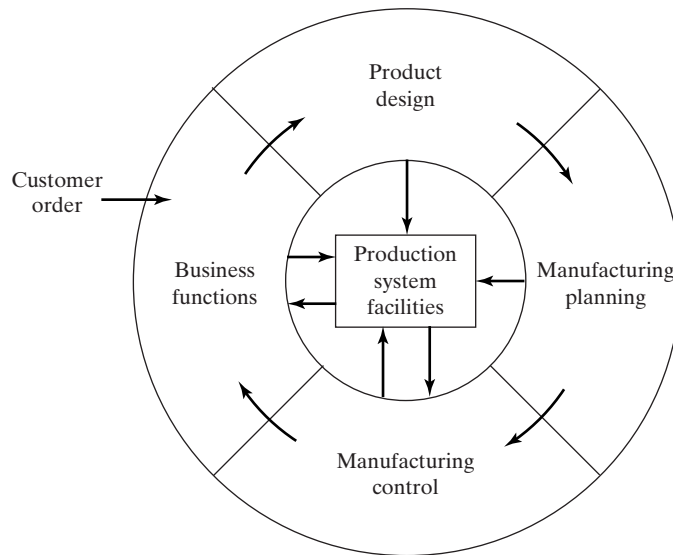
Figure 1.5 The information—processing cycle in a typical manufacturing firm.

The order to produce a product typically originates from the customer and proceeds into the company through the sales and marketing department of the firm. The production order will be in one of the following forms: (1) an order to manufacture an item to the customer's specifications, (2) a customer order to buy one or more of the manufacturer's proprietary products, or (3) an internal company order based on a forecast of future demand for a proprietary product.

Product Design.   If the product is to be manufactured to customer *design,* the design will have been provided by the customer. The manufacturer's product design department will not be involved. If the product is to be produced to customer *specifications,* the manufacturer's product design department may be contracted to do the design work for the product as well as to manufacture it.

If the product is proprietary, the manufacturing firm is responsible for its development and design. The cycle of events that initiates a new product design often originates in the sales and marketing department; the information flow is indicated in Figure 1.5. The departments of the firm that are organized to accomplish product design might include research and development, design engineering, drafting, and perhaps a prototype shop.

Manufacturing Planning.   The information and documentation that constitute the product design flows into the manufacturing planning function. The information-processing activities in manufacturing planning include process planning, master scheduling, requirements planning, and capacity planning. *Process planning* consists of determining the sequence of individual processing and assembly operations needed to produce the part. The manufacturing engineering and industrial engineering departments are responsible for planning the processes and related technical details.

Manufacturing planning includes logistics issues, commonly known as production planning. The authorization to produce the product must be translated into the master

production schedule. The *master production schedule* is a listing of the products to be made, when they are to be delivered, and in what quantities. Months are traditionally used to specify deliveries in the master schedule. Based on this schedule, the individual components and subassemblies that make up each product must be planned. Raw materials must be purchased or requisitioned from storage, purchased parts must be ordered from suppliers, and all of these items must be planned so that they are available when needed. This entire task is called *material requirements planning*. In addition, the master schedule must not list more quantities of products than the factory is capable of producing each month with its given number of machines and manpower. A function called *capacity planning* is concerned with planning the manpower and machine resources of the firm.

Manufacturing Control. Manufacturing control is concerned with managing and controlling the physical operations in the factory to implement the manufacturing plans. The flow of information is from planning to control as indicated in Figure 1.5. Information also flows back and forth between manufacturing control and the factory operations. Included in the manufacturing control function are shop floor control, inventory control, and quality control.

Shop floor control deals with the problem of monitoring the progress of the product as it is being processed, assembled, moved, and inspected in the factory. Shop floor control is concerned with inventory in the sense that the materials being processed in the factory are work-in-process inventory. Thus, shop floor control and inventory control overlap to some extent. *Inventory control* attempts to strike a proper balance between the danger of too little inventory (with possible stock-outs of materials) and the carrying cost of too much inventory. It deals with such issues as deciding the right quantities of materials to order and when to reorder a given item when stock is low.

The mission of *quality control* is to ensure that the quality of the product and its components meet the standards specified by the product designer. To accomplish its mission, quality control depends on inspection activities performed in the factory at various times during the manufacture of the product. Also, raw materials and component parts from outside sources are sometimes inspected when they are received, and final inspection and testing of the finished product is performed to ensure functional quality and appearance.

1.3 AUTOMATION IN PRODUCTION SYSTEMS

Some elements of the firm's production system are likely to be automated, whereas others will be operated manually or clerically. For our purposes here, *automation* can be defined as a technology concerned with the application of mechanical, electronic, and computer-based systems to operate and control production.

The automated elements of the production system can be separated into two categories: (1) automation of the manufacturing systems in the factory and (2) computerization of the manufacturing support systems. In modern production systems, the two categories overlap to some extent, because the automated manufacturing systems operating on the factory floor are themselves often implemented by computer systems and connected to the computerized manufacturing support systems and management information system operating at the plant and enterprise levels. The term computer-integrated manufacturing is used to indicate this extensive use of computers in production systems. The two categories of automation are shown in Figure 1.6 as an overlay on Figure 1.1.
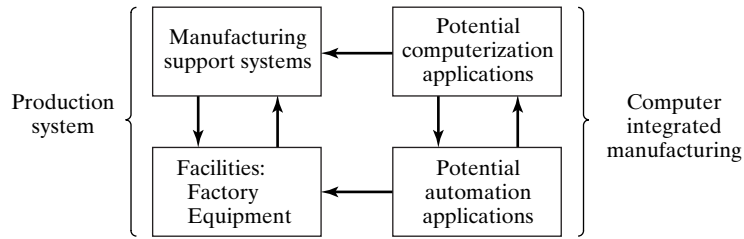
Figure 1.6 Opportunities of automation and computerization in a production system.

1.3.1 Automated Manufacturing Systems

Automated manufacturing systems operate in the factory on the physical product. They perform operations such as processing, assembly, inspection, or material handling, in some cases accomplishing more than one of these operations in the same system. They are called automated because they perform their operations with a reduced level of human participation compared with the corresponding manual process. In some highly automated systems, there is virtually no human participation. Examples of automated manufacturing systems include:

- automated machine tools that process parts
- transfer lines that perform a series of machining operations
- automated assembly systems
- manufacturing systems that use industrial robots to perform processing or assembly operations
- automatic material handling and storage systems to integrate manufacturing operations
- automatic inspection systems for quality control

Automated manufacturing systems can be classified into three basic types (for our purposes in this introduction; we explore the topic of automation in greater depth in Chapter 3): (1) fixed automation, (2) programmable automation, and (3) flexible automation.

Fixed Automation.   *Fixed automation* is a system in which the sequence of processing (or assembly) operations is fixed by the equipment configuration. Each of the operations in the sequence is usually simple, involving perhaps a plain linear or rotational motion or an uncomplicated combination of the two; for example, the feeding of a rotating spindle. It is the integration and coordination of many such operations into one piece of equipment that makes the system complex. Typical features of fixed automation are:

- high initial investment for custom-engineered equipment
- high production rates
- relatively inflexible in accommodating product variety

The economic justification for fixed automation is found in products that are produced in very large quantities and at high production rates. The high initial cost of the equipment can be spread over a very large number of units, thus making the unit cost attractive com-

pared with alternative methods of production. Examples of fixed automation include machining transfer lines and automated assembly machines.

Programmable Automation.   In *programmable automation*, the production equipment is designed with the capability to change the sequence of operations to accommodate different product configurations. The operation sequence is controlled by a *program,* which is a set of instructions coded so that they can be read and interpreted by the system. New programs can be prepared and entered into the equipment to produce new products. Some of the features that characterize programmable automation include:

- high investment in general purpose equipment
- lower production rates than fixed automation
- flexibility to deal with variations and changes in product configuration
- most suitable for batch production

Programmable automated production systems are used in low- and medium-volume production. The parts or products are typically made in batches. To produce each new batch of a different product, the system must be reprogrammed with the set of machine instructions that correspond to the new product. The physical setup of the machine must also be changed: Tools must be loaded, fixtures must be attached to the machine table, and the required machine settings must be entered. This changeover procedure takes time. Consequently, the typical cycle for a given product includes a period during which the setup and reprogramming takes place, followed by a period in which the batch is produced. Examples of programmable automation include numerically controlled (NC) machine tools, industrial robots, and programmable logic controllers.

Flexible Automation.   *Flexible automation* is an extension of programmable automation. A flexible automated system is capable of producing a variety of parts (or products) with virtually no time lost for changeovers from one part style to the next. There is no lost production time while reprogramming the system and altering the physical setup (tooling, fixtures, machine settings). Consequently, the system can produce various combinations and schedules of parts or products instead of requiring that they be made in batches. What makes flexible automation possible is that the differences between parts processed by the system are not significant. It is a case of soft variety, so that the amount of changeover required between styles is minimal. The features of flexible automation can be summarized as follows:

- high investment for a custom-engineered system
- continuous production of variable mixtures of products
- medium production rates
- flexibility to deal with product design variations

Examples of flexible automation are the flexible manufacturing systems for performing machining operations that date back to the late 1960s.

The relative positions of the three types of automation for different production volumes and product varieties are depicted in Figure 1.7. For low production quantities and new product introductions, manual production is competitive with programmable automation, as we indicate in the figure and discuss in Section 1.4.1.
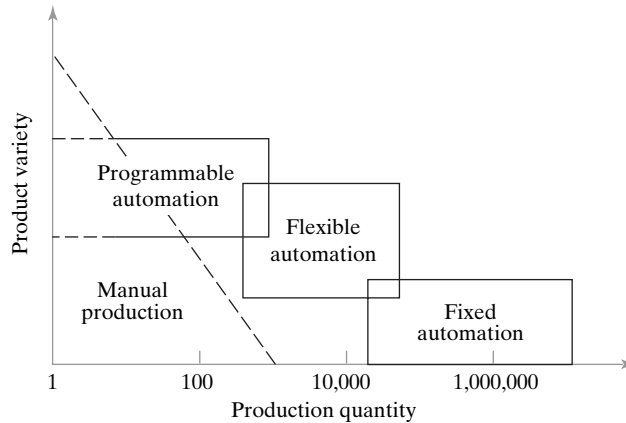
Figure 1.7 Three types of automation relative to production quantity and product variety.

1.3.2   Computerized Manufacturing Support Systems

Automation of the manufacturing support systems is aimed at reducing the amount of manual and clerical effort in product design, manufacturing planning and control, and the business functions of the firm. Nearly all modern manufacturing support systems are implemented using computer systems. Indeed, computer technology is used to implement automation of the manufacturing systems in the factory as well. The term *computer—integrated manufacturing* (CIM) denotes the pervasive use of computer systems to design the products, plan the production, control the operations, and perform the various business—related functions needed in a manufacturing firm. True CIM involves integrating all of these functions in one system that operates throughout the enterprise. Other terms are used to identify specific elements of the CIM system. For example, *computer-aided design* (CAD) denotes the use of computer systems to support the product design function. *Computer-aided manufacturing* (CAM) denotes the use of computer systems to perform functions related to manufacturing engineering, such as process planning and numerical control part programming. Some computer systems perform both CAD and CAM, and so the term *CAD/CAM* is used to indicate the integration of the two into one system. Computer—integrated manufacturing includes CAD/CAM, but it also includes the firm's business functions that are related to manufacturing.

Let us attempt to define the relationship between automation and CIM by developing a conceptual model of manufacturing. In a manufacturing firm, the physical production activities that take place in the factory can be distinguished from the information—processing activities, such as product design and production planning, that usually occur in an office environment. The physical activities include all of the processing, assembly, material handling, and inspection operations that are performed on the product in the factory. These operations come in direct contact with the product during manufacture. The relationship between the physical activities and the information—processing activities in our model is depicted in Figure 1.8. Raw materials flow into one end of the factory and finished products flow out the other end. The physical activities take place inside the factory. In our model, the information—processing activities form a ring that surrounds the factory, providing the data and knowledge required to successfully produce the product. These in-
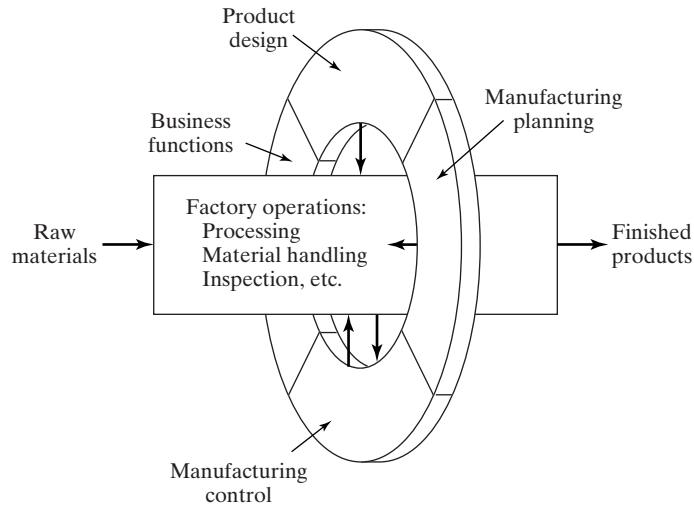
Figure 1.8 Model of manufacturing showing factory operations and the information—processing activities for manufacturing support.

formation—processing activities are accomplished to implement the four basic manufacturing support functions identified earlier: (1) business functions, (2) product design, (3) manufacturing planning, and (4) manufacturing control. These four functions form a cycle of events that must accompany the physical production activities but do not directly touch the product.

1.3.3 Reasons for Automating

Companies undertake projects in manufacturing automation and computer-integrated manufacturing for a variety of good reasons. Some of the reasons used to justify automation are the following:

1. *To increase labor productivity*. Automating a manufacturing operation usually increases production rate and labor productivity. This means greater output per hour of labor input.
2. *To reduce labor cost*. Ever-increasing labor cost has been and continues to be the trend in the world's industrialized societies. Consequently, higher investment in automation has become economically justifiable to replace manual operations. Machines are increasingly being substituted for human labor to reduce unit product cost.
3. *To mitigate the effects of labor shortages*. There is a general shortage of labor in many advanced nations, and this has stimulated the development of automated operations as a substitute for labor.
4. *To reduce or eliminate routine manual and clerical tasks*. An argument can be put forth that there is social value in automating operations that are routine, boring, fatiguing, and possibly irksome. Automating such tasks serves a purpose of improving the general level of working conditions.
5. *To improve worker safety*. By automating a given operation and transferring the worker from active participation in the process to a supervisory role, the work is made

safer. The safety and physical well-being of the worker has become a national objective with the enactment of the Occupational Safety and Health Act (OSHA) in 1970. This has provided an impetus for automation.

6. *To improve product quality*. Automation not only results in higher production rates than manual operations; it also performs the manufacturing process with greater uniformity and conformity to quality specifications. Reduction of fraction defect rate is one of the chief benefits of automation.

7. *To reduce manufacturing lead time*. Automation helps to reduce the elapsed time between customer order and product delivery, providing a competitive advantage to the manufacturer for future orders. By reducing manufacturing lead time, the manufacturer also reduces work-in-process inventory.

8. *To accomplish processes that cannot be done manually*. Certain operations cannot be accomplished without the aid of a machine. These processes have requirements for precision, miniaturization, or complexity of geometry, that cannot be achieved manually. Examples include certain integrated circuit fabrication operations, rapid prototyping processes based on computer graphics (CAD) models, and the machining of complex, mathematically defined surfaces using computer numerical control. These processes can only be realized by computer controlled systems.

9. *To avoid the high cost of not automating*. There is a significant competitive advantage gained in automating a manufacturing plant. The advantage cannot easily be demonstrated on a company's project authorization form. The benefits of automation often show up in unexpected and intangible ways, such as in improved quality, higher sales, better labor relations, and better company image. Companies that do not automate are likely to find themselves at a competitive disadvantage with their customers, their employees, and the general public.

1.4 MANUAL LABOR IN PRODUCTION SYSTEMS

Is there a place for manual labor in the modern production system? The answer is certainly yes. Even in a highly automated production system, humans are still a necessary component of the manufacturing enterprise. For the foreseeable future, people will be required to manage and maintain the plant, even in those cases where they do not participate directly in its manufacturing operations. Let us separate our discussion of the labor issue into two parts, corresponding to our previous distinction between facilities and manufacturing support: (1) manual labor in factory operations and (2) labor in the manufacturing support systems.

1.4.1 Manual Labor in Factory Operations

There is no denying that the long-term trend in manufacturing is toward greater use of automated machines to substitute for manual labor. This has been true throughout human history, and there is every reason to believe the trend will continue. It has been made possible by applying advances in technology to factory operations. In parallel, and sometimes in conflict, with this technologically driven trend are issues of economics that continue to find reasons for employing manual labor in manufacturing operations.

Certainly one of the current economic realities in the world is that there are countries whose average hourly wage rates are sufficiently low that most automation projects are im-

possible to justify strictly on the basis of cost reduction. At time of writing, these countries include Mexico, China, and most of the countries of Southeast Asia. With the recent passage of the North American Free Trade Agreement (NAFTA), the North American continent has become one large labor pool. Within this pool, Mexico's labor rate is an order of magnitude less than that in the United States. For U.S. corporate executives making decisions on a factory location or the outsourcing of work, this is an economic reality that must be reckoned with.

In addition to the labor rate issue, there are other reasons, ultimately based on economics, that make the use of manual labor a feasible alternative to automation. Humans possess certain attributes that give them an advantage over machines in certain situations and certain kinds of tasks. Table 1.1 lists the relative strengths and attributes of humans and machines. A number of situations can be listed in which manual labor is usually preferred over automation:

- *Task is too technological difficulty to automated*. Certain tasks are very difficult (either technologically or economically) to automate. Reasons for the difficulty include: (1) problems with physical access to the work location, (2) adjustments required in the task, (3) manual dexterity requirements, and (3) demands on hand-eye coordination. Manual labor is used to perform the tasks in these cases. Examples include automobile final assembly lines where many final trim operations are accomplished by human workers.

- *Short product life cycle*. If the product must be designed and introduced in a short period of time to meet a near-term window of opportunity in the marketplace, or if the product is anticipated to be on the market for a relatively short period, then a manufacturing method designed around manual labor allows for a much faster product launch than does an automated method. Tooling for manual production can be fabricated in much less time and at much lower cost than comparable automation tooling.

- *Customized product*. If the customer requires a one-of-a-kind item with unique features, manual labor may have the advantage as the appropriate production resource because of its versatility and adaptability. Humans are more flexible than any automated machine.

- *To cope with ups and downs in demand*. Changes in demand for a product necessitate changes in production output levels. Such changes are more easily made when manual labor is used as the means of production. An automated manufacturing system has a fixed cost associated with its investment. If output is reduced, that fixed cost must be spread over fewer units, driving up the unit cost of the product. On the other hand,

TABLE 1.1　Relative Strengths and Attributes of Humans and Machines

Relative Strengths of Humans	*Relative Strengths of Machines*
Sense unexpected stimuli	Perform repetitive tasks consistently
Develop new solutions to problems	Store large amounts of data
Cope with abstract problems	Retrieve data from memory reliably
Adapt to change	Perform multiple tasks at same time
Generalize from observations	Apply high forces and power
Learn from experience	Perform simple computations quickly
Make difficult decisions based on incomplete data	Make routine decisions quickly

an automated system has an ultimate upper limit on its output capacity. It cannot produce more than its rated capacity. By contrast, manual labor can be added or reduced as needed to meet demand, and the associated cost of the resource is in direct proportion to its usage. Manual labor can be used to augment the output of an existing automated system during those periods when demand exceeds the capacity of the automated system.

- *To reduce risk of product failure*. A company introducing a new product to the market never knows for sure what the ultimate success of that product will be. Some products will have long life cycles, while others will be on the market for relatively short lives. The use of manual labor as the productive resource at the beginning of the product's life reduces the company's risk of losing a significant investment in automation if the product fails to achieve a long market life. In Section 1.5.3, we discuss an automation migration strategy that is suitable for introducing a new product.

1.4.2   Labor in Manufacturing Support Systems

In manufacturing support functions, many of the routine manual and clerical tasks can be automated using computer systems. Certain production planning activities are better accomplished by computer than by clerks. Material requirements planning (MRP, Section 26.2) is an example: In material requirements planning, order releases are generated for component parts and raw materials based on the master production schedule for final products. This requires a massive amount of data processing that is best suited to computer automation. Many commercial software packages are available to perform MRP. With few exceptions, companies that need to accomplish MRP rely on the computer. Humans are still required to interpret and implement the output of these MRP computations and to otherwise manage the production planning function.

In modern production systems, the computer is used as an aid in performing virtually all manufacturing support activities. Computer-aided design systems are used in product design. The human designer is still required to do the creative work. The CAD system is a tool that assists and amplifies the designer's creative talents. Computer-aided process planning systems are used by manufacturing engineers to plan the production methods and routings. In these examples, humans are integral components in the operation of the manufacturing support functions, and the computer-aided systems are tools to increase productivity and improve quality. CAD and CAM systems rarely operate completely in automatic mode.

It is very unlikely that humans will never be needed in manufacturing support systems, no matter how automated the systems are. People will be needed to do the decision making, learning, engineering, evaluating, managing, and other functions for which humans are much better suited than are machines, according to Table 1.1.

Even if all of the manufacturing systems in the factory are automated, there will still be a need for the following kinds of work to be performed:

- *Equipment maintenance*. Skilled technicians will be required to maintain and repair the automated systems in the factory when these systems break down. To improve the reliability of the automated systems, preventive maintenance will have to be carried out.
- *Programming and computer operation*. There will be a continual demand to upgrade software, install new versions of software packages, and execute the programs. It is anticipated that much of the routine process planning, numerical control part pro-

gramming, and robot programming may be highly automated using artificial intelligence in the future.

- *Engineering project work.* The computer-automated and integrated factory is likely never to be finished. There will be a continual need to upgrade production machines, design tooling, and undertake continuous improvement projects. These activities require the skills of engineers working in the factory.
- *Plant management.* Someone must be responsible for running the factory. There will be a limited staff of professional managers and engineers who are responsible for plant operations. There is likely to be an increased emphasis on managers' technical skills rather than in traditional factory management positions, where the emphasis is on personnel skills.

1.5 AUTOMATION PRINCIPLES AND STRATEGIES

The preceding discussion leads us to conclude that automation is not always the right answer for a given production situation. A certain caution and respect must be observed in applying automation technologies. In this section, we offer three approaches for dealing with automation projects:[2] (1) the USA Principle, (2) the Ten Strategies for Automation and Production Systems, and (3) an Automation Migration Strategy.

1.5.1 USA Principle

The USA Principle is a common sense approach to automation projects. Similar procedures have been suggested in the manufacturing and automation trade literature, but none has a more captivating title than this one. USA stands for:

1. *Understand* the existing process
2. *Simplify* the process
3. *Automate* the process.

A statement of the USA principle appeared in an APICS[3] article [4]. The article was concerned with implementation of enterprise resource planning (ERP, Section 26.6), but the USA approach is so general that it is applicable to nearly any automation project. Going through each step of the procedure for an automation project may in fact reveal that simplifying the process is sufficient and automation is not necessary.

   Understand the Existing Process.   The obvious purpose of the first step in the USA approach is to comprehend the current process in all of its details. What are the inputs? What are the outputs? What exactly happens to the work unit between input and output? What is the function of the process? How does it add value to the product? What are the upstream and downstream operations in the production sequence, and can they be combined with the process under consideration?

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[2] There are additional approaches not discussed here, but in which the reader may be interested; for example, the ten steps to integrated manufacturing production systems discussed in J. Black's book: ***The Design of the Factory with a Future*** [1].

[3] APICS = American Production and Inventory Control Society.

Some of the basic charting tools used in methods analysis are useful in this regard, such as the operation process chart and the flow process chart [5]. Application of these tools to the existing process provides a model of the process that can be analyzed and searched for weaknesses (and strengths). The number of steps in the process, the number and placement of inspections, the number of moves and delays experienced by the work unit, and the time spent in storage can be ascertained by these charting techniques.

Mathematical models of the process may also be useful to indicate relationships between input parameters and output variables. What are the important output variables? How are these output variables affected by inputs to the process, such as raw material properties, process settings, operating parameters, and environmental conditions? This information may be valuable in identifying what output variables need to be measured for feedback purposes and in formulating algorithms for automatic process control.

Simplify the Process.   Once the existing process is understood, then the search can begin for ways to simplify. This often involves a checklist of questions about the existing process. What is the purpose of this step or this transport? Is this step necessary? Can this step be eliminated? Is the most appropriate technology being used in this step? How can this step be simplified? Are there unnecessary steps in the process that might be eliminated without detracting from function?

Some of the ten strategies of automation and production systems (Section 1.5.2) are applicable to try to simplify the process. Can steps be combined? Can steps be performed simultaneously? Can steps be integrated into a manually operated production line?

Automate the Process.   Once the process has been reduced to its simplest form, then automation can be considered. The possible forms of automation include those listed in the ten strategies discussed in the following section. An automation migration strategy (Section 1.5.3) might be implemented for a new product that has not yet proven itself.

1.5.2   Ten Strategies for Automation and Production Systems

Following the USA Principle is a good first step in any automation project. As suggested previously, it may turn out that automation of the process is unnecessary or cannot be cost justified after it has been simplified.

If automation seems a feasible solution to improving productivity, quality, or other measure of performance, then the following ten strategies provide a road map to search for these improvements. These ten strategies were first published in my first book.[4] They seem as relevant and appropriate today as they did in 1980. We refer to them as strategies for automation and production systems because some of them are applicable whether the process is a candidate for automation or just for simplification.

1. *Specialization of operations*. The first strategy involves the use of special—purpose equipment designed to perform one operation with the greatest possible efficiency. This is analogous to the concept of labor specialization, which is employed to improve labor productivity.

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[4] M. P. Groover, *Automation, Production Systems, and Computer-Aided Manufacturing*, Prentice Hall, Englewood Cliffs, New Jersey, 1980.

2. *Combined operations*. Production occurs as a sequence of operations. Complex parts may require dozens, or even hundreds, of processing steps. The strategy of combined operations involves reducing the number of distinct production machines or workstations through which the part must be routed. This is accomplished by performing more than one operation at a given machine, thereby reducing the number of separate machines needed. Since each machine typically involves a setup, setup time can usually be saved as a consequence of this strategy. Material handling effort and non-operation time are also reduced. Manufacturing lead time is reduced for better customer service.

3. *Simultaneous operations*. A logical extension of the combined operations strategy is to simultaneously perform the operations that are combined at one workstation. In effect, two or more processing (or assembly) operations are being performed simultaneously on the same workpart, thus reducing total processing time.

4. *Integration of operations*. Another strategy is to link several workstations together into a single integrated mechanism, using automated work handling devices to transfer parts between stations. In effect, this reduces the number of separate machines through which the product must be scheduled. With more than one workstation, several parts can be processed simultaneously, thereby increasing the overall output of the system.

5. *Increased flexibility*. This strategy attempts to achieve maximum utilization of equipment for job shop and medium volume situations by using the same equipment for a variety of parts or products. It involves the use of the flexible automation concepts (Section 1.3.1). Prime objectives are to reduce setup time and programming time for the production machine. This normally translates into lower manufacturing lead time and less work-in-process.

6. *Improved material handling and storage*. A great opportunity for reducing nonproductive time exists in the use of automated material handling and storage systems. Typical benefits include reduced work-in-process and shorter manufacturing lead times.

7. *On-line inspection*. Inspection for quality of work is traditionally performed after the process is completed. This means that any poor quality product has already been produced by the time it is inspected. Incorporating inspection into the manufacturing process permits corrections to the process as the product is being made. This reduces scrap and brings the overall quality of product closer to the nominal specifications intended by the designer.

8. *Process control and optimization*. This includes a wide range of control schemes intended to operate the individual processes and associated equipment more efficiently. By this strategy, the individual process times can be reduced and product quality improved.

9. *Plant operations control*. Whereas the previous strategy was concerned with the control of the individual manufacturing process, this strategy is concerned with control at the plant level. It attempts to manage and coordinate the aggregate operations in the plant more efficiently. Its implementation usually involves a high level of computer networking within the factory.

10. *Computer-integrated manufacturing* (CIM). Taking the previous strategy one level higher, we have the integration of factory operations with engineering design and the business functions of the firm. CIM involves extensive use of computer applications, computer data bases, and computer networking throughout the enterprise.

The ten strategies constitute a checklist of the possibilities for improving the production system through automation or simplification. They should not be considered as mutually exclusive. For most situations, multiple strategies can be implemented in one improvement project.

1.5.3   Automation Migration Strategy

Owing to competitive pressures in the marketplace, a company often needs to introduce a new product in the shortest possible time. As mentioned previously, the easiest and least expensive way to accomplish this objective is to design a manual production method, using a sequence of workstations operating independently. The tooling for a manual method can be fabricated quickly and at low cost. If more than a single set of workstations is required to make the product in sufficient quantities, as is often the case, then the manual cell is replicated as many times as needed to meet demand. If the product turns out to be successful, and high future demand is anticipated, then it makes sense for the company to automate production. The improvements are often carried out in phases. Many companies have an *automation migration strategy,* that is, a formalized plan for evolving the manufacturing systems used to produce new products as demand grows. A typical automation migration strategy is the following:

> Phase 1:   *Manual production* using single station manned cells operating independently. This is used for introduction of the new product for reasons already mentioned: quick and low cost tooling to get started.
>
> Phase 2:   *Automated production* using single station automated cells operating independently. As demand for the product grows, and it becomes clear that automation can be justified, then the single stations are automated to reduce labor and increase production rate. Work units are still moved between workstations manually.
>
> Phase 3:   *Automated integrated production* using a multistation automated system with serial operations and automated transfer of work units between stations. When the company is certain that the product will be produced in mass quantities and for several years, then integration of the single station automated cells is warranted to further reduce labor and increase production rate.

This strategy is illustrated in Figure 1.9. Details of the automation migration strategy vary from company to company, depending on the types of products they make and the manufacturing processes they perform. But well-managed manufacturing companies have policies like the automation migration strategy. Advantages of such a strategy include:

- It allows introduction of the new product in the shortest possible time, since production cells based on manual workstations are the easiest to design and implement.
- It allows automation to be introduced gradually (in planned phases), as demand for the product grows, engineering changes in the product are made, and time is allowed to do a thorough design job on the automated manufacturing system.
- It avoids the commitment to a high level of automation from the start, since there is always a risk that demand for the product will not justify it.
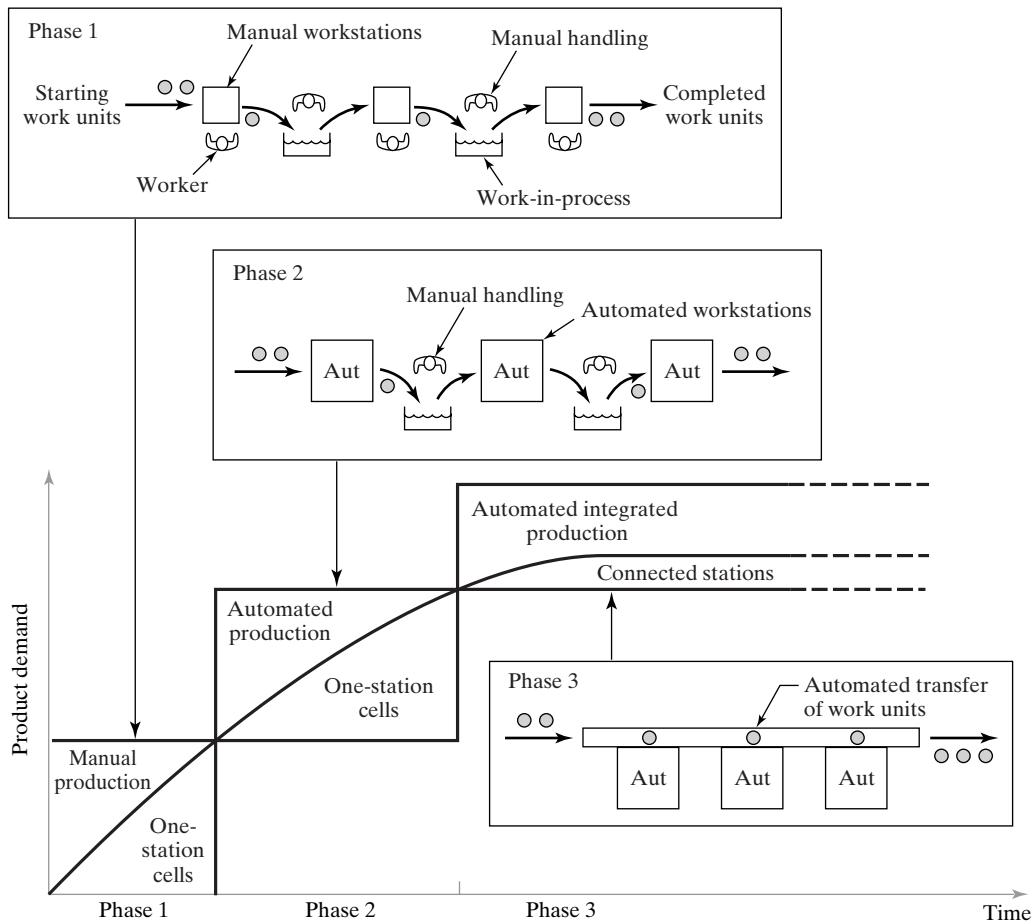
Figure 1.9 A typical automation migration strategy. (1) Phase 1: manual production with single independent workstations. (2) Phase 2: automated production stations with manual handling between stations. (3) Phase 3: automated integrated production with automated handling between stations. Key: Aut = automated workstation.

1.6 ORGANIZATION OF THE BOOK

This chapter has provided an overview of production systems and how automation is sometimes used in these systems. We see that people are needed in manufacturing, even when the production systems are highly automated. Chapter 2 takes a look at manufacturing operations: the manufacturing processes and other activities that take place in the factory. We also develop several mathematical models that are intended to increase the reader's understanding of the issues and parameters in manufacturing operations and to underscore their quantitative nature.

The remaining 25 chapters are organized into five parts. Let us describe the five parts with reference to Figure 1.10, which shows how the topics fit together. Part I includes six

Figure 1.10 Overview and relationships among the five parts of the book.
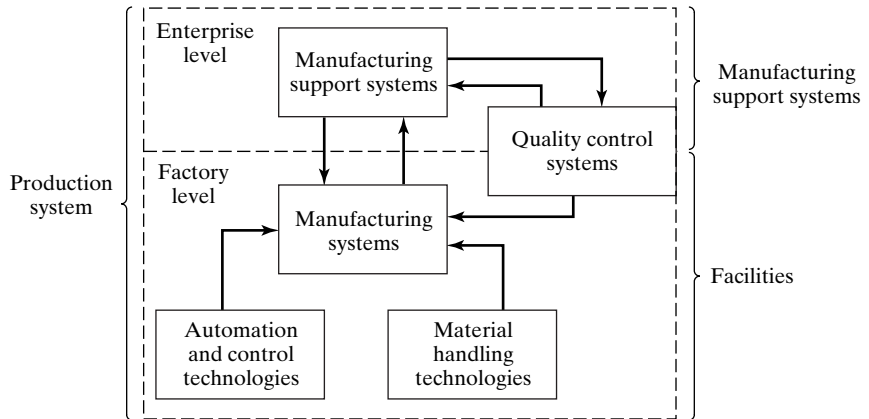
chapters that are concerned with automation technologies. Whereas Chapter 1 discusses automation in general terms, Part I describes the technical details. Automation relies heavily on control systems, so Part I is called *Automation and Control Technologies*. These technologies include numerical control, industrial robotics, and programmable logic controllers.

Part II is composed of four chapters on material handling technologies that are used primarily in factories and warehouses. This includes equipment for transporting materials, storing them, and automatically identifying them for material control purposes.

Part III is concerned with the integration of automation technologies and material handling technologies into manufacturing systems—those that operate in the factory and touch the product. Some of these manufacturing systems are highly automated, while others rely largely on manual labor. Part III contains seven chapters, covering such topics as production lines, assembly systems, group technology, and flexible manufacturing systems.

The importance of quality control must not be overlooked in modern production systems. Part IV covers this topic, dealing with statistical process control and inspection issues. We describe some of the significant inspection technologies here, such as machine vision and coordinate measuring machines. As suggested in Figure 1.10, quality control (QC) systems include elements of both facilities and manufacturing support systems. QC is an enterprise—level function, but it has equipment and procedures that operate in the factory.

Finally, Part V addresses the remaining manufacturing support functions in the production system. We include a chapter on product design and how it is supported by computer-aided design systems. The second chapter in Part V is concerned with process planning and how it is automated by computer-aided process planning. Here we also discuss concurrent engineering and design for manufacturing. Chapter 26 covers production planning and control, including topics such as material requirements planning (mentioned in Chapter 1), manufacturing resource planning, and just-in-time production systems. Our book concludes with a chapter on lean production and agile manufacturing, two production system paradigms that define the ways that modern manufacturing companies are attempting to run their businesses.

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chapter 2

Manufacturing Operations[1]

CHAPTER CONTENTS

Manufacturing can be defined as the application of physical and chemical processes to alter the geometry, properties, and/or appearance of a given starting material to make parts

[1] The chapter introduction and Sections 2.1 and 2.2 are based on M. P. Groover, *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*, Chapter 1.
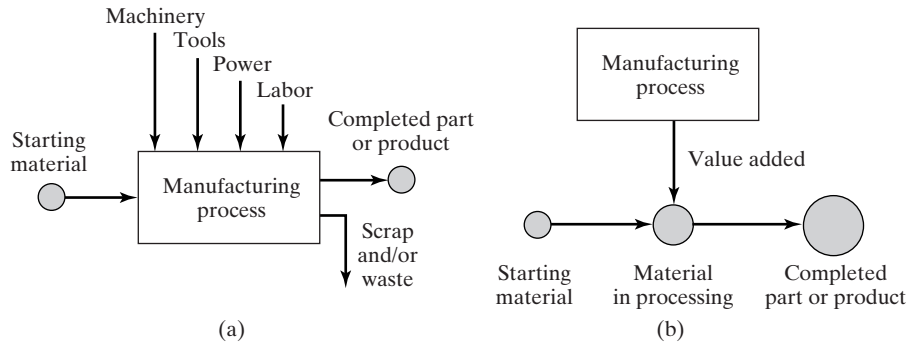
Figure 2.1 Alternative definitions of manufacturing: (a) as a technological process and (b) as an economic process.

or products; manufacturing also includes the joining of multiple parts to make assembled products. The processes that accomplish manufacturing involve a combination of machinery, tools, power, and manual labor, as depicted in Figure 2.1(a). Manufacturing is almost always carried out as a sequence of operations. Each successive operation brings the material closer to the desired final state.

From an economic viewpoint, manufacturing is the transformation of materials into items of greater value by means of one or more processing and/or assembly operations, as depicted in Figure 2.1(b). The key point is that manufacturing *adds value* to the material by changing its shape or properties or by combining it with other materials that have been similarly altered. The material has been made more valuable through the manufacturing operations performed on it. When iron ore is converted into steel, value is added. When sand is transformed into glass, value is added. When petroleum is refined into plastic, value is added. And when plastic is molded into the complex geometry of a patio chair, it is made even more valuable.

In this chapter, we provide a survey of manufacturing operations. We begin by examining the industries that are engaged in manufacturing and the types of products they produce. We then discuss fabrication and assembly processes used in manufacturing as well as the activities that support the processes, such as material handling and inspection. The chapter concludes with descriptions of several mathematical models of manufacturing operations. These models help to define certain issues and parameters that are important in manufacturing and to provide a quantitative perspective on manufacturing operations.

We might observe here that the manufacturing operations, the processes in particular, emphasize the preceding technological definition of manufacturing, while the production systems discussed in Chapter 1 stress the economic definition. Our emphasis in this book is on the systems. The history of manufacturing includes both the development of manufacturing processes, some of which date back thousands of years, and the evolution of the production systems required to apply and exploit these processes (Historical Note 2.1).

Historical Note 2.1   History of manufacturing

The history of manufacturing includes two related topics: (1) man's discovery and invention of materials and processes to make things and (2) the development of systems of production. The materials and processes predate the systems by several millennia. Systems of production

refer to the ways of organizing people and equipment so that production can be performed more efficiently. Some of the basic processes date as far back as the Neolithic period (circa 8000–3000 B.C.), when operations such as the following were developed: *woodworking*, *forming*, and *firing* of clay pottery, *grinding* and *polishing* of stone, *spinning* and *weaving* of textiles, and *dyeing* of cloth. Metallurgy and metalworking also began during the Neolithic, in Mesopotamia and other areas around the Mediterranean. It either spread to, or developed independently in, regions of Europe and Asia. Gold was found by early man in relatively pure form in nature; it could be *hammered* into shape. Copper was probably the first metal to be extracted from ores, thus requiring *smelting* as a processing technique. Copper could not be readily hammered because it strain-hardened; instead, it was shaped by *casting*. Other metals used during this period were silver and tin. It was discovered that copper alloyed with tin produced a more workable metal than copper alone (casting and hammering could both be used). This heralded the important period known as the *Bronze Age* (circa 3500–1500 B.C.).

Iron was also first smelted during the Bronze Age. Meteorites may have been one source of the metal, but iron ore was also mined. The temperatures required to reduce iron ore to metal are significantly higher than for copper, which made furnace operations more difficult. Other processing methods were also more difficult for the same reason. Early blacksmiths learned that when certain irons (those containing small amounts of carbon) were sufficiently *heated* and then *quenched*, they became very hard. This permitted the grinding of very sharp cutting edges on knives and weapons, but it also made the metal brittle. Toughness could be increased by reheating at a lower temperature, a process known as *tempering*. What we have described is, of course, the *heat treatment* of steel. The superior properties of steel caused it to succeed bronze in many applications (weaponry, agriculture, and mechanical devices). The period of its use has subsequently been named the *Iron Age* (starting around 1000 B.C.). It was not until much later, well into the nineteenth century, that the demand for steel grew significantly and more modern steelmaking techniques were developed.

The early fabrication of implements and weapons was accomplished more as crafts and trades than by manufacturing as we know it today. The ancient Romans had what might be called factories to produce weapons, scrolls, pottery, glassware, and other products of the time, but the procedures were largely based on handicraft. It was not until the *Industrial Revolution* (circa 1760–1830) that major changes began to affect the systems for making things. This period marked the beginning of the change from an economy based on agriculture and handicraft to one based on industry and manufacturing. The change began in England, where a series of important machines were invented, and steam power began to replace water, wind, and animal power. Initially, these advances gave British industry significant advantages over other nations, but eventually the revolution spread to other European countries and to the United States. The Industrial Revolution contributed to the development of manufacturing in the following ways: (1) *Watt's steam engine*, a new power-generating technology; (2) development of *machine tools*, starting with John Wilkinson's boring machine around 1775, which was used to bore the cylinder on Watt's steam engine; (3) invention of the *spinning jenny*, *power loom*, and other machinery for the textile industry, which permitted significant increases in productivity; and (4) the *factory system*, a new way of organizing large numbers of production workers based on the division of labor.

Wilkinson's boring machine is generally recognized as the beginning of machine tool technology. It was powered by water wheel. During the period 1775–1850, other machine tools were developed for most of the conventional *machining processes*, such as *boring*, *turning*, *drilling*, *milling*, *shaping*, and *planing*. As steam power became more prevalent, it gradually became the preferred power source for most of these machine tools. It is of interest to note that many of the individual processes predate the machine tools by centuries; for example, drilling and sawing (of wood) date from ancient times and turning (of wood) from around the time of Christ.

Assembly methods were used in ancient cultures to make ships, weapons, tools, farm implements, machinery, chariots and carts, furniture, and garments. The processes included

binding with twine and rope, *riveting* and *nailing*, and *soldering*. By around the time of Christ, *forge welding* and *adhesive bonding* had been developed. Widespread use of screws, bolts, and nuts—so common in today's assembly—required the development of machine tools, in particular, Maudsley's screw cutting lathe (1800), which could accurately form the helical threads. It was not until around 1900 that *fusion welding* processes started to be developed as assembly techniques.

While England was leading the Industrial Revolution, an important concept related to assembly technology was being introduced in the United States: *interchangeable parts* manufacture. Much credit for this concept is given to Eli Whitney (1765–1825), although its importance had been recognized by others [2]. In 1797, Whitney negotiated a contract to produce 10,000 muskets for the U.S. government. The traditional way of making guns at the time was to custom–fabricate each part for a particular gun and then hand–fit the parts together by filing. Each musket was therefore unique, and the time to make it was considerable. Whitney believed that the components could be made accurately enough to permit parts assembly without fitting. After several years of development in his Connecticut factory, he traveled to Washington in 1801 to demonstrate the principle. Before government officials, including Thomas Jefferson, he laid out components for 10 muskets and proceeded to select parts randomly to assemble the guns. No special filing or fitting was required, and all of the guns worked perfectly. The secret behind his achievement was the collection of special machines, fixtures, and gages that he had developed in his factory. Interchangeable parts manufacture required many years of development and refinement before becoming a practical reality, but it revolutionized methods of manufacturing. It is a prerequisite for mass production of assembled products. Because its origins were in the United States, interchangeable parts production came to be known as the *American System* of manufacture.

The mid- and late-1800s witnessed the expansion of railroads, steam–powered ships, and other machines that created a growing need for iron and steel. New methods for producing steel were developed to meet this demand. Also during this period, several consumer products were developed, including the sewing machine, bicycle, and automobile. To meet the mass demand for these products, more efficient production methods were required. Some historians identify developments during this period as the *Second Industrial Revolution*, characterized in terms of its effects on production systems by the following: (1) mass production, (2) assembly lines, (3) scientific management movement, and (4) electrification of factories.

Mass production was primarily an American phenomenon. Its motivation was the mass market that existed in the United States. Population in the United States in 1900 was 76 million and growing. By 1920 it exceeded 106 million. Such a large population, larger than any western European country, created a demand for large numbers of products. Mass production provided those products. Certainly one of the important technologies of mass production was the *assembly line*, introduced by Henry Ford (1863–1947) in 1913 at his Highland Park plant (Historical Note 17.1). The assembly line made mass production of complex consumer products possible. Use of assembly line methods permitted Ford to sell a Model T automobile for less than $500 in 1916, thus making ownership of cars feasible for a large segment of the American population.

The *scientific management* movement started in the late 1800s in the United States in response to the need to plan and control the activities of growing numbers of production workers. The movement was led by Frederick W. Taylor (1856–1915), Frank Gilbreath (1868–1924) and his wife Lilian (1878–1972), and others. Scientific management included: (1) *motion study*, aimed at finding the best method to perform a given task; (2) *time study,* to establish work standards for a job; (3) extensive use of *standards* in industry; (4) the *piece rate system* and similar labor incentive plans; and (5) use of data collection, record keeping, and cost accounting in factory operations.

In 1881, *electrification* began with the first electric power generating station being built in New York City, and soon electric motors were being used as the power source to operate factory machinery. This was a far more convenient power delivery system than the steam engine,

which required overhead belts to distribute power to the machines. By 1920, electricity had overtaken steam as the principal power source in U.S. factories. Electrification also motivated many new inventions that have affected manufacturing operations and production systems. The twentieth century has been a time of more technological advances than in all other centuries combined. Many of these developments have resulted in the *automation* of manufacturing. Historical notes on some of these advances in automation are covered in this book.

2.1 MANUFACTURING INDUSTRIES AND PRODUCTS

Manufacturing is an important commercial activity, carried out by companies that sell products to customers. The type of manufacturing performed by a company depends on the kinds of products it makes. Let us first take a look at the scope of the manufacturing industries and then consider their products.

    Manufacturing Industries.   Industry consists of enterprises and organizations that produce and/or supply goods and/or services. Industries can be classified as primary, secondary, and tertiary. *Primary industries* are those that cultivate and exploit natural resources, such as agriculture and mining. *Secondary industries* convert the outputs of the primary industries into products. Manufacturing is the principal activity in this category, but the secondary industries also include construction and power utilities. *Tertiary industries* constitute the service sector of the economy. A list of specific industries in these categories is presented in Table 2.1.

TABLE 2.1   Specific Industries in the Primary, Secondary, and Tertiary Categories, Based Roughly on the International Standard Industrial Classification (ISIC) Used by the United Nations

Primary	Secondary	Tertiary (Service)
Agriculture	Aerospace	Banking
Forestry	Apparel	Communications
Fishing	Automotive	Education
Livestock	Basic metals	Entertainment
Quarries	Beverages	Financial services
Mining	Building materials	Government
Petroleum	Chemicals	Health and medical
	Computers	Hotel
	Construction	Information
	Consumer appliances	Insurance
	Electronics	Legal
	Equipment	Real estate
	Fabricated metals	Repair and maintenance
	Food processing	Restaurant
	Glass, ceramics	Retail trade
	Heavy machinery	Tourism
	Paper	Transportation
	Petroleum refining	Wholesale trade
	Pharmaceuticals	
	Plastics (shaping)	
	Power utilities	
	Publishing	
	Textiles	
	Tire and rubber	
	Wood and furniture	

In this book, we are concerned with the secondary industries (middle column in Table 2.1), which are composed of the companies engaged in manufacturing. It is useful to distinguish the process industries from the industries that make discrete parts and products. The process industries include chemicals, pharmaceuticals, petroleum, basic metals, food, beverages, and electric power generation. The discrete product industries include automobiles, aircraft, appliances, computers, machinery, and the component parts that these products are assembled from. The International Standard Industrial Classification (ISIC) of industries according to types of products manufactured is listed in Table 2.2. In general, the process industries are included within ISIC codes 31–37, and the discrete product manufacturing industries are included in ISIC codes 38 and 39. However, it must be acknowledged that many of the products made by the process industries are finally sold to the consumer in discrete units. For example, beverages are sold in bottles and cans. Pharmaceuticals are often purchased as pills and capsules.

Production operations in the process industries and the discrete product industries can be divided into continuous production and batch production. The differences are shown in Figure 2.2. *Continuous production* occurs when the production equipment is used exclusively for the given product, and the output of the product is uninterrupted. In the process industries, continuous production means that the process is carried out on a continuous stream of material, with no interruptions in the output flow, as suggested by Figure 2.2(a) Once operating in steady state, the process does not depend on the length of time it is operating. The material being processed is likely to be in the form of a liquid, gas, powder, or similar physical state. In the discrete manufacturing industries, continuous production means 100% dedication of the production equipment to the part or product, with no breaks for product changeovers. The individual units of production are identifiable, as in Figure 2.2(b).

Batch production occurs when the materials are processed in finite amounts or quantities. The finite amount or quantity of material is called a *batch* in both the process and discrete manufacturing industries. Batch production is discontinuous because there are interruptions in production between batches. The reason for using batch production is

TABLE 2.2 International Standard Industrial Classification (ISIC) Codes for Various Industries in the Manufacturing Sector

| Basic Code	Products Manufactured
31	Food, beverages (alcoholic and nonalcoholic), tobacco
32	Textiles, wearing apparel, leather goods, fur products
33	Wood and wood products (e.g., furniture), cork products
34	Paper, paper products, printing, publishing, bookbinding
35	Chemicals, coal, petroleum, plastic, rubber, products made from these materials, pharmaceuticals
36	Ceramics (including glass), nonmetallic mineral products (e.g., cement)
37	Basic metals (e.g., steel, aluminum, etc.)
38	Fabricated metal products, machinery, equipment (e.g., aircraft, cameras, computers and other office equipment, machinery, motor vehicles, tools, televisions)
39	Other manufactured goods (e.g., jewelry, musical instruments, sporting goods, toys)
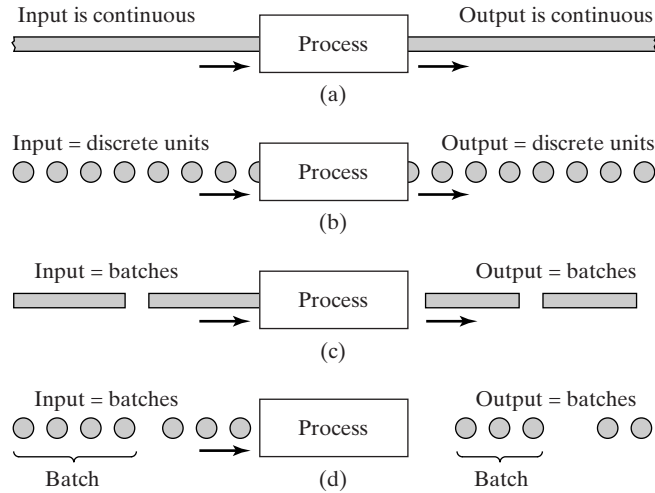
Figure 2.2 Continuous and batch production in the process and discrete manufacturing industries: (a) continuous production in the process industries, (b) continuous production in the discrete manufacturing industries, (c) batch production in the process industries, and (d) batch production in the discrete manufacturing industries.

because the nature of the process requires that only a finite amount of material can be accommodated at one time (e.g., the amount of material might be limited by the size of the container used in processing) or because there are differences between the parts or products made in different batches (e.g., a batch of 20 units of part A followed by a batch of 50 units of part B in a machining operation, where a setup changeover is required between batches because of differences in tooling and fixturing required). The differences in batch production between the process and discrete manufacturing industries are portrayed in Figure 2.2(c) and (d). Batch production in the process industries generally means that the starting materials are in liquid or bulk form, and they are processed altogether as a unit. By contrast, in the discrete manufacturing industries, a batch is a certain quantity of work units, and the work units are usually processed one at a time rather than altogether at once. The number of parts in a batch can range from as few as one to as many as thousands of units.

Manufactured Products.   As indicated in Table 2.2, the secondary industries include food, beverages, textiles, wood, paper, publishing, chemicals, and basic metals (ISIC codes 31–39). The scope of our book is primarily directed at the industries that produce discrete products (ISIC codes 38 and 39). The two groups interact with each other, and many of the concepts and systems discussed in the book are applicable to the process industries, but our attention is mainly on the production of discrete hardware, which ranges from nuts and bolts to cars, airplanes, and digital computers. Table 2.3 lists the manufacturing industries and corresponding products for which the production systems in this book are most applicable.

TABLE 2.3   Manufacturing Industries Whose Products Are Likely to Be Produced by the Production Systems Discussed in this Book

Industry	Typical Products
Aerospace	Commercial and military aircraft
Automotive	Cars, trucks, buses, motorcycles
Basic metals	Iron and steel, aluminum, copper, etc.
Computers	Mainframe and personal computers
Consumer appliances	Large and small household appliances
Electronics	TVs, VCRs, audio equipment
Equipment	Industrial machinery, railroad equipment
Fabricated metals	Machined parts, metal stampings, tools
Glass, ceramics	Glass products, ceramic tools, pottery
Heavy machinery	Machine tools, construction equipment
Plastics (shaping)	Plastic moldings, extrusions
Tire and rubber	Tires, shoe soles, tennis balls

Final products made by the industries listed in Table 2.3 can be divided into two major classes: consumer goods and capital goods. *Consumer goods* are products purchased directly by consumers, such as cars, personal computers, TVs, tires, toys, and tennis rackets. *Capital goods* are products purchased by other companies to produce goods and supply services. Examples of capital goods include commercial aircraft, mainframe computers, machine tools, railroad equipment, and construction machinery.

In addition to final products, which are usually assembled, there are companies in industry whose business is primarily to produce *materials, components,* and *supplies* for the companies that make the final products. Examples of these items include sheet steel, bar stock, metal stampings, machined parts, plastic moldings and extrusions, cutting tools, dies, molds, and lubricants. Thus, the manufacturing industries consist of a complex infrastructure with various categories and layers of intermediate suppliers that the final consumer never deals with.

2.2   MANUFACTURING OPERATIONS

There are certain basic activities that must be carried out in a factory to convert raw materials into finished products. Limiting our scope to a plant engaged in making discrete products, the factory activities are: (1) processing and assembly operations, (2) material handling, (3) inspection and test, and (4) coordination and control.

The first three activities are the physical activities that "touch" the product as it is being made. Processing and assembly operations alter the geometry, properties, and/or appearance of the work unit. They add value to the product. The product must be moved from one operation to the next in the manufacturing sequence, and it must be inspected and/or tested to insure high quality. It is sometimes argued that these material handling and inspection activities not add value to the product. However, our viewpoint is that value is added through the totality of manufacturing operations performed on the product. Unnecessary operations, whether they are processing, assembly, material handling, or inspection, must be eliminated from the sequence of steps performed to complete a given product.

2.2.1   Processing and Assembly Operations

Manufacturing processes can be divided into two basic types: (1) processing operations and (2) assembly operations. A *processing operation* transforms a work material from one state of completion to a more advanced state that is closer to the final desired part or product. It adds value by changing the geometry, properties, or appearance of the starting material. In general, processing operations are performed on discrete workparts, but some processing operations are also applicable to assembled items, for example, painting a welded sheet metal car body. An *assembly operation* joins two or more components to create a new entity, which is called an assembly, subassembly, or some other term that refers to the specific joining process.

Processing Operations.   A processing operation uses energy to alter a workpart's shape, physical properties, or appearance to add value to the material. The forms of energy include mechanical, thermal, electrical, and chemical. The energy is applied in a controlled way by means of machinery and tooling. Human energy may also be required, but human workers are generally employed to control the machines, to oversee the operations, and to load and unload parts before and after each cycle of operation. A general model of a processing operation is illustrated in Figure 2.1(a). Material is fed into the process, energy is applied by the machinery and tooling to transform the material, and the completed workpart exits the process. As shown in our model, most production operations produce waste or scrap, either as a natural byproduct of the process (e.g., removing material as in machining) or in the form of occasional defective pieces. An important objective in manufacturing is to reduce waste in either of these forms.

More than one processing operation are usually required to transform the starting material into final form. The operations are performed in the particular sequence to achieve the geometry and/or condition defined by the design specification.

Three categories of processing operations are distinguished: (1) shaping operations, (2) property–enhancing operations, and (3) surface processing operations. *Shaping operations* apply mechanical force or heat or other forms and combinations of energy to effect a change in geometry of the work material. There are various ways to classify these processes. The classification used here is based on the state of the starting material, by which we have four categories:

1. *Solidification processes.* The important processes in this category are *casting* (for metals) and *molding* (for plastics and glasses), in which the starting material is a heated liquid or semifluid, in which state it can be poured or otherwise forced to flow into a mold cavity where it cools and solidifies, taking a solid shape that is the same as the cavity.
2. *Particulate processing.* The starting material is a powder. The common technique involves *pressing* the powders in a die cavity under high pressure to cause the powders to take the shape of the cavity. However, the compacted workpart lacks sufficient strength for any useful application. To increase strength, the part is then *sintered*—heated to a temperature below the melting point, which causes the individual particles to bond together. Both metals (powder metallurgy) and ceramics can be formed by particulate processing.
3. *Deformation processes.* In most cases, the starting material is a ductile metal that is shaped by applying stresses that exceed the metal's yield strength. To increase ductility, the metal is often heated prior to forming. Deformation processes include *forg-*

ing, *extrusion*, and *rolling*. Also included in this category are sheet metal processes such as *drawing*, *forming*, and *bending*.

4. *Material removal processes*. The starting material is solid (commonly a metal, ductile or brittle), from which excess material is removed from the starting workpiece so that the resulting part has the desired geometry. Most important in this category are *machining* operations such as *turning*, *drilling*, and *milling*, accomplished using cutting tools that are harder and stronger than the work metal. *Grinding* is another common process in this category, in which an abrasive grinding wheel is used to remove material. Other material removal processes are known as *nontraditional processes* because they do not use traditional cutting and grinding tools. Instead, they are based on lasers, electron beams, chemical erosion, electric discharge, or electrochemical energy.

Property–enhancing operations are designed to improve mechanical or physical properties of the work material. The most important property–enhancing operations involve *heat treatments*, which include various temperature-induced strengthening and/or toughening processes for metals and glasses. *Sintering* of powdered metals and ceramics, mentioned previously, is also a heat treatment, which strengthens a pressed powder workpart. Property-enhancing operations do not alter part shape, except unintentionally in some cases, for example, warping of a metal part during heat treatment or shrinkage of a ceramic part during sintering.

Surface processing operations include: (1) cleaning, (2) surface treatments, and (3) coating and thin film deposition processes. *Cleaning* includes both chemical and mechanical processes to remove dirt, oil, and other contaminants from the surface. *Surface treatments* include mechanical working, such as shot peening and sand blasting, and physical processes, like diffusion and ion implantation. *Coating* and *thin film deposition* processes apply a coating of material to the exterior surface of the workpart. Common coating processes include *electroplating*, *anodizing* of aluminum, and organic *coating* (call it *painting*). Thin film deposition processes include *physical vapor deposition* and *chemical vapor deposition* to form extremely thin coatings of various substances. Several surface processing operations have been adapted to fabricate semiconductor materials (most commonly silicon) into integrated circuits for microelectronics. These processes include chemical vapor deposition, physical vapor deposition, and oxidation. They are applied to very localized areas on the surface of a thin wafer of silicon (or other semiconductor material) to create the microscopic circuit.

Assembly Operations.   The second basic type of manufacturing operation is assembly, in which two or more separate parts are joined to form a new entity. Components of the new entity are connected together either permanently or semipermanently. Permanent joining processes include *welding*, *brazing*, *soldering*, and *adhesive bonding*. They combine parts by forming a joint that cannot be easily disconnected. *Mechanical assembly* methods are available to fasten two (or more) parts together in a joint that can be conveniently disassembled. The use of *threaded fasteners* (e.g., screws, bolts, nuts) are important traditional methods in this category. Other mechanical assembly techniques that form a permanent connection include *rivets*, *press fitting*, and *expansion fits*. Special assembly methods are used in electronics. Some of the methods are identical to or adaptations of the above techniques. For example, soldering is widely used in electronics assembly. Electronics assembly is concerned primarily with the assembly of components (e.g., integrated circuit packages) to printed circuit boards to produce the complex circuits used in so many of today's products.

2.2.2   Other Factory Operations

Other activities that must be performed in the factory include material handling and storage, inspection and testing, and coordination and control.

Material Handling and Storage.   A means of moving and storing materials between processing and/or assembly operations is usually required. In most manufacturing plants, materials spend more time being moved and stored than being processed. In some cases, the majority of the labor cost in the factory is consumed in handling, moving, and storing materials. It is important that this function be carried out as efficiently as possible. In Part II of our book, we consider the material handling and storage technologies that are used in factory operations.

Eugene Merchant, an advocate and spokesman for the machine tool industry for many years, observed that materials in a typical metal machining batch factory or job shop spend more time waiting or being moved than in processing [3]. His observation is illustrated in Figure 2.3. About 95% of a part's time is spent either moving or waiting (temporary storage). Only 5% of its time is spent on the machine tool. Of this 5%, less than 30% of the time on the machine (1.5% of the total time of the part) is time during which actual cutting is taking place. The remaining 70% (3.5% of the total) is required for loading and unloading, part handling and positioning, tool positioning, gaging, and other elements of nonprocessing time. These time proportions provide evidence of the significance of material handling and storage in a typical factory.

Inspection and Test.   Inspection and test are quality control activities. The purpose of *inspection* is to determine whether the manufactured product meets the established design standards and specifications. For example, inspection examines whether the actual dimensions of a mechanical part are within the tolerances indicated on the engineering drawing for the part. *Testing* is generally concerned with the functional specifications of the final product rather than with the individual parts that go into the product. For example, final testing of the product ensures that it functions and operates in the manner specified by the product designer. In Part IV of this text, we examine the inspection and testing function.
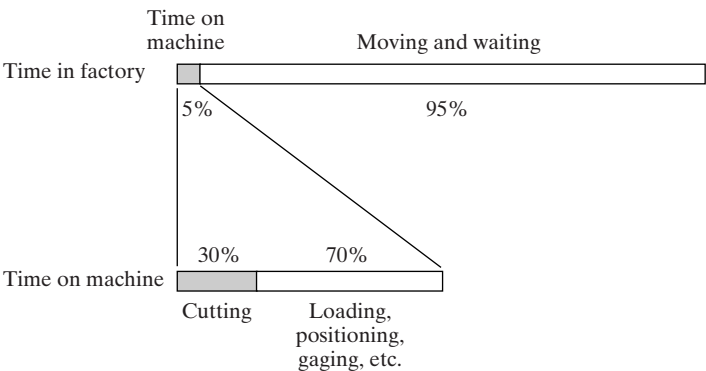

Figure 2.3 How time is spent by a typical part in a batch production machine shop [3].

Coordination and Control.   Coordination and control in manufacturing includes both the regulation of individual processing and assembly operations as well as the management of plant level activities. Control at the process level involves the achievement of certain performance objectives by properly manipulating the inputs and other parameters of the process. Control at the process level is discussed in Part I of the book.

Control at the plant level includes effective use of labor, maintenance of the equipment, moving materials in the factory, controlling inventory, shipping products of good quality on schedule, and keeping plant operating costs at a minimum possible level..The manufacturing control function at the plant level represents the major point of intersection between the physical operations in the factory and the information processing activities that occur in production. We discuss many of these plant and enterprise level control functions in Parts IV and V.

2.3 PRODUCT/PRODUCTION RELATIONSHIPS

Companies organize their manufacturing operations and production systems as a function of the particular products they make. It is instructive to recognize that there are certain product parameters that are influential in determining how the products are manufactured. Let us consider four key parameters: (1) production quantity, (2) product variety, (3) complexity of assembled products, and (4) complexity of individual parts.

2.3.1 Production Quantity and Product Variety

We previously discussed production quantity and product variety in Chapter 1 (Section 1.1). Let us develop a set of symbols to represent these important parameters. First, let Q = production quantity and P = product variety. Thus we can discuss product variety and production quantity relationships as PQ relationships.

Q refers to the number of units of a given part or product that are produced annually by a plant. Our interest includes both the quantities of each individual part or product style and the total quantity of all styles. Let us identify each part or product style by using the subscript j, so that Q_j = annual quantity of style j. Then let Q_f = total quantity of all parts or products made in the factory. Q_j and Q_f are related as follows:

$$Q_f = \sum_{j=1}^{P} = Q_j \qquad (2.1)$$

where P = total number of different part or product styles, and j is a subscript to identify products, $j = 1, 2, \ldots, P$.

P refers to the different product designs or types that are produced in a plant. It is a parameter that can be counted, and yet we recognize that the difference between products can be great or small. In Chapter 1, we distinguished between hard product variety and soft product variety. *Hard product variety* is when the products differ substantially. *Soft product variety* is when there are only small differences between products. Let us divide the parameter P into two levels, as in a tree structure. Call them P1 and P2. P1 refers to the number of distinct product lines produced by the factory, and P2 refers to the number of models in a product line. P1 represents hard product variety, and P2 is for soft variety.

EXAMPLE 2.1   Product Lines P1 and Product Models P2

A company specializes in consumer photographic products. It produces only cameras and projectors. Thus P2 = 2. In its camera line it offers 15 different models, and in its projector line it offers five models. Thus for cameras, $P2_1 = 15$, and for projectors, $P2_2 = 5$. The totality of product models offered is given by:

$$P = \sum_{j=1}^{P1} P2_j = \sum_{j=1}^{2} P2_j = 15 + 5 = 20 \tag{2.2}$$

2.3.2 Product and Part Complexity

How complex is each product made in the plant? Product complexity is a complicated issue. It has both qualitative and quantitative aspects. Let us deal with it using quantitative measures. For an assembled product, one possible indicator of *product complexity* is its number of components—the more parts, the more complex the product is. This is easily demonstrated by comparing the numbers of components in various assembled products, as in Table 2.4. Our list demonstrates that the more components a product has, the more complex it tends to be.

For a fabricated component, a possible measure of *part complexity* is the number of processing steps required to produce it. An integrated circuit, which is technically a monolithic silicon chip with localized alterations in its surface chemistry, requires hundreds of processing steps in its fabrication. Although it may measure only 9 mm (3/8 inch) on a side and is 0.5 mm (0.020 inch) thick, its complexity is orders of magnitude greater than a round washer of 9 mm (3/8 inch) outside diameter, stamped out of 0.80-mm (1/32-inch) thick stainless steel in one step. In Table 2.5, we have compiled a list of manufactured parts with the typical number of processing operations that would be required for each.

So, we have complexity of an assembled product defined as the number of distinct components; let n_p = the number of parts per product. And we have processing complexity of each part as the number of operations required to make it; let n_o = the number of operations or processing steps to make a part. We can draw some distinctions among production plants on the basis of n_p and n_o. As defined in Table 2.6, three different types of plant can be identified: parts producers, pure assembly plants, and vertically integrated plants.

TABLE 2.4 Typical Number of Separate Components in Various Assembled Products (Compiled from [2], [4], and Other Sources)

Product (Approx. Date or Circa)	Approx. Number of Components
Mechanical pencil (modern)	10
Ball bearing (modern)	20
Rifle (1800)	50
Sewing machine (1875)	150
Bicycle chain	300
Bicycle (modern)	750
Early automobile (1910)	2000
Automobile (modern)	20,000
Commercial airplane (1930)	100,000
Commercial airplane (modern)	1,000,000
Space shuttle (modern)	10,000,000

TABLE 2.5 Typical Number of Processing Operations Required To Fabricate Various Parts

Part	Approx. Number of Processing Operations	Typical Processing Operations Used
Plastic molded part	1	Injection molding
Washer (stainless steel)	1	Stamping
Washer (plated steel)	2	Stamping, electroplating
Forged part	3	Heating, forging, trimming
Pump shaft	10	Machining (from bar stock)
Coated carbide cutting tool	15	Pressing, sintering, coating, grinding
Pump housing, machined	20	Casting, machining
V-6 engine block	50	Casting, machining
Integrated circuit chip	75	Photolithography, various thermal and chemical processes

TABLE 2.6 Production Plants Distinguished by n_p and n_o Values

Type of Plant	$n_p - n_o$ Parameter Values	Description
Parts producer	$n_p = 1, n_o > 1$	This type of plant produces individual components, and each component requires multiple processing steps.
Assembly plant	$n_p > 1, n_o = 1$	A pure assembly plant produces no parts. Instead, it purchases all parts from suppliers. In this pure case, we assume that one operation is required to assemble each part to the product (thus, $n_o = 1$).
Vertically integrated plant	$n_p > 1, n_o > 1$	The pure plant of this type makes all its parts and assembles them into its final products. This plant type also includes intermediate suppliers that make assembled items such as ball bearings, car seats, and so on for final product assembly plants.

Let us develop some simple relationships among the parameters P, Q, n_p, and n_o that indicate the level of activity in a manufacturing plant. We will ignore the differences between P1 and P2 here. The total number of products made annually in a plant is the sum of the quantities of the individual product designs, as expressed in previous Eq. (2.1). Assuming that the products are all assembled and that all component parts used in these products are made in the plant (no purchased components), then the total number of parts manufactured by the plant per year is given by:

$$n_{pf} = \sum_{j=1}^{P} Q_j n_{pj} \qquad (2.3)$$

where n_{pf} = total number of parts made in the factory (pc/yr), Q_j = annual quantity of product style j (products/yr), and n_{pj} = number of parts in product j (pc/product).

Finally, if all parts are manufactured in the plant, then the total number of processing operations performed by the plant is given by:

$$n_{of} = \sum_{j=1}^{P} Q_j n_{pj} \sum_{k=1}^{n_{pj}} n_{ojk} \tag{2.4}$$

where n_{of} = total number of operation cycles performed in the factory (ops/yr), and n_{ojk} = number of processing operations for each part k, summed over the number of parts in product j, n_{pj}. Parameter n_{of} provides a numerical value for the total activity level in the factory.

We might try to simplify this to better conceptualize the situation by assuming that the number of product designs P are produced in equal quantities Q, all products have the same number of components n_p, and all components require an equal number of processing steps n_o. In this case, the total number of product units produced by the factory is given by:

$$Q_f = PQ \tag{2.5}$$

The total number of parts produced by the factory is given by:

$$n_{pf} = PQn_p \tag{2.6}$$

And the total number of manufacturing operation cycles performed by the factory is given by:

$$n_{of} = PQn_p n_o \tag{2.7}$$

Using these simplified equations, consider the following example.

EXAMPLE 2.2   A Manufacturing Operations (and Production Systems) Problem

Suppose a company has designed a new product line and is planning to build a new plant to manufacture this product line. The new line consists of 100 different product types, and for each product type the company wants to produce 10,000 units annually. The products average 1000 components each, and the average number of processing steps required for each component is 10. All parts will be made in the factory. Each processing step takes an average of 1 min. Determine: (a) how many products, (b) how many parts, and (c) how many production operations will be required each year, and (d) how many workers will be needed for the plant, if it operates one shift for 250 day/yr?

Solution: The total number of units to be produced by the factory is given by Eq (2.5):

$$Q = PQ = 100 \times 10,000 = 1,000,000 \text{ products annually.}$$

The total number of parts produced is:

$$n_{pf} = PQn_p = 1,000,000 \times 1000 = \textit{1,000,000,000 parts annually.}$$

The number of distinct production operations is:

$$n_{of} = PQn_p n_o = 1,000,000,000 \times 10 = \textit{10,000,000,000 operations.}$$

Let us try to estimate the number of workers required. First consider the total time to perform these operations. If each operation takes 1 min (1/60 hr),

$$\text{Total time} = 10,000,000,000 \times 1/60 = 166,666,667 \text{ hr}$$

If each worker works 2000 hr/yr (40 hr/wk $\times$ 50 wk/yr), then the total number of workers required is:

$$w = \frac{166,666,667}{2000} = 83,333 \text{ workers.}$$

The factory in our example is a fully integrated factory. It would be a big factory. The number of workers we have calculated only includes direct labor. Add indirect labor, staff, and management, and the number increases to well over 100,000 employees. Imagine the parking lot. And inside the factory, the logistics problems of dealing with all of the products, parts, and operations would be overwhelming. No organization in its right mind would consider building or operating such a plant today—not even the federal government.

2.3.3 Limitations and Capabilities of a Manufacturing Plant

Companies do not attempt the kind of factory in our example. Instead, today's factory is designed with a much more specific mission. Referred to as a *focused factory* [5], it is a plant which concentrates "on a limited, concise, manageable set of products, technologies, volumes, and markets." It is a recognition that a manufacturing plant cannot do everything. It must limit its mission only to a certain scope of products and activities in which it can best compete. Its size is typically limited to about 500 workers, although that number may vary widely for different types of products and manufacturing operations.

Let us consider how a plant, or its parent company, limits the scope of its manufacturing operations and production systems. In limiting its scope, the plant in effect makes a set of deliberate decisions about what it will not try to do. Certainly one way to limit a plant's scope is by avoiding being a fully integrated factory, at least to the extent of our Example 2.2. Instead, it specializes in being either a parts producer or an assembly plant. Just as it decides what it will not do, the plant must also decide on the specific technologies, products, and volumes in which it will specialize. These decisions define the plant's intended manufacturing capability. *Manufacturing capability* refers to the technical and physical limitations of a manufacturing firm and each of its plants. We can identify several dimensions of this capability: (1) technological processing capability, (2) physical size and weight of product, and (3) production capacity.

Technological Processing Capability.   The technological processing capability of a plant (or company) is its available set of manufacturing processes. Certain plants perform machining operations, others roll steel billets into sheet stock, and others build automobiles. A machine shop cannot roll steel, and a rolling mill cannot build cars. The underlying feature that distinguishes these plants is the set of processes they can perform. Technological processing capability is closely related to the material being processed. Certain manufacturing processes are suited to certain materials, while other processes are suited to other materials. By specializing in a certain process or group of processes, the plant is simultaneously specializing in a certain material type or range of materials.

Technological processing capability includes not only the physical processes, but also the expertise possessed by plant personnel in these processing technologies. Companies are

limited by their available processes. They must focus on designing and manufacturing products for which their technological processing capability provides a competitive advantage.

Physical Product Limitations.   A second aspect of manufacturing capability is imposed by the physical product. Given a plant with a certain set of processes, there are size and weight limitations on the products that can be accommodated in the plant. Big, heavy products are difficult to move. To move products about, the plant must be equipped with cranes of large load capacity. Smaller parts and products made in large quantities can be moved by conveyor or fork lift truck. The limitation on product size and weight extends to the physical capacity of the manufacturing equipment as well. Production machines come in different sizes. Larger machines can be used to process larger parts. Smaller machines limit the size of the work that can be processed. The set of production equipment, material handling, storage capability, and plant size must be planned for products that lie within a certain size and weight range.

Production Capacity.   A third limitation on a plant's manufacturing capability is the production quantity that can be produced in a given time period (e.g., month or year). This quantity limitation is commonly called *plant capacity*, or *production capacity*, which is defined as the maximum rate of production per period that a plant can achieve under assumed operating conditions. The operating conditions refer to number of shifts per week, hours per shift, direct labor manning levels in the plant, and similar conditions under which the plant has been designed to operate. These factors represent inputs to the manufacturing plant. Given these inputs, how much output can the factory produce?
Plant capacity is often measured in terms of output units, such as annual tons of steel produced by a steel mill, or number of cars produced by a final assembly plant. In these cases, the outputs are homogeneous, more or less. In cases where the output units are not homogeneous, other factors may be more appropriate measures, such as available labor hours of productive capacity in a machine shop that produces a variety of parts.

2.4   PRODUCTION CONCEPTS AND MATHEMATICAL MODELS

A number of production concepts are quantitative, or they require a quantitative approach to measure them. The purpose of this section is to define some of these concepts. In subsequent chapters, we refer back to these production concepts in our discussion of specific topics in automation and production systems. The models developed in this section are ideal, in the sense that they neglect some of the realities and complications that are present in the factory. For example, our models do not include the effect of scrap rates. In some manufacturing operations, the percentage of scrap produced is high enough to adversely affect production rate, plant capacity, and product costs. Most of these issues are considered in later chapters as we focus on specific types of production systems.

2.4.1   Production Rate

The production rate for an individual processing or assembly operation is usually expressed as an hourly rate, that is, parts or products per hour. Let us consider how this rate is determined for the three types of production: job shop production, batch production, and mass production.

For any production operation, the *operation cycle time* T_c is defined as the time that one work unit spends being processed or assembled. It is the time between when one work unit begins processing (or assembly) and when the next unit begins. T_c is the time an individual part spends at the machine, but not all of this time is productive (recall the Merchant study, Section 2.2.2). In a typical processing operation, such as machining, T_c consists of: (1) actual machining operation time, (2) workpart handling time, and (3) tool handling time per workpiece. As an equation, this can be expressed:

$$T_c = T_o + T_h + T_{th} \tag{2.8}$$

where T_c = operation cycle time (min/pc), T_o = time of the actual processing or assembly operation (min/pc), T_h = handling time (min/pc), and T_{th} = tool handling time (min/pc). The tool handling time consists of time spent changing tools when they wear out, time changing from one tool to the next, tool indexing time for indexable inserts or for tools on a turret lathe or turret drill, tool repositioning for a next pass, and so on. Some of these tool handling activities do not occur every cycle; therefore, they must be spread over the number of parts between their occurrences to obtain an average time per workpiece.

Each of the terms, T_o, T_h, and T_{th} has its counterpart in other types of discrete-item production. There is a portion of the cycle when the part is actually being processed (T_o); there is a portion of the cycle when the part is being handled (T_h); and there is, on average, a portion when the tooling is being adjusted or changed (T_{th}). Accordingly, we can generalize Eq. (2.8) to cover most processing operations in manufacturing.

Let us first consider the batch production case and then consider the job shop and mass production. In *batch production*, the time to process one batch consisting of Q work units is the sum of the setup time and processing time; that is,

$$T_b = T_{su} + QT_c \tag{2.9}$$

where T_b = batch processing time (min), T_{su} = setup time to prepare for the batch(min), Q = batch quantity (pc), and T_c = operation cycle time per work unit (min/cycle). We assume that one work unit is completed each cycle and so T_c also has units of min/pc. If more than one part is produced each cycle, then Eq. (2.9) must be adjusted accordingly. Dividing batch time by batch quantity, we have the average production time per work unit T_p for the given machine:

$$T_p = \frac{T_b}{Q} \tag{2.10}$$

The average production rate for the machine is simply the reciprocal of production time. It is usually expressed as an hourly rate:

$$R_p = \frac{60}{T_p} \tag{2.11}$$

where R_p = hourly production rate (pc/hr), T_p = average production time per minute (min/pc), and the constant 60 converts minutes to hours.

For *job shop production* when quantity $Q = 1$, the production time per work unit is the sum of setup and operation cycle times:

$$T_p = T_{su} + T_c \tag{2.12}$$

For job shop production when the quantity is greater than one, then this reverts to the batch production case discussed above.

For *quantity type mass production*, we can say that the production rate equals the cycle rate of the machine (reciprocal of operation cycle time) after production is underway and the effects of setup time become insignificant. That is, as Q becomes very large, $(T_{su}/Q) \to 0$ and

$$R_p \to R_c = \frac{60}{T_c} \qquad (2.13)$$

where R_c = operation cycle rate of the machine (pc/hr), and T_c = operation cycle time (min/pc).

For *flow line mass production*, the production rate approximates the cycle rate of the production line, again neglecting setup time. However, the operation of production lines is complicated by the interdependence of the workstations on the line. One complication is that it is usually impossible to divide the total work equally among all of the workstations on the line; therefore, one station ends up with the longest operation time, and this station sets the pace for the entire line. The term *bottleneck station* is sometimes used to refer to this station. Also included in the cycle time is the time to move parts from one station to the next at the end of each operation. In many production lines, all work units on the line are moved simultaneously, each to its respective next station. Taking these factors into account, the cycle time of a production line is the sum of the longest processing (or assembly) time plus the time to transfer work units between stations. This can be expressed:

$$T_c = T_r + \text{Max } T_o \qquad (2.14)$$

where T_c = cycle time of the production line (min/cycle), T_r = time to transfer work units between stations each cycle (min/pc), and Max T_o = operation time at the bottleneck station (the maximum of the operation times for all stations on the line, min/cycle). Theoretically, the production rate can be determined by taking the reciprocal of T_c as follows:

$$R_c = \frac{60}{T_c} \qquad (2.15)$$

where R_c = theoretical or ideal production rate, but let us call it the cycle rate to be more precise (cycles/hr), and T_c = ideal cycle time from Eq. (2.14) (min/cycle).

Production lines are of two basic types: (1) manual and (2) automated. In the operation of automated production lines, another complicating factor is reliability. Poor reliability reduces the available production time on the line. This results from the interdependence of workstations in an automated line, in which the entire line is forced to stop when one station breaks down. The actual average production rate R_p is reduced to a value that is often substantially below the ideal R_c given by Eq. (2.15). We discuss reliability and some of its terminology in Section 2.4.3. The effect of reliability on automated production lines is examined in Chapters 18 and 19.

It is important to design the manufacturing method to be consistent with the pace at which the customer is demanding the part or product, sometimes referred to as the *takt* time (a German word for cadence or pace). The takt time is the reciprocal of demand rate, but adjusted for the available shift time in the factory. For example, if 100 product units

were demanded from a customer each day, and the factory operated one shift/day, with 400 min of time available per shift, then the takt time would be 400 min/100 units = 4.0 min/work unit.

2.4.2 Production Capacity

We mentioned production capacity in our discussion of manufacturing capabilities (Section 2.3.3). *Production capacity* is defined as the maximum rate of output that a production facility (or production line, work center, or group of work centers) is able to produce under a given set of assumed operating conditions. The production facility usually refers to a plant or factory, and so the term *plant capacity* is often used for this measure. As mentioned before, the assumed operating conditions refer to the number of shifts per day (one, two, or three), number of days in the week (or month) that the plant operates, employment levels, and so forth.

The number of hours of plant operation per week is a critical issue in defining plant capacity. For continuous chemical production in which the reactions occur at elevated temperatures, the plant is usually operated 24 hr/day, 7 day/wk. For an automobile assembly plant, capacity is typically defined as one or two shifts. In the manufacture of discrete parts and products, a growing trend is to define plant capacity for the full 7-day week, 24 hr/day. This is the maximum time available (168 hr/wk), and if the plant operates fewer hours than the maximum, then its maximum possible capacity is not being fully utilized.

Quantitative measures of plant capacity can be developed based on the production rate models derived earlier. Let PC = the production capacity of a given facility under consideration. Let the measure of capacity = the number of units produced per week. Let n = the number of machines or work centers in the facility. A *work center* is a manufacturing system in the plant typically consisting of one worker and one machine. It might also be one automated machine with no worker, or multiple workers working together on a production line. It is capable of producing at a rate R_p unit/hr, as defined in Section 2.4.1. Each work center operates for H hr/shift. Provision for setup time is included in R_p, according to Eq. (2.11). Let S denote the number of shifts per week. These parameters can be combined to calculate the production capacity of the facility:

$$PC = n\,\mathrm{SHR}_p \tag{2.16}$$

where PC = production capacity of the facility (output units/wk), n = number of work centers producing in the facility, S = number of shifts per period (shift/wk), H = hr/shift (hr), and R_p = hourly production rate of each work center (output units/hr). Although we have used a week as the time period of interest, Eq. (2.16) can easily be revised to adopt other periods (months, years, etc.). As in previous equations, our assumption is that the units processed through the group of work centers are homogeneous, and therefore the value of R_p is the same for all units produced.

EXAMPLE 2.3   Production Capacity

The turret lathe section has six machines, all devoted to the production of the same part. The section operates 10 shift/wk. The number of hours per shift averages 8.0. Average production rate of each machine is 17 unit/hr. Determine the weekly production capacity of the turret lathe section.

Solution: From Eq. (2.16),

$$PC = 6(10)(8.0)(17) = 8160 \text{ output unit/wk}$$

If we include the possibility that each work unit is routed through n_o operations, with each operation requiring a new setup on either the same or different machine, then the plant capacity equation must be amended as follows:

$$PC = \frac{n \, \mathrm{SHR}_p}{n_o} \qquad (2.17)$$

where n_o = number of distinct operations through which work units are routed, and the other terms have the same meaning as before.

Eq. (2.17) indicates the operating parameters that affect plant capacity. Changes that can be made to increase or decrease plant capacity over the short term are:

1. Change the number of shifts per week (S). For example, Saturday shifts might be authorized to temporarily increase capacity.
2. Change the number of hours worked per shift (H). For example, overtime on each regular shift might be authorized to increase capacity.
   Over the intermediate or longer term, the following changes can be made to increase plant capacity:
3. Increase the number of work centers, n, in the shop. This might be done by using equipment that was formerly not in use and hiring new workers. Over the long term, new machines might be acquired. Decreasing capacity is easier, except for the social and economic impact: Workers must be laid off and machines decommissioned.
4. Increase the production rate, R_p by making improvements in methods or process technology.
5. Reduce the number of operations n_o required per work unit by using combined operations, simultaneous operations, or integration of operations (Section 1.5.2: strategies 2, 3, and 4).

This capacity model assumes that all n machines are producing 100% of the time, and there are no bottleneck operations due to variations in process routings to inhibit smooth flow of work through the plant. In real batch production machine shops where each product has a different operation sequence, it is unlikely that the work distribution among the productive resources (machines) can be perfectly balanced. Consequently, there are some operations that are fully utilized while other operations occasionally stand idle waiting for work. Let us examine the effect of utilization.

2.4.3   Utilization and Availability

Utilization refers to the amount of output of a production facility relative to its capacity. Expressing this as an equation,

$$U = \frac{Q}{PC} \qquad (2.18)$$

where U = utilization of the facility, Q = actual quantity produced by the facility during a given time period (i.e., pc/wk), and PC = production capacity for the same period (pc/wk).

Utilization can be assessed for an entire plant, a single machine in the plant, or any other productive resource (i.e., labor). For convenience, it is often defined as the proportion of time that the facility is operating relative to the time available under the definition of capacity. Utilization is usually expressed as a percentage.

EXAMPLE 2.4   Utilization

A production machine operates 80 hr/wk (two shifts, 5 days) at full capacity. Its production rate is 20 unit/hr. During a certain week, the machine produced 1000 parts and was idle the remaining time. (a) Determine the production capacity of the machine. (b) What was the utilization of the machine during the week under consideration?

Solution: (a) The capacity of the machine can be determined using the assumed 80-hr week as follows:

$$PC = 80(20) = 1600 \text{ unit/wk}$$

(b) tilization can be determined as the ratio of the number of parts made by the machine relative to its capacity.

$$U = 1000/1600 = 0.625 \qquad (62.5\%)$$

The alternative way of assessing utilization is by the time during the week that the machine was actually used. To produce 1000 units, the machine was operated

$$H = \frac{1000\text{pc}}{20\text{pc/hr}} = 50\text{hr}$$

Utilization is defined relative to the 80 hr available.

$$U = 50/80 = 0.625 \qquad (62.5\%)$$

Availability is a common measure of reliability for equipment. It is especially appropriate for automated production equipment. Availability is defined using two other reliability terms, *mean time between failure* (MTBF) and *mean time to repair* (MTTR). The MTBF indicates the average length of time the piece of equipment runs between breakdowns. The MTTR indicates the average time required to service the equipment and put it back into operation when a breakdown occurs. Availability is defined as follows:

$$A = \frac{\text{MTBF} - \text{MTTR}}{\text{MTBF}} \qquad (2.19)$$

where A = availability, MTBF = mean time between failures (hr), and MTTR = mean time to repair (hr). Availability is typically expressed as a percentage. When a piece of equipment is brand new (and being debugged), and later when it begins to age, its availability tends to be lower.

EXAMPLE 2.5   Effect of Utilization and Availability on Plant Capacity

Consider previous Example 2.3. Suppose the same data from that example were applicable, but that the availability of the machines $A = 90\%$, and the utilization of the machines $U = 80\%$. Given this additional data, compute the expected plant output.

Solution: Previous Eq. (2.16) can be altered to include availability and utilization as follows:

$$Q = AU(n\text{SHR}_p) \tag{2.20}$$

where $A =$ availability and $U =$ utilization. Combining the previous and new data, we have

$$Q = 0.90(0.80)(6)(10)(8.0)(17) = 5875 \text{ output unit/wk}$$

2.4.4   Manufacturing Lead Time

In the competitive environment of modern business, the ability of a manufacturing firm to deliver a product to the customer in the shortest possible time often wins the order. This time is referred to as the manufacturing lead time. Specifically, we define *manufacturing lead time* (MLT) as the total time required to process a given part or product through the plant. Let us examine the components of MLT.

Production usually consists of a series of individual processing and assembly operations. Between the operations are material handling, storage, inspections, and other nonproductive activities. Let us therefore divide the activities of production into two main categories, operations and nonoperation elements. An operation is performed on a work unit when it is in the production machine. The nonoperation elements include handling, temporary storage, inspections, and other sources of delay when the work unit is not in the machine. Let $T_c =$ the operation cycle time at a given machine or workstation, and $T_{no} =$ the nonoperation time associated with the same machine. Further, let us suppose that the number of separate operations (machines) through which the work unit must be routed to be completely processed $= n_o$. If we assume batch production, then there are Q work units in the batch. A setup is generally required to prepare each production machine for the particular product, which requires a time $= T_{su}$. Given these terms, we can define manufacturing lead time as:

$$\text{MLT}_j = \sum_{i=1}^{oj} \left(T_{suji} + Q_j T_{cji} + T_{noji}\right) \tag{2.21}$$

where $\text{MLT}_j =$ manufacturing lead time for part or product j (min), $T_{suji} =$ setup time for operation i (min), $Q_j =$ quantity of part or product j in the batch being processed (pc), $T_{cji} =$ operation cycle time for operation i (min/pc), $T_{noji} =$ nonoperation time associated with operation i (min), and i indicates the operation sequence in the processing; $i = 1, 2, \ldots n_{oj}$. The MLT equation does not include the time the raw workpart spends in storage before its turn in the production schedule begins.

To simplify and generalize our model, let us assume that all setup times, operation cycle times, and nonoperation times are equal for the n_{oj} machines. Further, let us suppose that the batch quantities of all parts or products processed through the plant are equal and that they are all processed through the same number of machines, so that $n_{oj} = n_o$. With these simplifications, Eq. (2.21) becomes:

$$\text{MLT} = n_o\left(T_{su} + QT_c + T_{no}\right) \tag{2.22}$$

where MLT = average manufacturing lead time for a part or product (min).

In an actual batch production factory, which this equation is intended to represent, the terms n_o, Q, T_{su}, T_c, and T_{no} would vary by product and by operation. These variations can be accounted for by using properly weighted average values of the various terms. The averaging procedure is explained in the Appendix at the end of this chapter.

EXAMPLE 2.6   Manufacturing Lead Time

A certain part is produced in a batch size of 100 units. The batch must be routed through five operations to complete the processing of the parts. Average setup time is 3 hr/operation, and average operation time is 6 min (0.1 hr). Average nonoperation time due to handling, delays, inspections, etc., is 7 hours for each operation. Determine how many days it will take to complete the batch, assuming the plant runs one 8-hr shift/day.

Solution: The manufacturing lead time is computed from Eq. (2.22)

$$\text{MLT} = 5(3 + 100 \times 0.1 + 7) = \textit{100 hours}$$

At 8 hr/day, this amounts to 100/8 = *12.5 days.*

Eq. (2.22) can be adapted for job shop production and mass production by making adjustments in the parameter values. For a job shop in which the batch size is one ($Q = 1$), Eq. (2.22) becomes

$$\text{MLT} = n_o\left(T_{su} + T_c + T_{no}\right) \tag{2.23}$$

For mass production, the Q term in Eq. (2.22) is very large and dominates the other terms. In the case of quantity type mass production in which a large number of units are made on a single machine $(n_o=1)$, the MLT simply becomes the operation cycle time for the machine after the setup has been completed and production begins.

For flow line mass production, the entire production line is set up in advance. Also, the nonoperation time between processing steps is simply the transfer time T_r to move the part or product from one workstation to the next. If the workstations are integrated so that all stations are processing their own respective work units, then the time to accomplish all of the operations is the time it takes each work unit to progress through all of the stations on the line. The station with the longest operation time sets the pace for all stations.

$$\text{MLT} = n_o\left(T_r + \text{Max } T_o\right) = n_o T_c \tag{2.24}$$

where MLT = time between start and completion of a given work unit on the line (min), n_o = number of operations on the line; T_r = transfer time (min), Max T_o = operation time at the bottleneck station (min) and T_c = cycle time of the production line (min/pc). $T_c = T_r + \text{Max } T_o$ from Eq. (2.14). Since the number of stations is equal to the number of operations $(n = n_o)$, Eq. (2.24) can also be stated as follows:

$$\text{MLT} = n\left(T_r + \text{Max } T_o\right) = nT_c \tag{2.25}$$

where the symbols have the same meaning as above, and we have substituted n (number of workstations or machines) for number of operations n_o.

2.4.5   Work-in-Process

Work-in-process (WIP) is the quantity of parts or products currently located in the factory that are either being processed or are between processing operations. WIP is inventory that is in the state of being transformed from raw material to finished product. An approximate measure of work-in-process can be obtained from the following, using terms previously defined:

$$\text{WIP} = \frac{AU(PC)(\text{MLT})}{SH} \qquad (2.26)$$

where WIP = work-in-process in the facility (pc), A = availability, U = utilization, PC = production capacity of the facility (pc/wk), MLT = manufacturing lead time, (wk), S = number of shifts per week (shift/wk), and H = hours per shift (hr/shift). Eq. (2.26) states that the level of WIP equals the rate at which parts flow through the factory multiplied by the length of time the parts spend in the factory. The units for $(PC)/SH$ (e.g., pc/wk) must be consistent with the units for MLT (e.g., weeks).

Work-in-process represents an investment by the firm, but one that cannot be turned into revenue until all processing has been completed. Many manufacturing companies sustain major costs because work remains in-process in the factory too long.

2.5   COSTS OF MANUFACTURING OPERATIONS

Decisions on automation and production systems are usually based on the relative costs of alternatives. In this section we examine how these costs and cost factors are determined.

2.2.1   Fixed and Variable Costs

Manufacturing costs can be classified into two major categories: (1) fixed costs and (2) variable costs. A *fixed cost* is one that remains constant for any level of production output. Examples include the cost of the factory building and production equipment, insurance, and property taxes. All of the fixed costs can be expressed as annual amounts. Expenses such as insurance and property taxes occur naturally as annual costs. Capital investments such as building and equipment can be converted to their equivalent uniform annual costs using interest rate factors.

A *variable cost* is one that varies in proportion to the level of production output. As output increases, variable cost increases. Examples include direct labor, raw materials, and electric power to operate the production equipment. The ideal concept of variable cost is that it is directly proportional to output level. When fixed cost and variable cost are added, we have the following total cost equation:

$$TC = FC + VC(Q) \qquad (2.27)$$

where TC = total annual cost ($/yr), FC = fixed annual cost ($/yr), VC = variable cost ($/pc), and Q = annual quantity produced (pc/yr).
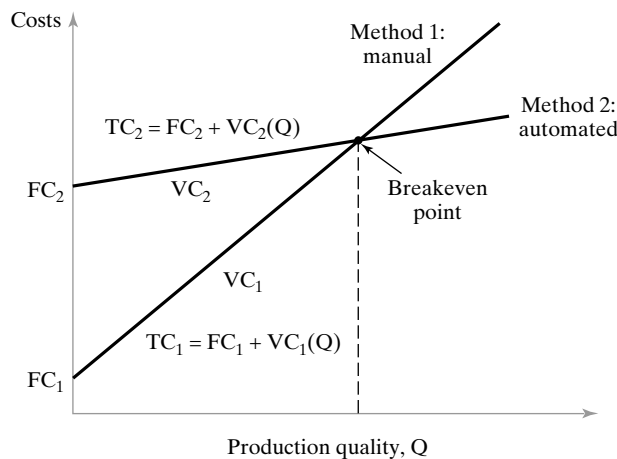
Figure 2.4 Fixed and variable costs as a function of production output for manual and automated production methods.

When comparing automated and manual production methods (Section 1.4), it is typical that the fixed cost of the automated method is high relative to the manual method, and the variable cost of automation is low relative to the manual method, as pictured in Figure 2.4. Consequently, the manual method has a cost advantage in the low quantity range, while automation has an advantage for high quantities. This reinforces the arguments presented in Section 1.4.1 on the appropriateness of manual labor for certain production situations.

2.5.2 Direct Labor, Material, and Overhead

Fixed versus variable are not the only possible classifications of costs in manufacturing. An alternative classification separates costs into: (1) direct labor, (2) material, and (3) overhead. This is often a more convenient way to analyze costs in production. The *direct labor cost* is the sum of the wages and benefits paid to the workers who operate the production equipment and perform the processing and assembly tasks. The *material cost* is the cost of all raw materials used to make the product. In the case of a stamping plant, the raw material consists of the steel sheet stock used to make stampings. For the rolling mill that made the sheet stock, the raw material is the iron ore or scrap iron out of which the sheet is rolled. In the case of an assembled product, materials include component parts manufactured by supplier firms. Thus, the definition of "raw material" depends on the company. The final product of one company can be the raw material for another company. In terms of fixed and variable costs, direct labor and material must be considered as variable costs.

Overhead costs are all of the other expenses associated with running the manufacturing firm. Overhead divides into two categories: (1) factory overhead and (2) corporate overhead. *Factory overhead* consists of the costs of operating the factory other than direct labor and materials. The types of expenses included in this category are listed in Table 2.7. Factory overhead is treated as fixed cost, although some of the items in our list could be correlated with the output level of the plant. *Corporate overhead* is the cost of running the company other than its manufacturing activities. A list of typical corporate overhead expenses is presented in Table 2.8. Many companies operate more than one factory, and this is one of the reasons for dividing overhead into factory and corporate categories. Different factories may have significantly different factory overhead expenses.

TABLE 2.7   Typical Factory Overhead Expenses

Plant supervision	Applicable taxes
Line foreman	Insurance
Maintenance crew	Heat and air conditioning
Custodial services	Light
Security personnel	Power for machinery
Tool crib attendant	Factory depreciation
Material handling	Equipment depreciation
Shipping and receiving	Fringe benefits

TABLE 2.8   Typical Corporate Overhead Expenses

Corporate executives	Applicable taxes
Sales and marketing	Cost of office space
Accounting department	Security personnel
Finance department	Heat and air conditioning
Legal counsel	Light
Engineering	Insurance
Research and development	Fringe benefits
Other support personnel	Other office costs

J. T. Black [6] provides some typical percentages for the different types of manufacturing and corporate expenses. These are presented in Figure 2.5. We might make several observations about these data. First, total manufacturing cost represents only about 40% of the product's selling price. Corporate overhead expenses and total manufacturing cost are about equal. Second, materials (and parts) make up the largest percentage of total manufacturing cost, at around 50%. And third, direct labor is a relatively small proportion of total manufacturing cost: 12% of manufacturing cost and only about 5% of final selling price.

Overhead costs can be allocated according to a number of different bases, including direct labor cost, material cost, direct labor hours, and space. Most common in industry is
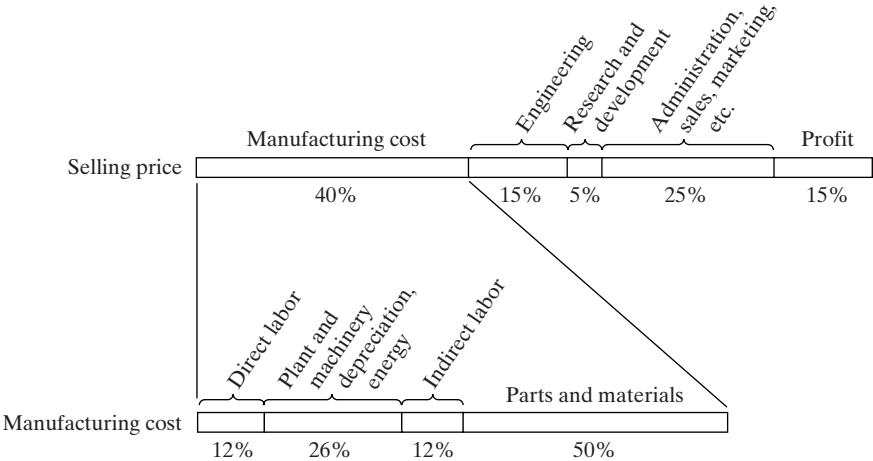

Figure 2.5 Breakdown of costs for a manufactured product [6].

direct labor cost, which we will use here to illustrate how overheads are allocated and sub-
sequently used to compute factors such as selling price of the product.

The allocation procedure (simplified) is as follows. For the most recent year (or
most recent several years), all costs are compiled and classified into four categories: (1)
direct labor, (2) material, (3) factory overhead, and (4) corporate overhead. The objective
is to determine an *overhead rate* (also called *burden rate*) that could be used in the fol-
lowing year to allocate overhead costs to a process or product as a function of the direct
labor costs associated with that process or product. In our treatment, separate overhead
rates will be developed for factory and corporate overheads. The *factory overhead rate* is
calculated as the ratio of factory overhead expenses (category 3) to direct labor expens-
es (category 1); that is,

$$FOHR = \frac{FOHC}{DLC} \tag{2.28}$$

where FOHR = factory overhead rate, FOHC = annual factory overhead costs ($/yr);
and DLC = annual direct labor costs ($/yr).

The *corporate overhead rate* is the ratio of corporate overhead expenses (category 4)
to direct labor expenses:

$$COHR = \frac{COHC}{DLC} \tag{2.29}$$

where COHR = corporate overhead rate, COHC = annual corporate overhead costs
($/yr), and DLC = annual direct labor costs ($/yr). Both rates are often expressed as per-
centages. If material cost were used as the allocation basis, then material cost would be
used as the denominator in both ratios. Let us present two examples to illustrate (1) how
overhead rates are determined and (2) how they are used to estimate manufacturing cost
and establish selling price.

EXAMPLE 2.7   Determining Overhead Rates

Suppose that all costs have been compiled for a certain manufacturing firm for
last year. The summary is shown in the table below. The company operates two
different manufacturing plants plus a corporate headquarters. Determine: (a) the
factory overhead rate for each plant and (b) the corporate overhead rate. These
rates will be used by the firm in the following year.

Expense Category	Plant 1 ($)	Plant 2 ($)	Corporate Headquarters (#)	Totals ($)
Direct labor	800,000	400,000		1,200,000
Materials	2,500,000	1,500,000		4,000,000
Factory expense	2,000,000	1,100,000		3,100,000
Corporate expense			7,200,000	7,200,000
Totals	5,300,000	3,000,000	3,000,000	15,500,000

Solution: (a) A separate factory overhead rate must be determined for each plant. For plant 1, we have:

$$FOHR_1 = \frac{\$2,000,000}{\$800,000} = 2.5 = 250\%$$

For plant 2,

$$FOHR_2 = \frac{\$1,100,000}{\$400,000} = 2.75 = 275\%$$

(b) The corporate overhead rate is based on the total labor cost at both plants.

$$COHR = \frac{\$7,700,000}{\$1,200,000} = 6.0 = 600\%$$

EXAMPLE 2.8   Estimating Manufacturing Costs and Establishing Selling Price

A customer order of 50 parts is to be processed through plant 1 of the previous example. Raw materials and tooling are supplied by the customer. The total time for processing the parts (including setup and other direct labor) is 100 hr. Direct labor cost is $10.00/hr. The factory overhead rate is 250% and the corporate overhead rate is 600%. Compute the cost of the job.

Solution: (a) The direct labor cost for the job is (100 hr)($10.00/hr) = $1000.
(b) The allocated factory overhead charge, at 250% of direct labor, is ($1000)(2.50) = $2500.
(c) The allocated corporate overhead charge, at 600% of direct labor, is ($1000)(6.00) = $6000.

Interpretation: (a) The direct labor cost of the job, representing actual cash spent on the customer's order = $1000. (b) The total factory cost of the job, including allocated factory overhead = $1000 + $2500 = $3500. (c) The total cost of the job including corporate overhead = $3500 + $6000 = $9500. To price the job for the customer and to earn a profit over the long run on jobs like this, the price would have to be greater than $9500. For example, if the company uses a 10% mark-up, the price quoted to the customer would be (1.10)($9500) = $10,450.

2.5.3   Cost of Equipment Usage

The trouble with overhead rates as we have developed them here is that they are based on labor cost alone. A machine operator who runs an old, small engine lathe whose book value is zero will be costed at the same overhead rate as an operator running a new CNC turning center just purchased for $500,000. Obviously, the time on the machining center is more productive and should be valued at a higher rate. If differences in rates of different production machines are not recognized, manufacturing costs will not be accurately measured by the overhead rate structure.

To deal with this difficulty, it is appropriate to divide the cost of a worker running a machine into two components: (1) direct labor and (2) machine. Associated with each is an applicable overhead rate. These costs apply not to the entire factory operations, but to individual work centers. A *work center* is a production cell consisting of (1) one worker and

one machine, (2) one worker and several machines, (3) several workers operating one machine, or (4) several workers and machines. In any of these cases, it is advantageous to separate the labor expense from the machine expense in estimating total production costs.

The direct labor cost consists of the wages and benefits paid to operate the work center. Applicable factory overhead expenses allocated to direct labor cost might include state taxes, certain fringe benefits, and line supervision. The machine annual cost is the initial cost of the machine apportioned over the life of the asset at the appropriate rate of return used by the firm. This is done using the capital recovery factor, as follows:

$$\text{UAC} = IC(A/P,i,n) \tag{2.30}$$

where UAC = equivalent uniform annual cost ($/yr); IC = initial cost of the machine ($); and $(A/P,i,n)$ = capital recovery factor that converts initial cost at year 0 into a series of equivalent uniform annual year-end values, where i = annual interest rate and n = number of years in the service life of the equipment. For given values of i and n, $(A/P,i,n)$ can be computed as follows:

$$(A/P, i, n) = \frac{i(1 + i)^n}{(1 + i)^n - 1} \tag{2.31}$$

Value of $(A/P, i, n)$ can also be found in interest tables that are widely available.

The uniform annual cost can be expressed as an hourly rate by dividing the annual cost by the number of annual hours of equipment use. The machine overhead rate is based on those factory expenses that are directly assignable to the machine. These include power to drive the machine, floor space, maintenance and repair expenses, and so on. In separating the factory overhead items in Table 2.7 between labor and machine, judgment must be used; admittedly, the judgment is sometimes arbitrary. Total cost rate for the work center is the sum of labor and machine costs. This can be summarized as follows:

$$C_o = C_L(1 + \text{FOHR}_L) + C_m(1 + \text{FOHR}_m) \tag{2.32}$$

where C_o = hourly rate to operate the work center ($/hr), C_L = direct labor wage rate ($/hr), FOHR_L = factory overhead rate for labor, C_m = machine hourly rate ($/hr), and FOHR_m = factory overhead rate applicable to machines.

It is the author's opinion that corporate overhead expenses should not be included in the analysis when comparing production methods. Including them serves no purpose other than to dramatically increase the costs of the alternatives. The fact is that these corporate overhead expenses are present whether or not either or none of the alternatives is selected. On the other hand, when estimating costs for pricing decisions, corporate overhead should be included because over the long run, these costs must be recovered through revenues generated from selling products.

EXAMPLE 2.9 Hourly Cost of a Work Center

The following data are given: direct labor rate = $10.00/hr; applicable factory overhead rate on labor = 60%; capital investment in machine = $100,000; service life of the machine = 8 yr; rate of return = 20%; salvage value in 8 yr = 0; and applicable factory overhead rate on machine = 50%. The work center will be operated one 8-hr shift, 250 day/yr. Determine the appropriate hourly rate for the work center.

Solution: Labor cost per hour $= C_L(1 + \text{FOHR}_L) = \$10.00(1 + 0.60) = \$16.00/\text{hr}$.
The investment cost of the machine must be annualized, using an 8-yr service life and a rate of return $= 20\%$. First we compute the capital recovery factor:

$$(A/P,20\%,8) = \frac{0.20(1 + 0.20)^8}{(1 + 0.20)^8 - 1} = \frac{0.20(4.2998)}{4.2998 - 1} = 0.2606$$

Now the uniform annual cost for the $100,000 initial cost can be determined:

$$\text{UAC} = \$100,000(A/P, 20\%, 8) = 100,000(0.2606) = \$26,060.00/\text{yr}$$

The number of hours per year $= (8\text{ hr/day})(250\text{ day/yr}) = 2000\text{ hr/yr}$. Dividing this into UAC gives $26,060/2000 = \$13.03/\text{hr}$. Then applying the factory overhead rate, we have

$$C_m(1 + \text{FOHR}_m) = \$13.03(1 + 0.50) = \$19.55/\text{hr}$$

Total cost rate is

$$C_o = 16.00 + 19.55 = \$35.55/\text{hr}.$$

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APPENDIX   AVERAGING PROCEDURES FOR PRODUCTION MODELS

As indicated in our presentation of the production models in Section 2.4, special averaging procedures are required to reduce the inherent variations in actual factory data to single parameter values used in our equations. This appendix explains the averaging procedures.

A straight arithmetic average is used to compute the value of batch quantity Q and the number of operations (machines) in the process routing n_o. Let $n_Q =$ number of batches of the various part or product styles to be considered. This might be the number of batches processed through the plant during a certain time period (i.e., week, month, year), or it might be a sample of size n_Q taken from this time period for analysis purposes. The average batch quantity is given by:

$$Q = \frac{\sum\limits_{j=1}^{n_Q} Q_j}{n_Q} \tag{A2.1}$$

where Q = average batch quantity, pc; Q_j = batch quantity for part or product style j of the total n_Q batches or styles being considered, pc, where $j = 1, 2, \ldots, n_Q$. The average number of operations in the process routing is a similar computation:

$$n_o = \frac{\sum\limits_{j=1}^{n_Q} n_{oj}}{n_Q} \tag{A2.2}$$

where n_o = average number of operations in all process routings under consideration; n_{oj} = number of operations in the process routing of part or product style j; and n_Q = number of batches under consideration.

When factory data are used to assess the terms T_{su}, T_c, and T_{no}, weighted averages must be used. To calculate the grand average setup time for n_Q different part or product styles, we first compute the average setup time for each style; that is,

$$T_{suj} = \frac{\sum\limits_{k=1}^{n_{oj}} T_{sujk}}{n_{oj}} \tag{A2.3}$$

where T_{suj} = average setup time for part or product style j, min; T_{sujk} = setup time for operation k in the processing sequence for part or product style j, min; where $k = 1, 2, \ldots, n_{oj}$; and n_{oj} = number of operations in the processing sequence for part or product style j. Using the n_Q values of T_{suj} calculated from the above equation, we can now compute the grand average setup time for all styles, given by:

$$T_{su} = \frac{\sum\limits_{j=1}^{n_Q} n_{oj} T_{suj}}{\sum\limits_{j=1}^{n_Q} n_{oj}} \tag{A2.4}$$

where T_{su} = setup time grand average for all n_Q part or product styles included in the group of interest, min; and the other terms are defined above.

A similar procedure is used to obtain grand averages for operation cycle time T_c and nonoperation time T_{no}. Considering cycle time first,

$$T_{cj} = \frac{\sum\limits_{k=1}^{n_{oj}} T_{cjk}}{n_{oj}} \tag{A2.5}$$

where T_{cj} = average operation cycle time for part or product style j, min; T_{cjk} = cycle time for operation k in the processing sequence for part or product style j, where $k = 1, 2, \ldots, n_{oj}$, min; and n_{oj} = number of operations in the processing sequence for style j. The grand average cycle time for all n_Q styles is given by:

$$T_c = \frac{\sum_{j=1}^{n_Q} n_{oj} T_{cj}}{\sum_{j=1}^{n_Q} n_{oj}} \tag{A2.6}$$

where T_c = operation cycle time grand average for all n_Q part or product styles being considered, min; and the other terms are defined above. The same forms of equation apply for nonoperation time T_{no}.

$$T_{noj} = \frac{\sum_{k=1}^{n_{oj}} T_{nojk}}{n_{oj}} \tag{A2.7}$$

where T_{noj} = average nonoperation time for part or product style j, min; T_{nojk} = nonoperation time for operation k in the processing sequence for part or product style j, min. The grand average for all styles (batches) is:

$$T_{no} = \frac{\sum_{j=1}^{n_Q} n_{oj} T_{noj}}{\sum_{j=1}^{n_Q} n_{oj}} \tag{A2.8}$$

where T_{no} = nonoperation time grand average for all parts or products considered, min; and other terms are defined above.

PROBLEMS

Product/Production Relationships

2.1 The ABC Company is planning a new product line and will build a new plant to manufacture the parts for a new product line. The product line will include 50 different models. Annual production of each model is expected to be 1000 units. Each product will be assembled of 400 components. All processing of parts will be accomplished in one factory. There are an average of 6 processing steps required to produce each component, and each processing step takes 1.0 min (includes an allowance for setup time and part handling). All processing operations are performed at workstations, each of which includes a production machine and a human worker. If each workstation requires a floor space of 250 ft^2, and the factory operates one shift (2000 hr/yr), determine (a) how many production operations, (b) how much floorspace, and (c) how many workers will be required in the plant.

2.2 The XYZ Company is planning to introduce a new product line and will build a new factory to produce the parts and assembly the final products for the product line. The new product line will include 100 different models. Annual production of each model is expected to be 1000 units. Each product will be assembled of 600 components. All processing of parts and assembly of products will be accomplished in one factory. There are an average of 10 processing steps required to produce each component, and each processing step takes 30 sec. (includes an allowance for setup time and part handling). Each final unit of product takes 3.0 hr to assemble. All processing operations are performed at work cells that each includes a production machine and a human worker. Products are assembled on single workstations con-

sisting of two workers each. If each work cell and each workstation require 200 ft², and the factory operates one shift (2000 hr/yr), determine: (a) how many production operations, (b) how much floorspace, and (c) how many workers will be required in the plant.

2.3 If the company in Problem 2.2 were to operate three shifts (6000 hr/yr) instead of one shift, determine the answers to (a), (b), and (c).

Production Concepts and Mathematical Models

2.4 Consider the batch production rate equations in Sect 2.4.1, Eqs. (2.9), (2.10), and (2.11). Suppose each cycle produced n_{pc} parts. Revise the equations accordingly to compute T_b, and R_p.

2.5 A certain part is routed through six machines in a batch production plant. The setup and operation times for each machine are given in the table below. The batch size is 100 and the average nonoperation time per machine is 12 hr. Determine: (a) manufacturing lead time and (b) production rate for operation 3.

Machine	Setup Time (hr)	Operation Time (min)
1	4	5.0
2	2	3.5
3	8	10.0
4	3	1.9
5	3	4.1
6	4	2.5

2.6 Suppose the part in previous Problem 2.5 is made in very large quantities on a production line in which an automated work handling system is used to transfer parts between machines. Transfer time between stations = 15 s. The total time required to set up the entire line is 150 hr. Assume that the operation times at the individual machines remain the same. Determine: (a) manufacturing lead time for a part coming off the line, (b) production rate for operation 3, (c) theoretical production rate for the entire production line?

2.7 The average part produced in a certain batch manufacturing plant must be processed through an average six machines. Twenty (20) new batches of parts are launched each week. Average operation time = 6 min, average setup time = 5 hr, average batch size = 25 parts, and average nonoperation time per batch = 10 hr/machine. There are 18 machines in the plant. The plant operates an average of 70 production hours per week. Scrap rate is negligible. Determine: (a) manufacturing lead time for an average part, (b) plant capacity, (c) plant utilization. (d) How would you expect the nonoperation time to be affected by the plant utilization?

2.8 Based on the data in previous Problem 2.7 and your answers to that problem, determine the average level of work-in-process (number of parts-in-process) in the plant.

2.9 An average of 20 new orders are started through a certain factory each month. On average, an order consists of 50 parts to be processed through 10 machines in the factory. The operation time per machine for each part = 15 min. The nonoperation time per order at each machine averages 8 hr, and the required setup time per order = 4 hr. There are 25 machines in the factory, 80% of which are operational at any time (the other 20% are in repair or maintenance). The plant operates 160 hr/mon. However, the plant manager complains that a total of 100 overtime machine–hours must be authorized each month to keep up with the production schedule. (a) What is the manufacturing lead time for an average order? (b) What is the plant capacity (on a monthly basis) and why must the overtime be authorized? (c) What is the utilization of the plant according to the definition given in the text? (d) Determine the average level of work-in-process (number of parts-in-process) in the plant.

2.10   The mean time between failure for a certain production machine is 250 hr, and the mean time to repair is 6 hr. Determine the availability of the machine.

2.11   One million units of a certain product are to be manufactured annually on dedicated production machines that run 24 hr/day, 5 day/wk, 50 wk/yr. (a) If the cycle time of a machine to produce one part is 1.0 min, how many of the dedicated machines will be required to keep up with demand? Assume that availability, utilization, and worker efficiency = 100%, and that no setup time will be lost. (b) Solve part (a) except that availability = 0.90.

2.12   The mean time between failures and mean time to repair in a certain department of the factory are 400 hr and 8 hr, respectively. The department operates 25 machines during one 8 hr shift/day, 5 day/wk, 52 wk/yr. Each time a machine breaks down, it costs the company $200/hr (per machine) in lost revenue. A proposal has been submitted to install a preventive maintenance program in this department. In this program, preventive maintenance would be performed on the machines during the evening so that there will be no interruptions to production during the regular shift. The effect of this program is expected to be that the average MTBF will double, and half of the emergency repair time normally accomplished during the day shift will be performed during the evening shift. The cost of the maintenance crew will be $1500/wk. However, a reduction of maintenance personnel on the day shift will result in a savings during the regular shift of $700/wk. (a) Compute the availability of machines in the department both before and after the preventive maintenance program is installed. (b) Determine how many total hours per year the 25 machines in the department are under repair both before and after the preventive maintenance program is installed. In this part and in part (c), ignore effects of queueing of the machines that might have to wait for a maintenance crew. (c) Will the preventive maintenance program pay for itself in terms of savings in the cost of lost revenues?

2.13   There are nine machines in the automatic lathe section of a certain machine shop. The setup time on an automatic lathe averages 6 hr. The average batch size for parts processed through the section is 90. The average operation time = 8.0 min. Under shop rules, an operator is permitted to be assigned to run up to three machines. Accordingly, there are three operators in the section for the nine lathes. In addition to the lathe operators, there are two setup workers who perform machine setups exclusively. These setup workers are kept busy the full shift. The section runs one 8 hr shift/day, 6 day/wk. However, an average of 15% of the production time is lost due to machine breakdowns. Scrap losses are negligible. The production control manager claims that the capacity of the section should be 1836 piece/wk. However, the actual output averages only 1440 unit/wk. What is the problem? Recommend a solution.

2.14   A certain job shop specializes in one-of-a-kind orders dealing with parts of medium-to-high complexity. A typical part is processed through ten machines in batch sizes of one. The shop contains eight conventional machine tools and operates 35 hr/wk of production time. Average time values on the part are: machining time per machine = 0.5 hr, work handling time per machine = 0.3 hr, tool change time per machine = 0.2 hr, setup time per machine = 6 hr, and nonoperation time per machine = 12 hr. A new programmable machine has been purchased by the shop which is capable of performing all ten operations in a single setup. The programming of the machine for this part will require 20 hr; however, the programming can be done off–line, without tying up the machine. The setup time will be 10 hr. The total machining time will be reduced to 80% of its previous value due to advanced tool control algorithms; the work handling time will be the same as for one machine; and the total tool change time will be reduced by 50% because it will be accomplished automatically under program control. For the one machine, nonoperation time is expected to be 12 hr. (a) Determine the manufacturing lead time for the traditional method and for the new method. (b) Compute the plant capacity for the following alternatives: (i) a job shop containing the eight traditional machines, and (ii) a job shop containing two of the new programmable machines. Assume the typical jobs are represented by the data given above. (c) Determine the average level of work-in-process for the two alternatives in part (b), if the alternative shops op-

erate at full capacity. (d) Identify which of the ten automation strategies are represented (or probably represented) by the new machine.

2.15 A factory produces cardboard boxes. The production sequence consists of three operations: (1) cutting, (2) indenting, and (3) printing. There are three machines in the factory, one for each operation. The machines are 100% reliable and operate as follows when operating at 100% utilization: (1) In **cutting**, large rolls of cardboard are fed into the cutting machine and cut into blanks. Each large roll contains enough material for 4,000 blanks. Production cycle time = 0.03 min/blank during a production run, but it takes 35 min to change rolls between runs. (2) In **indenting**, indentation lines are pressed into the blanks to allow the blanks to later be bent into boxes. The blanks from the previous cutting operation are divided and consolidated into batches whose starting quantity = 2,000 blanks. Indenting is performed at 4.5 min/100 blanks. Time to change dies on the indentation machine = 30 min. (3) In **printing**, the indented blanks are printed with labels for a particular customer. The blanks from the previous indenting operation are divided and consolidated into batches whose starting quantity = 1,000 blanks. Printing cycle rate = 30 blanks/min. Between batches, changeover of the printing plates is required, which takes 20 min. In-process inventory is allowed to build up between machines 1 and 2, and between machines 2 and 3, so that the machines can operate independently as much as possible. Based on this data and information, determine the maximum possible output of this factory during a 40 hr week, in completed blanks/wk (completed blanks have been cut, indented, and printed)? Assume steady state operation, not startup.

Costs of Manufacturing Operations

2.16 Theoretically, any given production plant has an optimum output level. Suppose a certain production plant has annual fixed costs FC = \$2,000,000. Variable cost VC is functionally related to annual output Q in a manner that can be described by the function VC = \$12 + \$0.005Q. Total annual cost is given by $TC = FC + VC \times Q$. The unit sales price for one production unit P = \$250. (a) Determine the value of Q that minimizes unit cost UC, where $UC = TC/Q$; and compute the annual profit earned by the plant at this quantity. (b) Determine the value of Q that maximizes the annual profit earned by the plant; and compute the annual profit earned by the plant at this quantity.

2.17 Costs have been compiled for a certain manufacturing company for the most recent year. The summary is shown in the table below. The company operates two different manufacturing plants, plus a corporate headquarters. Determine: (a) the factory overhead rate for each plant, and (b) the corporate overhead rate. These rates will be used by the firm in the following year.

Expense Category	Plant 1 ($)	Plant 2 ($)	Corporate Headquarters ($)
Direct labor	1,000,000	1,750,000	
Materials	3,500,000	4,000,000	
Factory expense	1,300,000	2,300,000	
Corporate expense			5,000,000

2.18 The hourly rate for a certain work center is to be determined based on the following data: direct labor rate = \$15.00/hr; applicable factory overhead rate on labor = 35%; capital investment in machine = \$200,000; service life of the machine = 5 years; rate of return = 15%; salvage value in five years = zero; and applicable factory overhead rate on machine = 40%. The work center will be operated two 8-hr shifts, 250 day/yr. Determine the appropriate hourly rate for the work center.

2.19 In previous Problem 2.18, if the work load for the cell can only justify a one-shift operation, determine the appropriate hourly rate for the work center.

2.20 In the operation of a certain production machine, one worker is required at a direct labor rate = \$10/hr. Applicable labor factory overhead rate = 50%. Capital investment in the system = \$250,000, expected service life = 10 years, no salvage value at the end of that period, and the applicable machine factory overhead rate = 30%. The work cell will operate 2000 hr/yr. Use a rate of return of 25% to determine the appropriate hourly rate for this work cell.

2.21 Same as previous Problem 2.20, except that the machine will be operated three shifts, or 6000 hr/yr. Note the effect of increased machine utilization on the hourly rate compared to the rate determined in Problem 2.20.

2.22 The break-even point is to be determined for two production methods, one a manual method and the other automated. The manual method requires two workers at \$9.00/hr each. Together, they produce at a rate of 36 units/hr. The automated method has an initial cost of \$125,000, a 4-year service life, no salvage value, and annual maintenance costs = \$3000. No labor (except for maintenance) is required to operate the machine, but the power required to run the machine is 50 kW (when running). Cost of electric power is \$0.05/kWh. If the production rate for the automated machine is 100 units/hr, determine the break-even point for the two methods, using a rate of return = 25%.