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Introduction and Overview of Manufacturing

Making things has been an essential activity of human civilizations since before recorded history. Today, the term *manufacturing* is used for this activity. For technological and economic reasons, manufacturing is important to the welfare of the United States and most other developed and developing nations. ***Technology*** can be defined as the application of science to provide society and its members with those things that are needed or desired. Technology affects our daily lives, directly and indirectly, in many ways. Consider the list of products in Table 1.1. They represent various technologies that help society and its members to live better. What do all these products have in common? They are all manufactured. These technological wonders would not be available to society if they could not be manufactured. Manufacturing is the critical factor that makes technology possible.

Economically, manufacturing is an important means by which a nation creates material wealth. In the United States, the manufacturing industries account for about 12% of gross domestic product (GDP). A country's natural resources, such as agricultural lands, mineral deposits, and oil reserves, also create wealth. In the United States, agriculture, mining, and similar industries account for less than 5% of GDP (agriculture alone is

Table 1.1 Products representing various technologies, most of which affect nearly all of us.

Athletic shoes	Fax machine	One-piece molded plastic patio chair
Automatic teller machine	Global positioning system	Optical scanner
Automatic dishwasher	Hand-held electronic calculator	Personal computer (PC)
Automobile	High-density PC diskette	Photocopying machine
Ballpoint pen	Home security system	Pull-tab beverage cans
Camcorder	Hybrid gas-electric automobile	Quartz crystal wrist watch
Cell phone	Industrial robot	Self-propelled mulching lawnmower
Compact disc (CD)	Ink-jet color printer	Smart phone
Compact disc player	Laptop computer	Supersonic aircraft
Compact fluorescent light bulb	LED lamps	Tablet computer
Contact lenses	LED TVs	Tennis racket of composite materials
Digital camera	Magnetic resonance imaging (MRI) machine for medical diagnosis	Video games
Digital video disc (DVD)	Medicines	Washing machine and dryer
Digital video disc player	Microwave oven	
E-book reader		

Key: LED = light-emitting diode.

only about 1%). Construction and public utilities make up around 5%. The rest is service industries, which include retail, transportation, banking, communication, education, and government. The service sector accounts for more than 75% of U.S. GDP. Government (federal, state, and local) accounts for more of GDP than the manufacturing sector; however, government services do not create wealth. In the modern global economy, a nation must have a strong manufacturing base (or it must have significant natural resources) if it is to provide a strong economy and a high standard of living for its people.

This opening chapter considers some general topics about manufacturing. What is manufacturing? How is it organized in industry? What are the materials, processes, and systems by which it is accomplished?

1.1 What Is Manufacturing?

The word *manufacture* is derived from two Latin words: *manus* (hand) and *factus* (make); the combination means made by hand. The English word manufacture is several centuries old, and "made by hand" accurately described the manual methods used when the word was first coined.[1] Most modern manufacturing is accomplished by automated and computer-controlled machinery (see Historical Note 1.1).

Historical Note 1.1 *History of manufacturing*

The history of manufacturing can be separated into two subjects: (1) the discovery and invention of materials and processes to make things and (2) the development of the systems of production. The materials and processes to make things predate the systems by several millennia. Some of the processes—casting, hammering (forging), and grinding—date back 6000 years or more. The early fabrication of implements and weapons was accomplished more as crafts and trades than manufacturing as it is known today. The ancient Romans had what might be called factories to produce weapons, scrolls, pottery and glassware, and other products of the time, but the procedures were largely based on handicraft.

The systems aspects of manufacturing are examined here, and the materials and processes are discussed in Historical Note 1.2. *Systems of manufacturing* refer to the ways of organizing people and equipment so that production can be performed more efficiently. Several historical events and discoveries stand out as having had a major impact on the development of modern manufacturing systems.

Certainly one significant discovery was the principle of *division of labor*—dividing the total work into tasks and having individual workers each become a specialist at performing only one task. This principle had been practiced for centuries, but the economist Adam Smith (1723–1790) is credited with first explaining its economic significance in *The Wealth of Nations*.

The *Industrial Revolution* (circa 1760–1830) had a major impact on production in several ways. It marked 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 machines were invented and steam power replaced water, wind, and animal power. These advances gave British industry significant advantages over other nations, and England attempted to restrict export of the new technologies. However, the revolution eventually spread to other European countries and the United States. Several inventions of the Industrial Revolution greatly contributed to the development of manufacturing: (1) *Watt's steam engine*—a new power-generating technology for industry; (2) *machine tools*, starting with John Wilkinson's boring machine around 1775 (Historical Note 21.1); (3) the *spinning jenny, power loom*, and other machinery for the textile industry that permitted significant increases in productivity; and

[1] As a noun, the word *manufacture* first appeared in English around 1567 A.D. As a verb, it first appeared around 1683 A.D.

(4) the *factory system*—a new way of organizing large numbers of production workers based on division of labor.

While England was leading the industrial revolution, an important concept 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 [3]. 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 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. He laid out components for 10 muskets before government officials, including Thomas Jefferson, 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 before becoming a practical reality, but it revolutionized methods of manufacturing. It is a prerequisite for mass production. 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 steel production methods were developed to meet this demand (Historical Note 6.1). 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 manufacturing systems by (1) mass production, (2) scientific management movement, (3) assembly lines, and (4) electrification of factories.

In the late 1800s, the *scientific management* movement was developing in the United States in response to the need to plan and control the activities of growing numbers of production workers. The movement's leaders included Frederick W. Taylor (1856–1915), Frank Gilbreth (1868–1924), and his wife Lillian (1878–1972). Scientific management included several features [1]: (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.

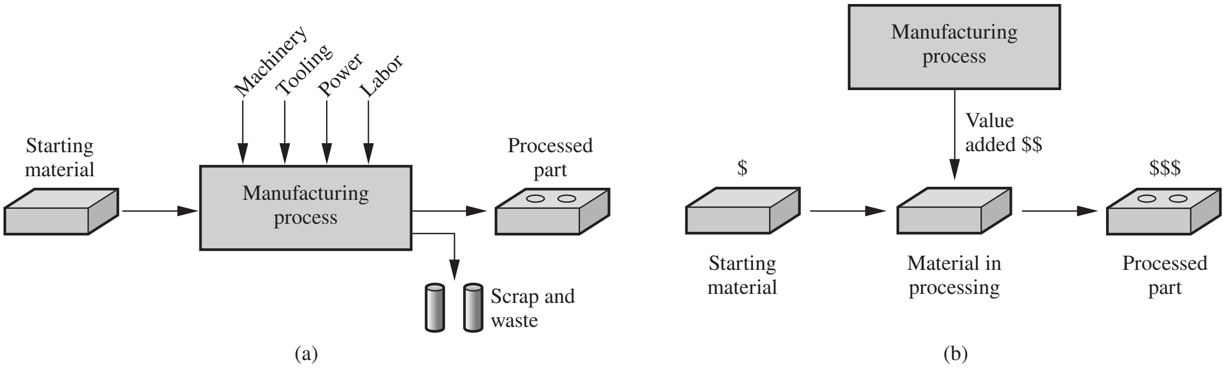
Henry Ford (1863–1947) introduced the *assembly line* in 1913 at his Highland Park, Michigan plant. The assembly line made possible the mass production of complex consumer products. Use of assembly line methods permitted Ford to sell a Model T automobile for as little as $500, thus making ownership of cars feasible for a large segment of the U.S. population.

In 1881, the first electric power generating station had been built in New York City, and soon electric motors were being used as a power source to operate factory machinery. This was a far more convenient power delivery system than steam engines, 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. The twentieth century was a time of more technological advances than in all other centuries combined. Many of these developments resulted in the *automation* of manufacturing.

1.1.1 | MANUFACTURING DEFINED

As a field of study in the modern context, manufacturing can be defined two ways, one technologic and the other economic. Technologically, ***manufacturing*** is the application of physical and chemical processes to alter the geometry, properties, and/or appearance of a given starting material to make parts or products; manufacturing also includes assembly of multiple parts to make products. The processes to accomplish manufacturing involve a combination of machinery, tools, power, and labor, as depicted in Figure 1.1(a). Manufacturing is almost always carried out as a sequence of operations. Each operation brings the material closer to the desired final state.

Economically, ***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 1.1(b). The key

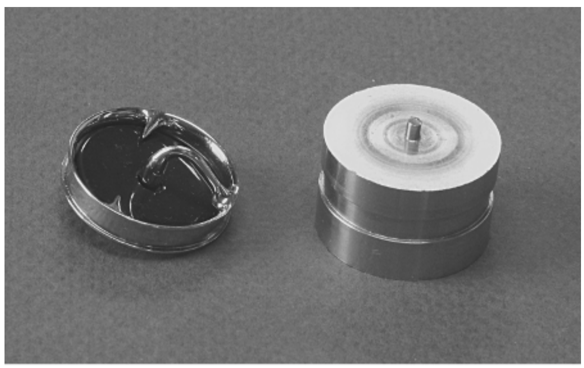


■ **Figure 1.1** Two ways to define manufacturing: (a) as a technical process and (b) as an economic process.

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.

Figure 1.2 shows a product on the left and the starting workpiece from which the circular frame of the product was produced on the right. The starting workpiece is a titanium billet, and the product consists of a carbon wafer assembled to the hook that protrudes from the right of the frame. The product is an artificial heart valve costing thousands of dollars, well worth it for patients who need one. In addition, the surgeon who implants it charges several more thousand dollars (call it an "installation fee"). The titanium billet costs a small fraction of the selling price. It measures about 25 mm (1 in) in diameter. The frame was machined (a material removal process, Section 1.3.1) from the starting billet. Machining time is about 1 hour. Note the added value provided by this operation. Note also the waste in the operation, as depicted in Figure 1.1(a); the finished frame has only about 5% of the mass of the starting workpiece (although the titanium swarf can be recycled).

The words *manufacturing* and *production* are often used interchangeably. The author's view is that production has a broader meaning than manufacturing. To illustrate, one might speak of "crude oil production," but the phrase "crude oil manufacturing" seems out of place. Yet when used in the context of products such as metal parts or automobiles, either word seems okay.



Courtesy George E. Kane Manufacturing Technology Laboratory, Lehigh University

■ **Figure 1.2** A mechanical heart valve on the left and the titanium workpiece from which the circular frame of the valve is machined on the right.

1.1.2 | MANUFACTURING INDUSTRIES AND PRODUCTS

Manufacturing is an important commercial activity performed by companies that sell products to customers. The type of manufacturing done by a company depends on the kinds of products it makes.

MANUFACTURING INDUSTRIES Industry consists of enterprises and organizations that produce goods and/or provide services. Industries can be classified as primary, secondary, or tertiary. ***Primary industries*** cultivate and exploit natural resources, such as agriculture and mining. ***Secondary industries*** take the outputs of the primary industries and convert them into consumer and capital goods. Manufacturing is the principal activity in this category, but construction and power utilities are also included. ***Tertiary industries*** constitute the service sector of the economy. A list of specific industries in these categories is presented in Table 1.2.

This book is concerned with the secondary industries in Table 1.2, which include the companies engaged in manufacturing. However, the International Standard Industrial Classification (ISIC) used to compile Table 1.2 includes several industries whose production technologies are not covered in this text; for example, beverages, chemicals, and food processing. In this book, manufacturing means production of *hardware*, which ranges from nuts and bolts to digital computers and military weapons. Plastic and ceramic products are included, but apparel, paper, pharmaceuticals, power utilities, publishing, and wood products are not.

MANUFACTURED PRODUCTS Final products made by the manufacturing industries can be divided into two major classes: consumer goods and capital goods. ***Consumer goods*** are products purchased directly by consumers, such as cars, smart phones, TVs, tires, and tennis rackets. ***Capital goods*** are those purchased by companies to produce goods and/or provide services. Examples of capital goods include aircraft, computers, communication equipment, medical apparatus, trucks and buses, railroad locomotives, machine tools, and construction equipment. Most of these capital goods are purchased by the service industries. It was noted in the introduction that manufacturing accounts for about 12% of gross domestic product and services about 75% of GDP in the United States. Yet, the manufactured capital goods purchased by the service sector are the enablers of that sector. Without the capital goods, the service industries could not function.

Table 1.2 Specific industries in the primary, secondary, and tertiary categories.

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

In addition to final products, other manufactured items include the materials, components, tools, and supplies used by the companies that make the final products. Examples of these items include sheet steel, bar stock, metal stampings, machined parts, plastic moldings, 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.

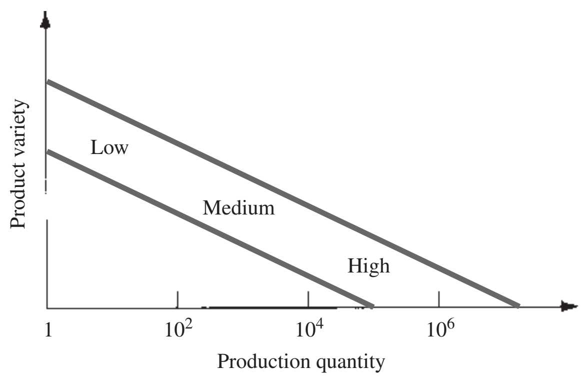
This book is generally concerned with *discrete items*—individual parts and assembled products rather than items produced by *continuous processes*. A metal stamping is a discrete item, but the sheet-metal coil from which it is made is continuous (almost). Many discrete parts start out as continuous or semicontinuous products, such as extrusions and electrical wire. Long sections made in almost continuous lengths are cut to the desired size. An oil refinery is a better example of a continuous process.

PRODUCTION QUANTITY AND PRODUCT VARIETY The quantity of products made by a factory has an important influence on the way its people, facilities, and procedures are organized. Annual production quantities can be classified into three ranges: (1) ***low*** production, quantities in the range 1 to 100 units per year; (2) ***medium*** production, from 100 to 10,000 units annually; and (3) ***high*** production, 10,000 to millions of units. The boundaries between the three ranges are somewhat arbitrary (author's judgment). Depending on the kinds of products, these boundaries may shift by an order of magnitude or so.

Production quantity refers to the number of units produced annually of a particular product type. 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 different product designs or types that are produced in the plant. Different products have different shapes and sizes; they perform different functions; they are 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 the factory is high, this indicates high product variety.

There is an inverse correlation between product variety and production quantity in terms of factory operations. If a factory's product variety is high, then its production quantity is likely to be low; but if production quantity is high, then product variety will be low, as depicted in Figure 1.3. Manufacturing plants tend to specialize in a combination of production quantity and product variety that lies somewhere inside the diagonal band in Figure 1.3.

Although product variety has been identified 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 because details on how much the designs differ are not captured simply by the number of



■ **Figure 1.3** Relationship between product variety and production quantity in discrete product manufacturing.

different designs. Differences between an automobile and an air conditioner are far greater than between an air conditioner and a heat pump. Within each product type, there are differences among specific models.

The extent of the product differences may be small or great, as illustrated in the automotive industry. 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 virtually the same. In different plants, the company builds heavy trucks. The terms "soft" and "hard" might be used to describe these differences in product variety. ***Soft product variety*** occurs when there are only small differences among products, such as the differences among car models made on the same production line. In an assembled product, soft variety is characterized by a high proportion of common parts among the models. ***Hard product variety*** occurs when the products differ substantially, and there are few common parts, if any. The difference between a car and a truck exemplifies hard variety.

1.1.3 | MANUFACTURING CAPABILITY

A manufacturing plant consists of a set of *processes* and *systems* (and people, of course) designed to transform a certain limited range of *materials* into products of increased value. These three building blocks—materials, processes, and systems—constitute the subject of modern manufacturing. There is a strong interdependence among these factors. A company engaged in manufacturing cannot do everything. It must do only certain things, and it must do those things well. ***Manufacturing capability*** refers to the scope of technical and physical capabilities and limitations of a manufacturing company and each of its plants. Manufacturing capability has three dimensions: (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 processes they can perform. Technological processing capability is closely related to material type. Certain manufacturing processes are suited to certain materials, whereas other processes are suited to other materials. By specializing in a certain process or group of processes, the plant is simultaneously specializing in certain material types. Technological processing capability includes not only the physical processes, but also the expertise possessed by plant personnel in these processing technologies. Companies must concentrate on the design and manufacture of products that are compatible with their technological processing capability.

PHYSICAL PRODUCT LIMITATIONS A second aspect of manufacturing capability is imposed by the *physical product*. A plant with a given set of processes is limited in terms of the size and weight of the products that can be accommodated. Large, heavy products are difficult to move. To move these products about, the plant must be equipped with cranes of the required load capacity. Smaller parts and products made in large quantities can be moved by conveyor or other means. 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 must be used to process larger parts. The production and material handling equipment 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***, defined as the maximum rate of production output 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 so on. These factors represent inputs to the manufacturing plant. Given these inputs, how much output can the factory produce?

Plant capacity is usually 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 in which 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.

Materials, processes, and systems are the fundamental topics of manufacturing and the three broad subject areas of this book. This introductory chapter provides an overview of these areas before embarking on a detailed coverage in the remaining chapters.

1.2 Materials in Manufacturing

Most engineering materials can be classified into one of three basic categories: (1) metals, (2) ceramics, and (3) polymers. Their chemistries are different, their mechanical and physical properties are different, and these differences affect the manufacturing processes that can be used to produce products from them. In addition to the three basic categories, there are (4) ***composites***—nonhomogeneous mixtures of the other three basic types rather than a unique category. The classification of the four groups is pictured in Figure 1.4. This section provides a survey of these materials. Chapters 6 through 9 cover the four material types in more detail.

1.2.1 | METALS

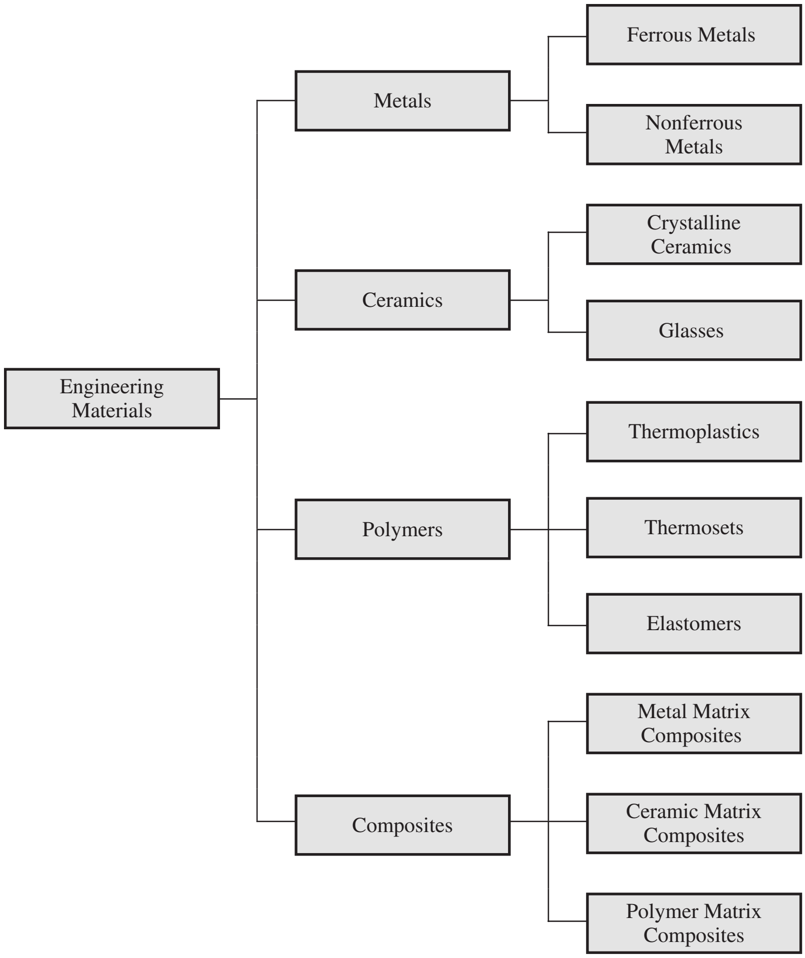
Metals used in manufacturing are usually ***alloys***, which are composed of two or more elements, at least one of which is a metallic element. Metals and alloys can be divided into two basic groups: (1) ferrous and (2) nonferrous.

FERROUS METALS Ferrous metals are based on iron; the group includes steel and cast iron. These metals constitute the most important group commercially, more than three-fourths of the metal tonnage throughout the world. Pure iron has limited commercial use, but when alloyed with carbon, iron has more uses and greater commercial value than any other metal. Alloys of iron and carbon form steel and cast iron.

Steel is defined as an iron–carbon alloy containing 0.02% to 2.11% carbon. It is the most important category within the ferrous metal group. Its composition often includes other alloying elements as well, such as manganese, chromium, nickel, and molybdenum, to enhance the properties of the metal. Applications of steel include construction (bridges, I-beams, and nails), transportation (trucks, rails, and rolling stock for railroads), and consumer products (automobiles and appliances).

Cast iron is an alloy of iron and carbon (2% to 4%) used in casting (primarily sand casting); silicon is also present in the alloy (in amounts from 0.5% to 3%). Other elements are often added also, to obtain desirable properties in the cast part. Cast iron is available in several different forms, of which gray cast iron is the most common; its applications include blocks and heads for internal combustion engines.

NONFERROUS METALS Nonferrous metals include the other metallic elements and their alloys. In almost all cases, the alloys are more important commercially than the pure metals. The nonferrous metals include the pure metals and alloys of aluminum, copper, gold, magnesium, nickel, silver, tin, titanium, zinc, and other metals.



■ **Figure 1.4** Classification of engineering materials.

1.2.2 | CERAMICS

A ceramic is a compound containing metallic (or semimetallic) and nonmetallic elements. Typical nonmetallic elements are oxygen, nitrogen, and carbon. Ceramics include a variety of traditional and modern materials. Traditional ceramics, some of which have been used for thousands of years, include *clay*, abundantly available, consisting of fine particles of hydrous aluminum silicates and other minerals used in making brick, tile, and pottery; *silica*, the basis for nearly all glass products; and *alumina* and *silicon carbide*, two abrasive materials used in grinding. Modern ceramics include some of the preceding materials, such as alumina, whose properties are enhanced in various ways through modern processing methods. Newer ceramics include *carbides*, metal carbides such as tungsten carbide and titanium carbide, which are widely used as cutting tool materials; and *nitrides*, metal and semimetal nitrides such as titanium nitride and boron nitride, used as cutting tools and grinding abrasives.

For processing purposes, ceramics can be divided into crystalline ceramics and glasses. Different manufacturing methods are required for the two types. Crystalline ceramics are formed in various ways from powders and then heated to a temperature below the melting point to achieve bonding between the powders. The glass ceramics (namely, glass) can be melted and cast, and then formed in processes such as traditional glass blowing.

1.2.3 | POLYMERS

A polymer is a compound formed of repeating structural units called *mers*, whose atoms share electrons to form very large molecules. Polymers usually consist of carbon plus one or more other elements such as hydrogen, nitrogen, oxygen, and chlorine. Polymers are divided into three categories: (1) thermoplastic polymers, (2) thermosetting polymers, and (3) elastomers.

Thermoplastic polymers can be subjected to multiple heating and cooling cycles without substantially altering the molecular structure of the polymer. Common thermoplastics include polyethylene, polypropylene, polystyrene, polyvinylchloride, and nylon. ***Thermosetting polymers*** chemically transform (*cure*) into a rigid structure upon cooling from a heated plastic condition, hence the name thermosetting. Members of this type include phenolics, amino resins, and epoxies. Although the name "thermosetting" is used, some of these polymers cure by mechanisms other than heating. ***Elastomers*** are polymers that exhibit significant elastic behavior. They include natural rubber, neoprene, silicone, and polyurethane.

1.2.4 | COMPOSITES

Composites do not really constitute a separate category of materials; they are mixtures of the other three types. A ***composite*** is a material consisting of two or more phases that are processed separately and then bonded together to achieve properties superior to those of its constituents. The term ***phase*** refers to a homogeneous mass of material, such as an aggregation of grains of identical unit cell structure in a solid metal. The usual structure of a composite consists of particles or fibers of one phase mixed in a second phase, called the *matrix*.

Composites are found in nature (e.g., wood), and they can be produced synthetically. The synthesized type is of greater interest here, and it includes glass fibers in a polymer matrix, such as fiber-reinforced plastic; polymer fibers of one type in a matrix of a second polymer, such as an epoxy-Kevlar composite; and ceramic in a metal matrix, such as a tungsten carbide in a cobalt binder to form cemented carbide.

Properties of a composite depend on its components, the physical shapes of the components, and the way they are combined to form the final material. Some composites combine high strength with light weight and are suited to applications such as aircraft components, car bodies, boat hulls, tennis rackets, and fishing rods. Other composites are strong, hard, and capable of maintaining these properties at elevated temperatures, for example, cemented carbide cutting tools.

1.3 Manufacturing Processes

A ***manufacturing process*** is a designed procedure that results in physical and/or chemical changes to a starting work material with the intention of increasing the value of that material. A manufacturing process is usually carried out as a ***unit operation***, which means it is a single step in the sequence of steps required to transform a starting material into a final part or product. Manufacturing operations 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 product. It adds value by changing the geometry, properties, or appearance of the starting material. In general, processing operations are performed on discrete work parts, but certain processing operations are also applicable to assembled items (e.g., painting a spot-welded car body). An ***assembly operation*** joins two or more components to create a new entity, called an assembly, subassembly, or some other term that refers to the joining process (e.g., a welded assembly is called a *weldment*). A classification of manufacturing processes is presented in Figure 1.5. Some of the basic processes date from antiquity (see Historical Note 1.2).

Historical Note 1.2 *Manufacturing materials and processes*

Although most of the historical developments that form the modern practice of manufacturing have occurred only during the last few centuries (Historical Note 1.1), several of the basic fabrication processes date as far back as the Neolithic period (circa 8000–3000 B.C.E.). It was during this period that processes such as the following were developed: carving and other *woodworking,* hand 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 period, 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 humans 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 hammered readily because it strain hardened; instead, it was shaped by *casting* (Historical Note 10.1). 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 3300–1200 B.C.E.).

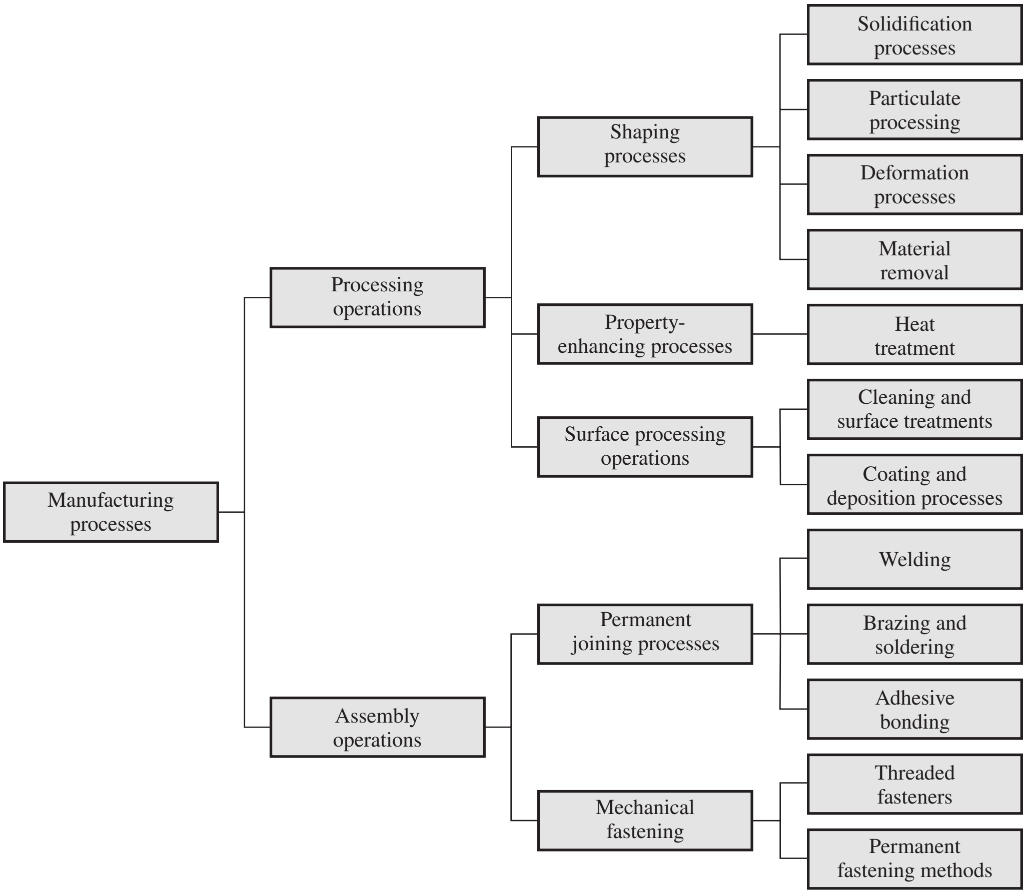
Iron was also first smelted during the Bronze Age. Meteorites may have been one source of the metal, but iron ore was also mined. Temperatures required to reduce iron ore to metal are significantly higher than for copper, which made furnace operations more difficult. Other processing methods were also 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 grinding a very sharp cutting edge 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 has been described here 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.E.). 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 (Historical Note 6.1).

The beginnings of machine tool technology occurred during the Industrial Revolution. During the period 1770–1850, machine tools were developed for most of the conventional *material removal processes*, such as *boring*, *turning*, *drilling*, *milling*, *shaping*, and *planing* (Historical Note 21.1). 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 earliest processes included *binding* with twine and rope, *riveting* and *nailing*, and *soldering*. Around 2000 years ago, *forge welding* and *adhesive bonding* had been developed. Widespread use of screws, bolts, and nuts as fasteners—so common in today's assembly—required the development of machine tools that could accurately cut the required helical shapes (e.g., Maudsley's screw cutting lathe, 1800). It was not until around 1900 that *fusion welding* processes started to be developed as assembly techniques (Historical Note 28.1).

Natural rubber was the first polymer to be used in manufacturing (if wood is excluded, for it is a polymer composite). The *vulcanization* process, discovered by Charles Goodyear in 1839, made rubber a useful engineering material (Historical Note 8.2). Subsequent developments included plastics such as cellulose nitrate in 1870, Bakelite in 1900, polyvinylchloride in 1927, polyethylene in 1932, and nylon in the late 1930s (Historical Note 8.1). Processing requirements for plastics led to the development of *injection molding* (based on die casting, one of the metal casting processes) and other polymer shaping techniques.

Electronics products have imposed unusual demands on manufacturing in terms of miniaturization. The evolution of the technology has been to package more and more devices into a smaller area—in some cases millions of transistors onto a flat piece of semiconductor material that is only 12 mm (0.50 in) on a side. The history of electronics processing and packaging dates from around 1960 (Historical Notes 33.1, 34.1, and 34.2).



■ **Figure 1.5** Classification of manufacturing processes.

1.3.1 | PROCESSING OPERATIONS

A processing operation uses energy to alter a work part'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 the human workers are generally employed to control the machines, oversee the operations, and load and unload parts before and after each cycle of operation. A general model of a processing operation is illustrated in Figure 1.1(a). Material is fed into the process, energy is applied by the machinery and tooling to transform the material, and the completed work part exits the process. Most production operations produce waste or scrap, either as a natural aspect 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 is usually required to transform the starting material into final form. The operations are performed in the particular sequence required to achieve the geometry and condition defined by the design specification.

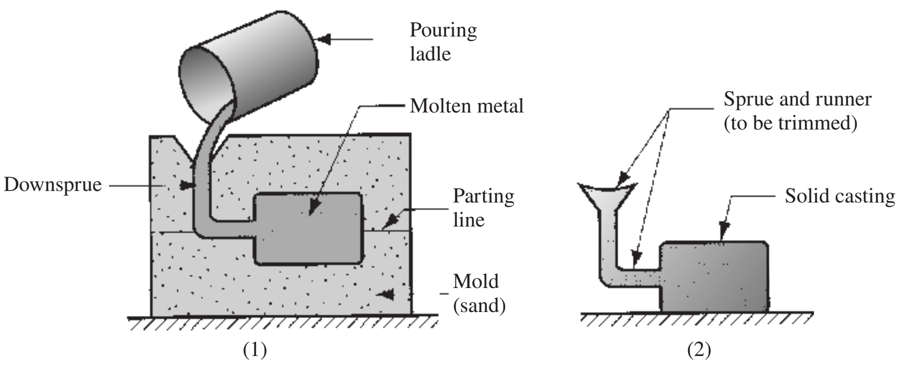
Three categories of processing operations are distinguished: (1) shaping operations, (2) property-enhancing operations, and (3) surface processing operations. ***Shaping operations*** alter the geometry of the starting work material by various methods. Common shaping processes include casting, forging, and machining. ***Property-enhancing operations*** improve its physical properties without changing its shape; heat treatment is the most common example. ***Surface processing operations*** are performed to clean, treat, coat, or deposit material onto the exterior surface of the work. Common examples of coating are plating and painting. Shaping processes are covered in Parts III through VI, corresponding to the four main categories of shaping processes in Figure 1.5. Property-enhancing processes and surface processing operations are covered in Part VII.

SHAPING PROCESSES Most shape processing operations apply heat, mechanical force, or a combination of these to effect a change in geometry of the work material. There are various ways to classify the shaping processes. The classification used in this book is based on the state of the starting material, by which there are four categories: (1) ***solidification processes***, in which the starting material is a heated liquid or semifluid that cools and solidifies to form the part geometry; (2) ***particulate processing***, in which the starting material is a powder, and the powders are formed and heated into the desired geometry; (3) ***deformation processes***, in which the starting material is a ductile solid (commonly metal) that is deformed to shape the part; and (4) ***material removal processes***, in which the starting material is a solid (ductile or brittle), from which material is removed so that the resulting part has the desired geometry.

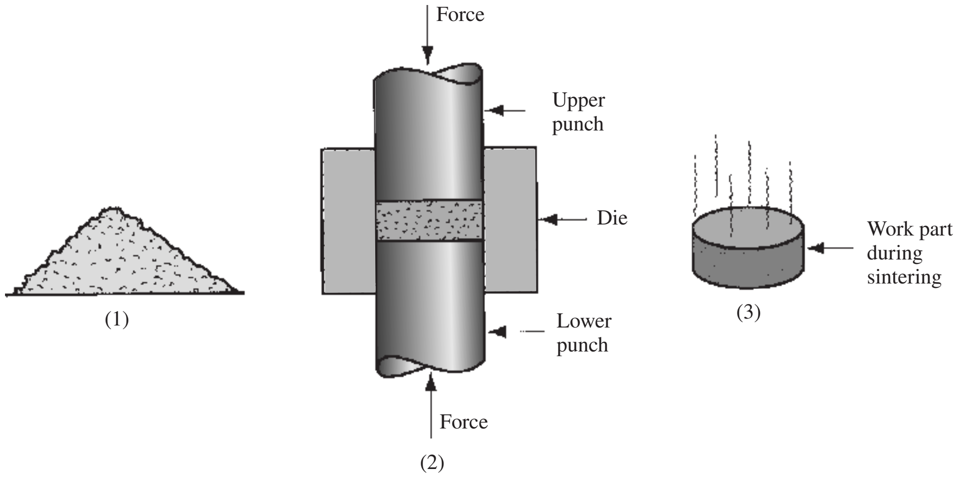
In the first category, the starting material is heated sufficiently to transform it into a liquid or highly plastic (semifluid) state. Nearly all materials can be processed in this way. Metals, ceramic glasses, and plastics can all be heated to sufficiently high temperatures to convert them into liquids. With the material in a liquid or semifluid form, it can be poured or otherwise forced to flow into a mold cavity and allowed to solidify, thus taking a solid shape that is the same as the cavity. Most processes that operate this way are called casting or molding. *Casting* is the name used for metals, and *molding* is the common term used for plastics. This category of shaping process is depicted in Figure 1.6. Figure 11.6 shows a cast aluminum engine head, and a collection of plastic molded parts is displayed in Figure 13.20.

In particulate processing, the starting materials are powders of metals or ceramics. Although these two materials are quite different, the processes to shape them in particulate processing are quite similar. The common technique in powder metallurgy involves pressing and sintering, illustrated in Figure 1.7, in which the powders are first squeezed into a die cavity under high pressure and then heated to bond the individual particles together. Examples of parts produced by powder metallurgy are shown in Figure 15.1.

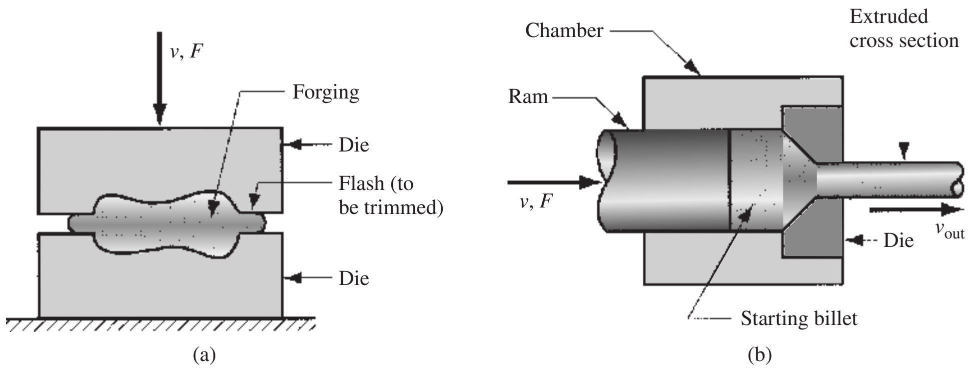
In the deformation processes, the starting work part is shaped by the application of forces that exceed the yield strength of the material. For the material to be formed in this way, it must be sufficiently ductile to avoid fracture during deformation. To increase ductility (and for other reasons), the work material is often heated before forming to a temperature below the melting point. Deformation processes are associated most closely with metalworking and include operations such as *forging* and *extrusion*, shown in Figure 1.8. Figure 18.18 shows a forging operation performed by a drop hammer.



■ **Figure 1.6** Casting and molding processes start with a work material heated to a fluid or semifluid state. The process consists of (1) pouring the fluid into a mold cavity and (2) allowing the fluid to solidify, after which the solid part is removed from the mold.



■ **Figure 1.7** Particulate processing: (1) the starting material is powder; the usual process consists of (2) pressing and (3) sintering.

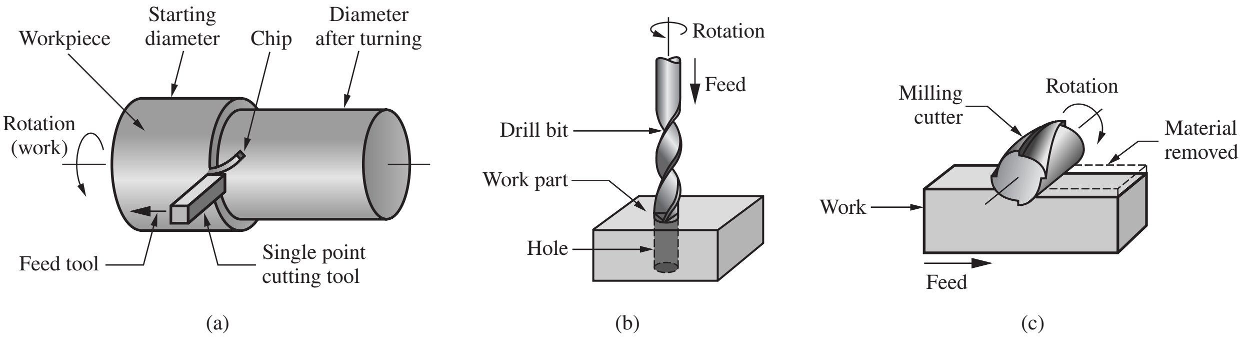


■ **Figure 1.8** Some common deformation processes: (a) *forging*, in which two halves of a die squeeze the work part, causing it to assume the shape of the die cavity; (b) *extrusion*, in which a billet is forced to flow through a die orifice, thus taking the cross-sectional shape of the orifice.

Also included within the deformation processes category is ***sheet metalworking***, which involves bending, forming, and shearing operations performed on starting blanks and strips of sheet metal. Several sheet metal parts, called stampings because they are made on a stamping press, are illustrated in Figure 19.30.

Material removal processes are operations that remove excess material from the starting workpiece so that the resulting shape is the desired geometry. The most important processes in this category are *machining* operations such as *turning*, *drilling*, and *milling*, shown in Figure 1.9. These cutting operations are most commonly applied to solid metals, performed using cutting tools that are harder and stronger than the work metal. The front cover of this book shows a turning operation. *Grinding* is another common material removal process. Other processes in this category are known as *nontraditional processes* because they use lasers, electron beams, chemical erosion, electric discharges, and electrochemical energy to remove material rather than cutting or grinding tools.

It is desirable to minimize waste and scrap in converting a starting work part into its subsequent geometry. Certain shaping processes are more efficient than others in terms of material conservation. Material removal processes (e.g., machining) tend to be wasteful of material, simply by the way they work. The material removed from the starting shape is waste, at least in terms of the unit operation. Other processes, such as certain casting and molding operations, often convert close to 100%



■ **Figure 1.9** Common machining operations: (a) *turning*, in which a single-point cutting tool removes metal from a rotating workpiece to reduce its diameter; (b) *drilling*, in which a rotating drill bit is fed into the work to create a round hole; and (c) *milling*, in which a work part is fed past a rotating cutter with multiple cutting teeth.

of the starting material into final product. Manufacturing processes that transform nearly all of the starting material into product and require no subsequent machining to achieve final part geometry are called *net shape processes*. Other processes require minimum machining to produce the final shape and are called *near net shape processes*.

PROPERTY-ENHANCING PROCESSES The second major type of part processing is performed to improve mechanical or physical properties of the work material. These processes do not alter the shape of the part, except unintentionally in some cases. The most important property-enhancing processes involve heat treatments, which include various annealing and strengthening processes for metals and glasses. Sintering of powdered metals is also a heat treatment that strengthens a pressed powder metal work part. Its counterpart in ceramics is called *firing*.

SURFACE PROCESSING 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 such as diffusion and ion implantation. ***Coating*** and ***thin film deposition*** processes apply a coating of material to the exterior surface of the work part. Common coating processes include *electroplating*, *anodizing* of aluminum, organic *coating* (call it *painting*), and porcelain enameling. Thin film deposition processes include *physical vapor deposition* and *chemical vapor deposition* to form extremely thin coatings of various substances.

1.3.2 | 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 either permanently or semipermanently. Permanent joining processes include *welding*, *brazing*, *soldering*, and *adhesive bonding*. They form a joint between components that cannot be easily disconnected. Certain *mechanical assembly* methods are available to fasten together two (or more) parts in a joint that can be conveniently disassembled. The use of screws, bolts, and other *threaded fasteners* are important traditional methods in this category. Other mechanical assembly techniques form a more permanent connection; these include *rivets*, *press fitting*, and *expansion fits*. Joining and assembly processes are discussed in Part VIII.

1.3.3 | PRODUCTION MACHINES AND TOOLING

Manufacturing operations are accomplished using machinery and tooling (and people). The extensive use of machinery in manufacturing began with the Industrial Revolution. It was at that time that metal cutting machines started to be developed and widely used. These were called ***machine tools***—power-driven machines used to operate cutting tools previously operated by hand. Modern machine tools are described by the same basic definition, except that the power is electrical rather than water or steam, and the level of precision and automation is much greater today. Machine tools are among the most versatile of all production machines. They are used to make not only parts for consumer products but also components for other production machines. Both in a historic and a reproductive sense, the machine tool is the mother of all machinery.

Other production machines include *presses* for stamping operations, *forge hammers* for forging, *rolling mills* for rolling sheet metal, *welding machines* for welding, and *placement machines* for assembling electronic components to printed circuit boards. The name of the equipment usually follows from the name of the process.

Production equipment can be general purpose or special purpose. General purpose equipment is more flexible and adaptable to a variety of jobs. It is commercially available for any manufacturing company to invest in. Special purpose equipment is usually designed to produce a specific part or product in very large quantities. The economics of mass production justify large investments in special purpose machinery to achieve high efficiencies and short cycle times. This is not the only reason for special purpose equipment, but it is the dominant one. Another reason may be because the process is unique and commercial equipment is not available. Some companies with unique processing requirements develop their own special purpose equipment.

Production machinery usually requires tooling that customizes the equipment for the particular part or product. In many cases, the tooling must be designed specifically for the part or product configuration. When used with general purpose equipment, it is designed to be exchanged. For each work part type, the tooling is fastened to the machine and the production run is made. When the run is completed, the tooling is changed for the next work part type. When used with special purpose machines, the tooling is often designed as an integral part of the machine. Because the special purpose machine is likely being used for mass production, the tooling may never need changing except for replacement of worn components or for repair of worn surfaces.

The type of tooling depends on the type of process. Table 1.3 lists examples of special tooling used in various operations. Details are provided in the chapters that discuss these processes.

Table 1.3 Production equipment and tooling used in various manufacturing processes.

Process	Equipment	Special tooling (function)
Casting	[a]	Mold (cavity for molten metal)
Molding	Molding machine	Mold (cavity for hot polymer)
Rolling	Rolling mill	Roll (reduce work thickness)
Forging	Forge hammer or press	Die (squeeze work to shape)
Extrusion	Press	Extrusion die (reduce cross section)
Stamping	Press	Die (shearing, forming sheet metal)
Machining	Machine tool	Cutting tool (material removal)
		Fixture (hold work part)
		Jig (hold part and guide tool)
Grinding	Grinding machine	Grinding wheel (material removal)
Welding	Welding machine	Electrode (fusion of work metal)
		Fixture (hold parts during welding)

[a]Various types of casting setups and equipment (Chapter 11).

1.4 Production Systems

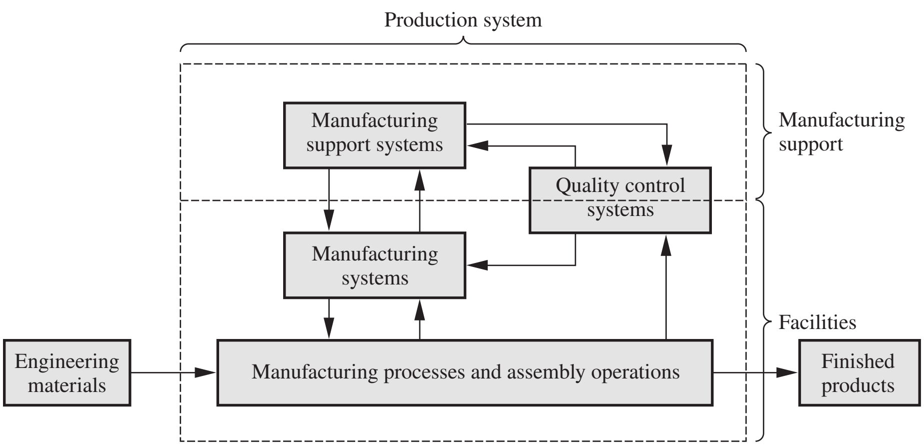
To operate effectively, a manufacturing firm must have systems that allow it to efficiently accomplish its type of production. Production systems consist of people, equipment, and procedures designed for the combination of materials and processes that constitute a firm's manufacturing operations. Production systems can be divided into two categories: (1) production facilities and (2) manufacturing support systems, as shown in Figure 1.10.[2] ***Production facilities*** consist of the factory, physical equipment, and the arrangement of equipment in the factory. ***Manufacturing support systems*** are the procedures used by the company to manage production and solve the technical and logistics problems encountered in ordering materials, moving work through the factory, and ensuring that products meet quality standards. Both categories include people. People make these systems work. In general, direct labor workers are responsible for operating the manufacturing equipment, and professional staff workers are responsible for manufacturing support.

1.4.1 | PRODUCTION FACILITIES

Production facilities consist of the factory and the production, material handling, and other equipment in the factory. The equipment comes in direct physical contact with the parts and/or assemblies as they are being made. The facilities "touch" the product. Facilities also include the way the equipment is arranged in the factory, called the *plant layout*. The equipment is usually organized into logical groupings; in this book, they are called *manufacturing systems*, such as an automated production line, or a machine cell consisting of an industrial robot and a machine tool.

A manufacturing company attempts to design its manufacturing systems and organize its factories to serve the particular mission of each plant in the most efficient way. Over the years, certain types of production facilities have come to be recognized as the most appropriate way to organize for a given combination of product variety and production quantity, as discussed in Section 1.1.2. Different types of facilities are required for each of the three ranges of annual production quantities.

LOW-QUANTITY PRODUCTION In the low-quantity range (1–100 units per year), the term *job shop* is often used to describe the type of production facility. A job shop makes low quantities of specialized and customized products. The products are typically complex, such as a prototype



■ **Figure 1.10** Model of the production system and overview of major topics in the book.

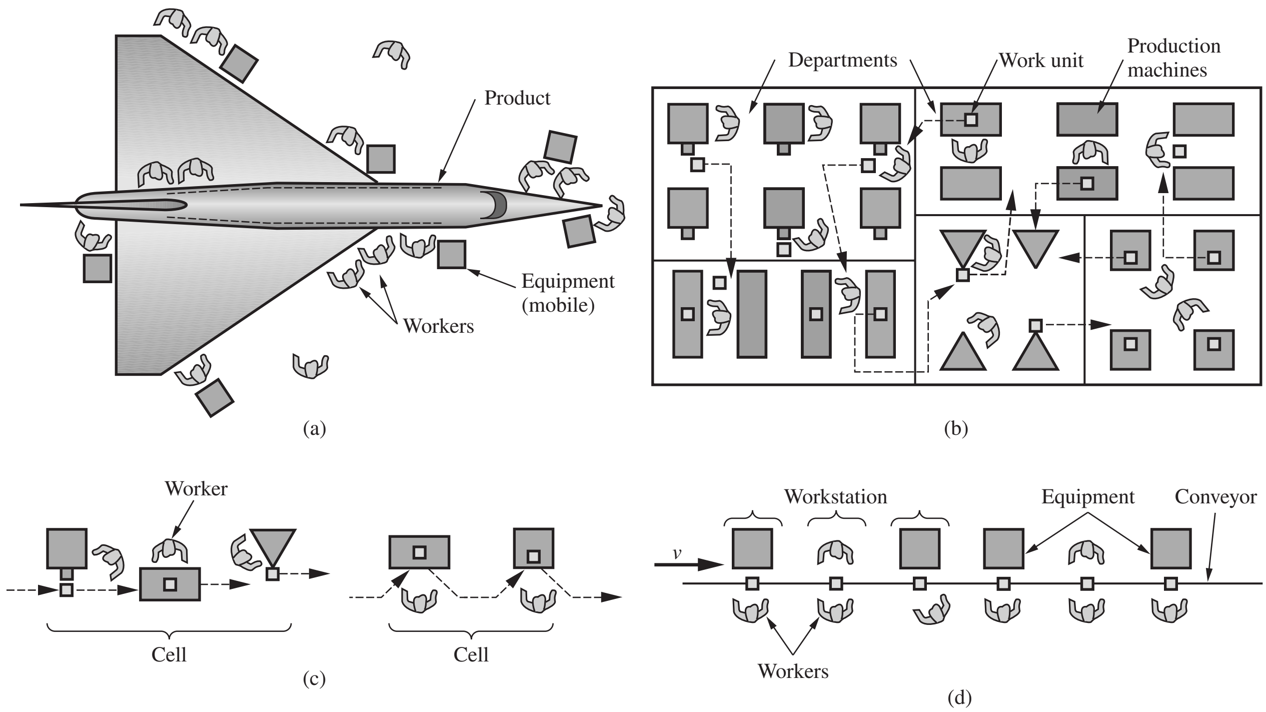
[2] This diagram also indicates the major topic areas covered in this book.

aircraft and special machinery. The 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 product variations encountered (hard product variety). If the product is large and heavy, and therefore difficult to move, it typically remains in a single location during its fabrication or 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 1.11(a). In a pure situation, the product remains in a single location during its entire production. Examples of such products include ships, large aircraft, 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 components of these low-quantity products are often made in factories in which the equipment is arranged according to function or type. This arrangement is called a *process layout*. The lathes are in one department, the milling machines are in another department, and so on, as in Figure 1.11(b). Different parts, each requiring a different operation sequence, 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 operation sequences for different part configurations. Its disadvantage is that the machinery and methods to produce a part are not designed for high efficiency.

MEDIUM QUANTITY PRODUCTION In the medium-quantity range (100–10,000 units annually), two different types of facility are distinguished, depending on product variety. When product variety is hard, the usual approach is ***batch production***, in which a batch of one product is made, after which the manufacturing equipment is changed over to produce a batch of the next product, and



■ **Figure 1.11** Various types of plant layout: (a) fixed-position layout, (b) process layout, (c) cellular layout, and (d) product layout.

so on. 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—time to change tooling and set up the machinery. This setup time is lost production time, and this is a disadvantage of batch manufacturing. Batch production is commonly used for 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, as in Figure 1.11(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 necessary. It is often possible to configure the manufacturing system so that groups of similar products can be made on the same equipment without significant lost time because of setup. 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, according to the principles of *group technology* (Section 38.5). The layout is called a *cellular layout*, depicted in Figure 1.11(c).

HIGH PRODUCTION The high-quantity range (10,000 to millions of units per year) is referred to as *mass production*. The situation is characterized by a high demand rate for the product, and the manufacturing system is dedicated to the production of that single item. Two categories of mass production can be distinguished: quantity production and flow line production. ***Quantity production*** involves the mass production of single parts on single pieces of equipment. It typically involves standard machines (e.g., 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. Typical layouts used in quantity production are the process layout and cellular layout (if several machines are involved).

Flow line production involves multiple pieces of equipment or workstations arranged in sequence, and the work units are physically moved through the sequence to complete the product. The workstations and equipment are 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 1.11(d), or into a series of connected line segments. The work is usually moved between stations by mechanized 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 occurs when 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*. To successfully market a given product, it is often beneficial to introduce feature and model variations so that individual customers can choose the exact merchandise that appeals to them. From a production viewpoint, the feature differences represent a case of soft product variety. The term *mixed-model production line* applies to these situations in which 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.

1.4.2 | MANUFACTURING SUPPORT SYSTEMS

To operate its 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 functions are often carried out in the firm by people organized into departments such as the following:

- ***Manufacturing engineering.*** The manufacturing engineering department is responsible for planning the manufacturing processes—deciding what processes should be used to make the parts and assemble the products. This department is also involved in designing and ordering the machine tools and other equipment used by the operating departments to accomplish processing and assembly.
- ***Production planning and control.*** This department is responsible for solving the logistics problem in manufacturing—ordering materials and purchased parts, scheduling production, and making sure that the operating departments have the necessary capacity to meet the production schedules.
- ***Quality control.*** Producing high-quality products should be a top priority of any manufacturing firm in today's competitive environment. It means designing and building products that conform to specifications and satisfy or exceed customer expectations. Much of this effort is the responsibility of the QC department.

1.5 Manufacturing Economics

In Section 1.1.1, manufacturing was defined as a transformation process that adds value to a starting work material. In Section 1.1.2, it was noted that manufacturing is a commercial activity performed by companies that sell products to customers. It is appropriate to consider some of the economic aspects of manufacturing, and that is the purpose of this section. The coverage consists of (1) production cycle time analysis and (2) manufacturing cost models.

1.5.1 | PRODUCTION CYCLE TIME ANALYSIS

"Time is money," as the saying goes. The total time to make a product is one of the components that determine its total cost and the price that can be charged for it. The total time is the sum of all of the individual cycle times of the unit operations needed to manufacture the product. As defined in Section 1.3, a unit operation is a single step in the sequence of steps required to make the final product. The cycle time of a unit operation is defined as the time that one work unit spends being processed or assembled. It is the time interval between when one work unit begins the operation and the next unit begins. A typical production cycle time consists of the actual processing time plus the work handling time, for example, loading and unloading the part in the machine. In some processes, such as machining, time is also required to periodically change the tooling used in the operation when it wears out. In equation form,

$$T_c = T_o + T_h + T_t \tag{1.1}$$

where T_c = cycle time of the unit operation, min/pc; T_o = actual processing time in the operation, min/pc; T_h = work part handling time, min/pc; and T_t = tool handling time if that applies in the operation, min/pc. As indicated, the tool handling time usually occurs periodically, not every cycle, so the time per workpiece must be determined by dividing the actual time associated with changing the tool by the number of pieces between tool changes. It should be mentioned that many production operations do not include a tool change, so that term is omitted from Equation (1.1) in those cases.

Batch production and job shop production are common types of manufacturing. They both involve setting up a piece of production equipment to prepare for the particular style of work part to be processed, and then making the production run for the desired batch quantity. The quantities in job shop production are less than in batch production, as described in Section 1.4.1. Batch processing is accomplished in either of two ways: (1) *sequential batch processing*, in which the parts in the batch are processed one after the other and (2) *simultaneous batch processing*, in which all of the parts in the batch are processed together at the same time. An example of sequential batch processing is machining a given quantity of identical work parts in sequence on a metal-cutting machine tool. The machine tool can only machine one part at a time. An example of simultaneous batch processing is a heat treating operation in which the entire batch of parts is placed in the furnace and processed simultaneously.

The time to produce a batch of parts in a unit operation consists of the setup time plus the run time. In sequential batch production, the time to produce the batch is determined as follows:

$$T_b = T_{su} + Q_b T_c \tag{1.2a}$$

where T_b = total time to complete the batch, min/batch; T_{su} = setup time, min/batch; Q_b = batch quantity, pc/batch; and T_c = cycle time as defined in Equation (1.1). This assumes that one part is produced in each cycle. In simultaneous batch production, the cycle time is interpreted to mean the time to process all parts in the batch together, in which case the batch time is given by the following:

$$T_b = T_{su} + T_c \tag{1.2b}$$

where T_c = the cycle time to load, process, and unload all Q_b parts in the batch, min/batch.

To obtain a realistic value of the average production time per piece, including the effect of setup time, the batch time in either Equations (1.2a) or (1.2b) is divided by the batch quantity:

$$T_p = \frac{T_b}{Q_b} \tag{1.3}$$

where T_p = average production time per piece, min/pc; and the other terms are defined above. Equation (1.3) is applicable in both sequential and simultaneous batch production.

If the batch size is one part, then Equations (1.2) and (1.3) are still applicable, and $Q_b = 1$. In high production (mass production), these equations can also be used, but the value of Q_b is so large that the setup time loses significance: As $Q_b \rightarrow \infty$, $T_{su}/Q_b \rightarrow 0$.

The average production time per piece in Equation (1.3) can be used to determine the actual average production rate in the operation:

$$R_p = \frac{60}{T_p} \tag{1.4}$$

where R_p = average hourly production rate, pc/hr. This production rate includes the effect of setup time.

During the production run in sequential batch production (after the equipment is set up), the rate of production is the reciprocal of the cycle time:

$$R_c = \frac{60}{T_c} \tag{1.5}$$

where R_c = hourly cycle rate, cycles/hr (pc/hr if one part is completed each cycle). The cycle rate will always be larger than the actual average production rate unless the setup time is zero ($R_c \geq R_p$). By similar reasoning, Equation (1.5) also applies to mass production.

Equation (1.5) is not applicable to simultaneous batch production because the meaning of cycle time T_c is different when the parts in a batch are processed simultaneously.

1.5.2 | MANUFACTURING COST MODELS

The cycle time analysis can be used to estimate the costs of production, which include not only the cost of time but also materials and overhead. The cost of time consists of labor and equipment costs, which are applied to the average production time per piece as cost rates (e.g., \$/hr or \$/min). Thus, the cost model for production cost per piece can be stated as follows:

$$C_{pc} = C_m + C_o T_p + C_t \tag{1.6}$$

where C_{pc} = cost per piece, \$/pc; C_m = starting material cost, \$/pc; C_o = cost rate of operating the work cell, \$/min; T_p = average production time per piece from Equation (1.3), min/pc; and C_t = cost of tooling if used in the unit operation, \$/pc.

If tooling is used in the manufacturing process, then C_t is determined by dividing the cost of that tooling by the number of pieces produced by that tooling. For instance, in a machining operation, cutting tools must be replaced periodically because they wear out. In this case, the cost to replace the tool is divided by the number of parts completed between replacements. (Section 23.3.2 considers this cutting tooling issue in more detail.) Other processes require special tooling in the form of dies or molds. Sheet-metal pressworking and plastic-injection molding are examples. In these cases, the cost of the special tooling is divided by the total number of parts produced during the life of that tooling to obtain the value of C_t. If the die or mold is expected to produce a quantity of parts Q during its life, then the cost to fabricate or purchase the special tooling is divided by Q. Note that Q may be much larger than the batch quantity Q_b produced during a given production run, so the tooling is expected to produce multiple batches during its life.

The cost rate to operate the work cell C_o consists of labor and equipment components:

$$C_o = C_L + C_{eq} \tag{1.7}$$

where C_L = cost rate of labor, \$/min; and C_{eq} = cost rate of equipment in the work cell, \$/min.

Equation (1.6) implies that the piece is produced in one unit operation, but as noted in the technological definition of manufacturing in Section 1.1.1, manufacturing is almost always carried out as a sequence of operations. The cost equation can be amended to reflect this reality by summing up the costs of each unit operation:

$$C_{pc} = C_m + \sum_{i=1}^{n_o} C_{oi} T_{pi} + \sum_{i=1}^{n_o} C_{ti} \tag{1.8}$$

where n_o = the number of unit operations in the manufacturing sequence for the part or product, and the subscript i is used to identify the costs and times associated with each operation, $i = 1, 2, \ldots n_o$. There are sometimes additional costs that must be included in certain processes, such as the cost of heating energy in casting and welding.

OVERHEAD COSTS The two cost rates, C_L and C_{eq}, include overhead costs, which consist of all of the expenses of operating the company other than material, labor, and equipment. Overhead costs can be divided into two categories: (1) factory overhead and (2) corporate overhead. Factory overhead consists of the costs of running the factory excluding materials, direct labor, and equipment. This overhead category includes plant supervision, maintenance, insurance, heat and light, and so forth. A worker who operates a piece of equipment may earn an hourly wage of \$15/hr, but when fringe benefits and other overhead costs are figured in, the worker may cost the company \$30/hr. Corporate overhead consists of company expenses not related to the factory, such as sales, marketing, accounting, legal, engineering, research and development, office space, utilities, and health benefits.[3] These functions are required in the company, but they are not directly related to the cost of manufacturing. On the other hand, for pricing the product, they must be added in, or else the company will lose money on every product it sells.

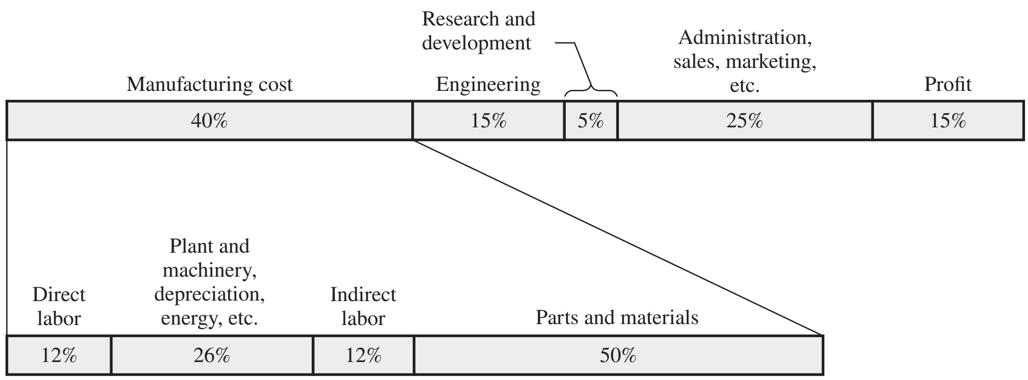
J. Black [1] offers some estimates of the typical costs associated with manufacturing a product, presented in Figure 1.12. Several observations are worth noting. First, total manufacturing costs constitute only 40% of the product's selling price. Corporate overhead expenses (engineering, research and development, administration, sales, marketing, etc.) add up to more than the manufacturing cost. Second, parts and materials are 50% of total manufacturing cost, so that is about 20% of selling price. Third, direct labor is only about 12% of manufacturing cost, so that is less than 5% of selling price. Factory overhead, which includes plant and machinery, depreciation, and energy at 26% and indirect labor at 12%, adds up to more than three times direct labor cost.

The issue of overhead costs can become quite complicated. A more complete treatment can be found in [6] and most introductory accounting textbooks. The approach in this book is simply to include an appropriate overhead expense in the labor and equipment cost rates. For example, the labor cost rate is

$$C_L = \frac{R_H}{60}\left(1 + R_{LOH}\right) \tag{1.9}$$

where C_L = labor cost rate, \$/min; R_H = worker's hourly wage rate, \$/hr; and R_{LOH} = labor overhead rate, %. If the worker is not utilized full time in the operation of interest, then the labor cost rate must be multiplied by the labor utilization rate for the operation.

EQUIPMENT COST RATE The cost of production equipment used in the factory is a ***fixed cost***, meaning that it remains constant for any level of production output. It is a capital investment that is made in the hope that it will pay for itself by producing a revenue stream that ultimately exceeds its cost. The company puts up the money to purchase the equipment as an initial cost, and then the equipment pays back over a certain number of years until it is replaced or disposed of. This is



■ **Figure 1.12** Typical breakdown of costs for a manufactured product [1].

[3] Health benefits, if available from the company, are fringe benefits that apply to all regular employees, and so they would be included in the direct labor overhead in the factory as well as the corporate offices.

different from direct labor and material costs, which are ***variable costs***, meaning they are paid for as they are used. Direct labor cost is a cost per time (\$/min), and material cost is a cost per piece (\$/pc).

In order to determine an equipment cost rate, the initial cost plus installation cost of the equipment must be amortized over the number of minutes it is used during its lifetime. The equipment cost rate is defined by the following:

$$C_{eq} = \frac{IC}{60NH}\left(1 + R_{OH}\right) \tag{1.10}$$

where C_{eq} = equipment cost rate, \$/min; IC = initial cost of the equipment, \$; N = anticipated number of years of service; H = annual number of hours of operation, hr/yr; and R_{OH} = applicable overhead rate for the equipment, %.

Example 1.1

Equipment Cost Rate

A production machine is purchased for an initial cost plus installation of \$500,000. Its anticipated life = 7 yr. The machine is planned for a two-shift operation, 8 hours per shift, 5 days per week, 50 weeks per year. The applicable overhead rate on this type of equipment = 35%. Determine the equipment cost rate.

Solution: The number of hours of operation per year H = 50(2)(5)(8) = 4000 hr/yr. Using Equation (1.10),

$$C_{eq} = \frac{500{,}000}{60(7)(4000)}(1 + 0.35) = \mathbf{\$0.402/min} = \mathbf{\$24.11/hr}$$

Example 1.2

Cycle Time and Cost per Piece

The production machine in Example 1.1 is used to sequentially produce a batch of parts that each has a starting material cost of \$2.35. Batch quantity = 100. The actual processing time in the operation = 3.72 min. Time to load and unload each workpiece = 1.60 min. Tool cost = \$4.40, and each tool can be used for 20 pieces before it is changed, which takes 2.0 minutes. Before production can begin, the machine must be set up, which takes 2.5 hours. Hourly wage rate of the operator = \$16.50/hr, and the applicable labor overhead rate = 40%. Determine (a) the cycle time for the piece, (b) average production rate when setup time is figured in, and (c) cost per piece.

Solution: (a) For Equation (1.1), processing time T_o = 3.72 min, part handling time T_h = 1.50 min, and tool handling time T_t = 2.00 min/20 = 0.10 min.

$$T_c = 3.72 + 1.60 + 0.10 = \mathbf{5.42\ min/pc}$$

(b) The average production time per piece, including setup time, is

$$T_p = \frac{2.5(60)}{100} + 5.42 = \mathbf{6.92\ min/pc}$$

Hourly production rate is the reciprocal of T_p, correcting for time units:

$$R_p = \frac{60}{6.92} = \mathbf{8.67\ pc/hr}$$

(c) The equipment cost rate from Example 1.1 is C_{eq} = \$0.402/min (\$24.11/hr). The labor rate is calculated as follows:

$$C_L = \frac{16.50}{60}(1+0.40) = \$0.385/\text{min}\,(\$23.10/\text{hr})$$

Cost of tooling C_t = 4.40/20 = \$0.22/pc. Finally, cost per piece is calculated as

$$C_{pc} = 2.35 + (0.385 + 0.402)(6.92) + 0.22 = \mathbf{\$8.02/pc}$$

Equipment reliability and scrap rate of parts are sometimes issues in production. Equipment reliability is represented by the term *availability* (denoted by the symbol A), which is simply the proportion of uptime of the equipment. For example, if A = 97%, then for every 100 hours of machine operation, one would expect on average that the machine would be running for 97 hours and be down for maintenance and repairs for 3 hours. Scrap rate refers to the proportion of parts produced that are defective. Let q denote the scrap rate. In batch production, more than the specified batch quantity is often produced to compensate for the losses due to scrap. Let Q = the required quantity of parts to be delivered and Q_o = the starting quantity. The following equation can be used to determine how many starting parts are needed, on average, to satisfy an order for Q finished parts:

$$Q_o = \frac{Q}{1-q} \tag{1.11}$$

Example 1.3

Scrap Rate

A customer has ordered a batch of 1000 parts to be produced by a machine shop. Historical data indicate that the scrap rate on this type of part = 4%. How many parts should the machine shop plan to make in order to account for this scrap rate?

Solution: Given Q = 1000 parts and q = 4% = 0.04, then the starting quantity is determined as follows:

$$Q_o = \frac{1000}{1-0.04} = \frac{1000}{0.96} = 1041.7 \text{ rounded to } \mathbf{1042\ starting\ parts}$$

Of course, in modern manufacturing practice, every effort is made to minimize scrap rate, with the goal being zero defects. Availability and scrap rate also figure into calculations of production rate and part cost, as demonstrated in the following example.

Example 1.4

Cycle Time and Cost per Piece

A high-production operation manufactures a part for the automotive industry. Starting material cost = \$1.75, and cycle time = 2.20 min. Equipment cost rate = \$42.00/hr, and labor cost rate = \$24.00/hr, including overhead costs in both cases. Availability of the production machine in this job = 97%, and the scrap rate of parts produced = 5%. Because this is a long-running job, setup time is ignored, and there is no tooling cost to be considered. (a) Determine the production rate and finished part cost in this operation. (b) If availability could be increased to 100% and scrap rate could be reduced to zero, what would be the production rate and finished part cost?

Solution: (a) Production rate, including effect of availability $R_p = \frac{60}{2.20}(0.97) = 26.45\text{ pc/hr}$

However, because of the 5% scrap rate, the production rate of acceptable parts is

$$R_p = 26.45(1-0.05) = \mathbf{25.13\ pc/hr}$$

Because of availability and scrap rate, the part cost is

$$C_{pc} = \frac{1.75}{(1-0.05)} + \frac{(24+42)}{(0.97)}\left(\frac{2.20}{60(1-0.05)}\right) = \mathbf{\$4.47/pc}$$

(b) If $A = 100\%$ and $q = 0$, $R_p = \frac{60}{2.20} = \mathbf{27.27\ pc/hr}$

Part cost $C_{pc} = 1.75 + (42 + 24)(2.20/60) = \mathbf{\$4.17/pc}$

This is an 8.5% increase in production rate and a 6.7% reduction in cost.

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