

Dedicated to our families, whose patience and  
support made this book possible.

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# Preface

Since the mid-2000s, manufacturing has undergone a rebirth in its development and research activities. With the recognition that manufacturing adds value to products, and wealth to national economies, governments around the world have been investing in their infrastructure and are now partnering with industry to bring new manufacturing capabilities to the global marketplace.

Manufacturing continues to be a dynamic activity, providing all-encompassing opportunities for contributions from several traditional disciplines. The proliferation of powerful software and Internet communication tools, especially their wireless capabilities, has made new approaches possible. The engineering terminology now includes such terms as Big Data, mass customization, cobots, and cybersecurity. Traditional manufacturing approaches and the materials involved are constantly being adjusted for ever-increasing efficiency and continuous improvements in performance.

In view of the advances being made in all aspects of manufacturing, the authors have continued their efforts to present a comprehensive, balanced, and, most importantly, an up-to-date coverage of the science, engineering, and technology of manufacturing. As in its previous editions, this text maintains the same number of chapters, while continuing to emphasize the interdisciplinary nature of all manufacturing activities, including complex interactions among materials, design, and manufacturing processes and operations.

Every attempt has been made to motivate and challenge students to understand and develop an appreciation of the vital importance of manufacturing in the modern global economy. The extensive questions and problems, at the end of each chapter, are designed to encourage students to explore viable solutions to a wide variety of challenges, giving them an opportunity to describe and assess the capabilities as well as limitations of all manufacturing processes and operations. These challenges include economic considerations and the competitive aspects in a global marketplace. The numerous examples and case studies throughout the book also help give students a perspective on real-world applications of the topics described throughout the book.

## What's New in This Edition

- This new 8th edition was developed as a Pearson eText and is filled with content and tools that help bring the course content to life. Pearson eText is a simple-to-use, mobile-optimized, personalized reading experience. It lets students add bookmarks, highlight, and take notes all in one place, even when offline. Instructors can customize the content to fit the way they teach their course and even share notes and resources with students directly through the eText. A loose-leaf print upgrade is available to students to purchase within the eText.
- The text has been thoroughly updated, with numerous new topics and illustrations relevant to all aspects of manufacturing. See the table on Page xxiv for specifics.
- Wherever appropriate, illustrations and examples have been replaced, indicating recent advances in manufacturing.
- The text contains more cross references to other relevant sections, tables, and illustrations in the book.
- The Questions, Qualitative Problems, Quantitative Problems, and Design/Projects at the end of each chapter have been expanded.
- The Bibliographies at the end of each chapter have been thoroughly *updated*.

- A Solutions Manual, available for use by instructors, has been expanded; it now provides MATLAB code for numerous problems, allowing instructors to easily be able change relevant parameters.
- Reflecting the rapid advances in additive manufacturing, Chapter 20 has been thoroughly revised to include the latest technologies.

New or expanded topics in this edition are:

Chapter	Topics
Introduction	Complexity of products; definition of Technology Readiness Level and Manufacturing Readiness Level, to show the stages in product development and manufacturing at scale; case study on three-dimensional printing of guitars; expansion and update of the section on Trends in Manufacturing.
1	ISO for grain size number.
5	Second- and third-generation high-strength steels; nano-structured steels; and new case study on high-strength steels in automobiles.
6	Addition of the Hall-Héarley process for aluminum manufacture; new sections on lithium and rare earth metals; a case study on Tesla automobile design and manufacture; metamaterials.
7	Electrically conductive and semi-conductive polymers; gels and aerogels.
8	Porous ceramics; graphene; carbon and graphite foam.
10	Freeze casting.
11	Integrated computational materials engineering (ICME); machining of sand molds; new case study on a die-cast magnesium liftgate.
13	Tailor-rolled blanks and tailored coils.
15	Friction stir extrusion.
16	Expansion of hot stamping of sheet metal; camera-based forming-limit diagrams; electrically assisted forming; new case study on single-point incremental forming.
17	Expansion of powder morphology effects.
20	Additive Manufacturing: mass customization; distributed manufacturing; composite AM; projection stereolithography; continuous liquid interface production (CLIPS); new case study on AM of athletic shoes; powder bed processes; JetFusion; wire and arc AM; bioprinting; architectural applications of AM; conformal cooling; expanded section on design for AM; topology optimization; economic considerations; new case study on the implications of powder reuse.
23-24	Design considerations in machining; new case study on machining aerospace parts from monolithic aluminum.
25	Stability lobes in chatter.
26	Engineered abrasives; new case study on gear grinding with engineered abrasives.
27	Electrolytic trepanning; shaped-tube electrolytic machining.
28	Roll-to-roll printing; flexible electronics; conductive and semi-conductive inks; rotogravure, flexography, flat and rotary screen printing; self-aligned imprint lithography; flexible hybrid electronics; new case study on a flexible Arduino.
29	Photonic integrated circuits; mesoscale manufacturing.
31	Friction stir spot welding; expansion of linear friction welding.
37	Microcontrollers; cloud computing; cybersecurity; gain scheduling; cobot; design considerations.
38	Cloud storage; expansion of ERP and MES.
39	Mass customization; Internet of Things; cloud computing; MTConnect; Big Data; digital twin.
40	Life-cycle engineering; energy use in manufacturing.

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# Chapter I

## General Introduction

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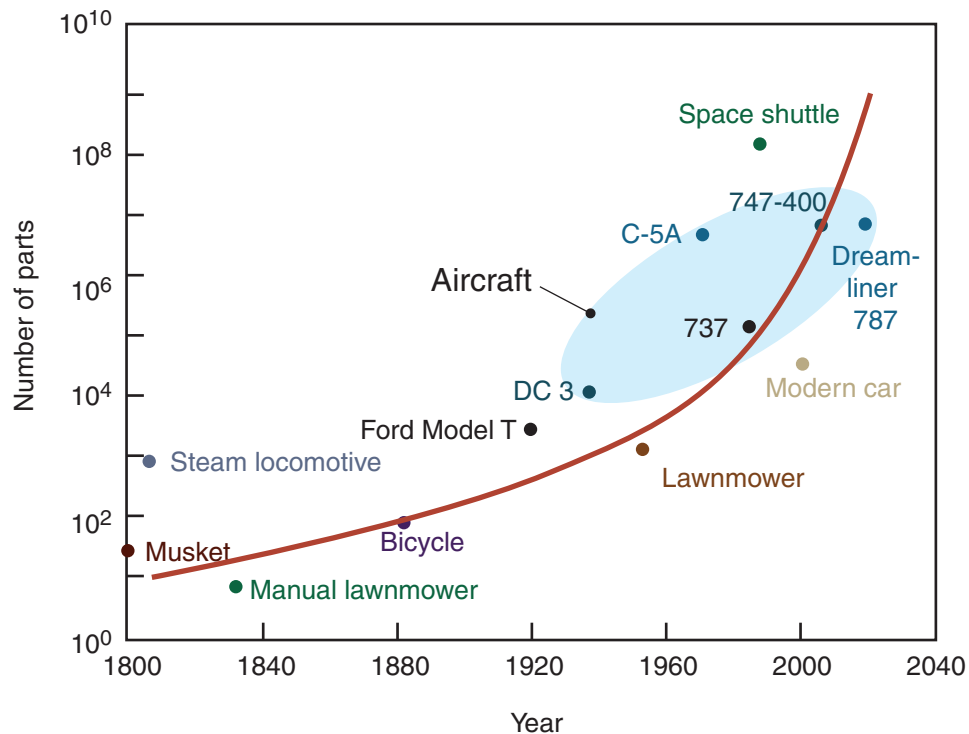
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## I.1 What is Manufacturing?

As you begin to read this chapter, take a few moments to inspect various objects around you: mechanical pencil, light fixture, chair, cell phone, and computer. You soon will note that all these objects, and their numerous individual components, are made from a variety of materials and have been produced and assembled into the products you now see. You also will note that some objects, such as a paper clip, nail, spoon, and door key, are made of a single component. However, as shown in Table I.1 and Fig. I.1, the vast majority of objects around us consist of numerous individual parts that are built and assembled by a combination of processes called **manufacturing** (Fig. I.2).





**Figure I.1:** Increasing complexity of products since the Industrial Revolution. *Source:* After J. Jeswiet.

The word *manufacture* first appeared in English in 1567, and is derived from the Latin *manu factus*, meaning made by hand. The word *manufacturing* first appeared in 1683, and the word *production*, which is often used interchangeably with the word *manufacturing*, first appeared sometime during the 15th century.

Manufacturing is making products. A manufactured product may, in turn, itself be used to make other products, such as (a) a large press, to shape flat sheet metal into appliances, (b) a drill, for producing holes, and (c) machinery, to produce a countless variety of individual items.

Nails, bolts, screws, nuts, paper clips, tires are *discrete products*, meaning individual items. By contrast, a spool of wire, metal or plastic tubing, and a roll of aluminum foil are *continuous products*, which are then cut into individual pieces of various lengths for specific purposes.

Because a manufactured item typically begins with raw materials, which are then subjected to a sequence of processes to make individual products, it has a certain *value*. Clay, for example, has some value as mined, but when made into pottery, electrical insulator, or cutting tool, it has *added value*. Similarly, a nail has a value over and above the cost of a short piece of wire from which it is made. Products such as computer chips, electric motors, medical implants, machine tools, and aircraft are known as *high-value-added products*.

**Table I.1:** Approximate Number of Parts in Products.

Common pencil	4
Rotary lawn mower	300
Grand piano	12,000
Automobile	15,000
Boeing 747–400	6,000,000



**Figure I.2:** John Deere tractor showing the variety of materials and processes incorporated. *Source:* Shutterstock/Nils Versemann.

**A Brief History of Manufacturing.** Manufacturing dates back to the period 5000 to 4000 B.C. (Table I.2). Thus, it is older than recorded history, which dates back to the Sumerians, around 3500 B.C. Primitive cave drawings, as well as markings on clay tablets and stones, needed (a) some form of a brush and some sort of pigment, as in the prehistoric cave paintings in Lascaux, France, estimated to be 16,000 years old; (b) a means of first scratching the clay tablets and then baking them, as in cuneiform scripts and pictograms of 3000 B.C.; and (c) simple tools for making incisions and carvings on the surfaces of stone, as in the hieroglyphs in ancient Egypt.

Manufacturing items for specific uses began with the production of household artifacts, typically made of wood, stone, or metal. The materials first used in making utensils and ornamental objects included gold, copper, and iron, followed by silver, lead, tin, bronze, and brass. The processing methods first employed involved mostly *casting* and *hammering*, because they were relatively easy to perform. Over the centuries, these simple processes gradually began to be developed into more and more complex operations, at increasing rates of production, and at higher levels of product quality. Note from Table I.2 that, for example, lathes for cutting screw threads already were available during the period from 1600 to 1700, but it was not until three centuries later that automatic screw machines were developed.

Although ironmaking began in about 1100 B.C. in the Middle East, a major milestone was the production of steel, in Asia, during the period 600 to 800 A.D. A wide variety of materials then began to be developed. Today, countless metallic and nonmetallic materials with unique properties are available, including *engineered materials* and other advanced materials. Among the available materials now are industrial ceramics, composite materials (often in the form of fiber reinforced plastics), and nanomaterials

Table I.2: Historical Development of Materials and Manufacturing Processes.

Period	Dates	Metals and casting	Various materials and composites	Forming and shaping	Joining	Tools, machining and manufacturing systems
Egypt: ~ 3100 B.C. to ~ 300 B.C. Greece: ~ 1100 B.C. to ~ 146 B.C. Roman Empire: ~ 500 B.C. to 476 A.D.	Before 4000 B.C.	Gold, copper, meteoric iron	Earthenware, glazing, natural fibers	Hammering		Tools of stone, flint, wood, bone, ivory, composite tools
	4000-3000 B.C.	Copper casting, stone and metal molds, lost-wax process, silver, lead, tin, bronze		Stamping, jewelry	Soldering (Cu-Au, Cu-Pb, Pb-Sn)	Corundum (alumina, emery)
	3000-2000 B.C.	Bronze casting and drawing, gold leaf	Glass beads, potter's wheel, glass vessels	Wire by slitting sheet metal	Riveting, brazing	Hoe making, hammered axes, tools for ironmaking and carpentry
	2000-1000 B.C.	Wrought iron, brass				
Middle Ages: ~ 476 to 1492. Renaissance: 14th to 16th centuries.	1000-1 B.C.	Cast iron, cast steel	Glass pressing and blowing	Stamping of coins	Forge welding of iron and steel, gluing	Improved chisels, saws, files, wood-working lathes
	1-1000 A.D.	Zinc, steel	Venetian glass	Armor, coining, forging, steel swords		Etching of armor
	1000-1500	Blast furnace, type metals, casting of bells, pewter	Crystal glass	Wire drawing, gold- and silver-smith work		Sandpaper, windmill-driven saw
Middle Ages: ~ 476 to 1492. Renaissance: 14th to 16th centuries.	1500-1600	Cast-iron cannon, tinplate	Cast plate glass, flint glass	Water power for metalworking, rolling mill for coinage strips		Hand lathe for wood
	1600-1700	Permanent-mold casting, brass from copper and metallic zinc	Porcelain	Rolling (lead, gold, silver), shape rolling (lead)		Boring, turning, screw-cutting lathe, drill press

(continues on next page)

**Table I.2:** Historical Development of Materials and Manufacturing Processes (continued).

Period	Dates	Metals and casting	Various materials and composites	Forming and shaping	Joining	Tools, machining and manufacturing systems
Industrial Revolution: ~ 1750 to 1850	1700-1800	Malleable cast iron, crucible steel (iron bars and rods)		Extrusion (lead pipe), deep drawing, rolling		
	1800-1900	Centrifugal casting, Bessemer process, electrolytic aluminum, nickel steel, babbitt, galvanized steel, powder metallurgy, open-hearth steel	Window glass from slit cylinder, light bulb, vulcanization, rubber processing, polyester, styrene, celluloid, rubber extrusion, molding	Steam hammer, steel rolling, seamless tube, steel-rail rolling, continuous rolling, electroplating		Shaping, milling, copying lathe for gunstocks, turret lathe, universal milling machine, vitrified grinding wheel
	1900-1920		Automatic bottle making, bakelite, borosilicate glass	Tube rolling, hot extrusion	Oxyacetylene; arc, electrical-resistance, and thermit welding	Geared lathe, automatic screw machine, hobbing, high-speed steel tools, aluminum oxide and silicon carbide (synthetic)
WWI	1920-1940	Die casting	Development of plastics, casting, molding, polyvinyl chloride, cellulose acetate, polyethylene, glass fibers	Tungsten wire from metal powder	Coated electrodes	Tungsten carbide, mass production, transfer machines
	1940-1950	Lost-wax process for engineering parts	Acrylics, synthetic rubber, epoxies, photosensitive glass	Extrusion (steel), swaging, powder metals for engineering parts	Submerged arc welding	Phosphate conversion coatings, total quality control
	1950-1960	Ceramic mold, nodular iron, semiconductors, continuous casting	Acrylonitrile-butadiene-styrene, silicones, fluorocarbons, polyurethane, float glass, tempered glass, glass ceramics	Cold extrusion (steel), explosive forming, thermochemical processing	Gas metal arc, gas tungsten arc, and electroslag welding; explosion welding	Electrical and chemical machining, automatic control.

(concludes on next page)

**Table I.2:** Historical Development of Materials and Manufacturing Processes (concluded).

Period	Dates	Metals and casting	Various materials and composites	Forming and shaping	Joining	Tools, machining and manufacturing systems
Space Age	1960-1970	Squeeze casting, single-crystal turbine blades	Acetals, polycarbonate, cold forming of plastics, reinforced plastics, filament winding	Hydroforming, hydrostatic extrusion, electroforming	Plasma-arc and electron-beam welding, adhesive bonding	Titanium carbide, synthetic diamond, numerical control, integrated circuit chip
	1970-1990	Compacted graphite, vacuum casting, organically-bonded sand, automation of molding and pouring, rapid solidification, metal-matrix composites, semi-solid metalworking, amorphous metals, shape-memory alloys	Adhesives, composite materials, semiconductors, optical fibers, structural ceramics, ceramic-matrix composites, biodegradable plastics, electrically-conducting polymers	Precision forging, isothermal forging, superplastic forming, dies made by computer-aided design and manufacturing, net-shape forging and forming, computer simulation	Laser beam, diffusion bonding (also combined with superplastic forming), surface-mount soldering	Cubic boron nitride, coated tools, diamond turning, ultraprecision machining, computer-integrated manufacturing, industrial robots, machining and turning centers, flexible manufacturing systems, sensor technology, automated inspection, computer simulation and optimization
Information Age	1990-2000	Rheocasting, computer-aided design of molds and dies, rapid tooling	Nanophase materials, metal foams, high-temperature superconductors, machinable ceramics, diamond-like carbon	Additive manufacturing, rapid tooling, environmentally-friendly metalworking fluids	Friction stir welding, lead-free solders, laser butt-welded (tailored) sheet-metal blanks	Micro- and nanofabrication, LIGA, dry etching, linear motor drives, artificial neural networks, six sigma
	2000-2010s	TRIP and TWIP steels	Carbon nanotubes, graphene	Single point incremental forming, hot stamping, electrically assisted forming	linear friction welding	Digital manufacturing, three-dimensional computer chips, blue-arc machining, soft lithography, flexible electronics



that are now used in an extensive variety of products, ranging from prosthetic devices and computers to supersonic aircraft.

Until the **Industrial Revolution**, which began in England in the 1750s (also called the *First Industrial Revolution*), goods had been produced in batches, which required high reliance on manual labor in all phases of production. The *Second Industrial Revolution* is regarded, by some, as having begun in the mid-1900s, with the development of solid-state electronic devices and computers (Table I.2). **Mechanization** began in England and other countries of Europe with the development of textile machinery and machine tools for cutting metal. Mechanization soon moved to the United States, where it continued to be further developed.

A major advance in manufacturing began in the early 1800s, with the design, production, and use of **interchangeable parts**, conceived by the American manufacturer and inventor E. Whitney (1765–1825). Prior to the introduction of interchangeable parts, much hand fitting was necessary, because no two parts could be made exactly alike. By contrast, it is now taken for granted that a broken bolt can easily be replaced with an identical one produced decades after the original was made. Further developments soon followed, resulting in countless consumer and industrial products which we now cannot imagine being without.

Beginning in the early 1940s, several milestones were reached in all aspects of manufacturing, as can be observed by a review of Table I.2. Note particularly the progress that has been made during the 20th century, as compared with those achieved during the 40-century long period from 4000 B.C. to 1 B.C.

For example, in the Roman Empire (around 500 B.C. to 476 A.D.), factories were available for mass production of glassware; the methods used were generally very slow, and much manpower was required in handling the parts and operating the machinery. Today, production methods have advanced to such an extent that (a) aluminum beverage cans are made at rates of more than 500 per minute, with each can costing about four cents to make; (b) holes in sheet metal can be punched at rates of 800 holes per minute; and (c) light bulbs are made at rates of more than 2000 bulbs per minute, each costing less than one dollar.

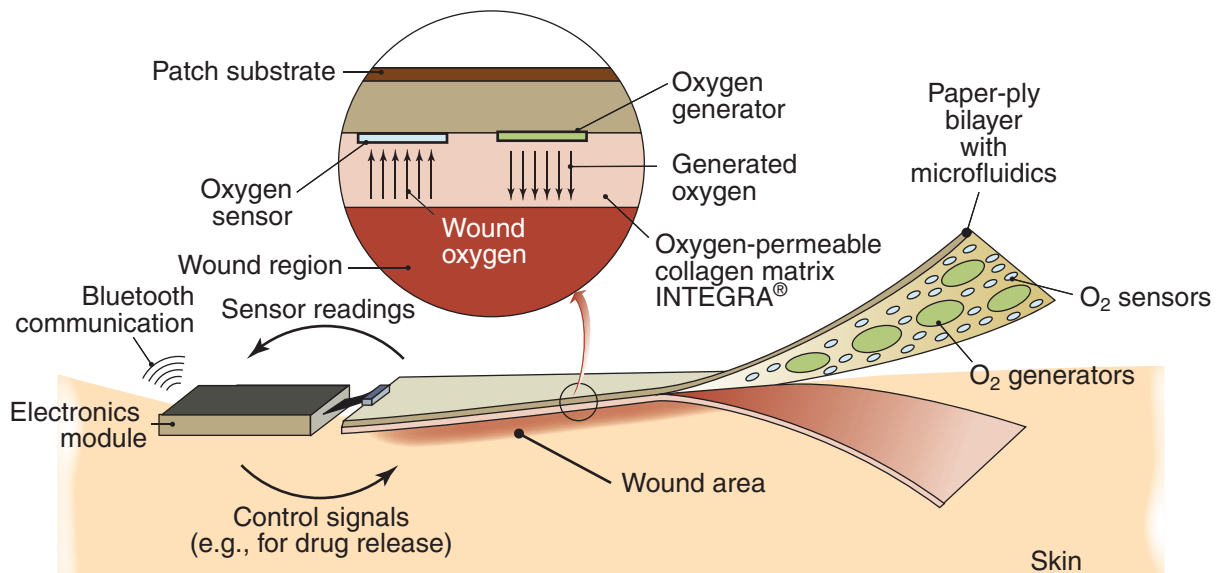
The period from the 1940s to the 1990s was characterized by *mass production* and expanding *global* markets. Initially, the United States had a dominant position, as it was the only developed nation with an intact infrastructure following World War II; however, this advantage dissipated by the 1960s. The *quality* revolution began to change manufacturing in the 1960s and 1970s, and in the 1980s, programmable computers became widely used.

The **digital manufacturing** era began around 1990. As a fundamental change in manufacturing operations, powerful computers and software are now fully integrated across the design and manufacturing enterprise. Advances in communications, some Internet-based, have led to further improvements in organizations and their capabilities. The effects are most striking when considering the origin and proliferation of **additive manufacturing**, described in Chapter 20.

Prior to 1990, the prototype of a part could be produced only through intensive effort and costly manufacturing approaches, requiring significant operator skill. Today, a part can first be drafted in a CAD program, then produced generally in a matter of minutes or hours (depending on size and part complexity) without the need for hard tools or skilled labor. Prototyping systems have become more economical, faster, and with improved raw materials. The term *digital manufacturing* has been applied to reflect the notion that manufacturing parts and components can take place completely through such computer-driven CAD and production machinery.

Recent innovations are the proliferation of communications protocols, sensors and controls throughout the manufacturing enterprise. Referred to as **Industry 4.0** (Section 37.2.2) or *Digital Manufacturing*, some of the key developments are the following:

1. Sensors and smart device designs can be printed from conductive and insulate inks, or use very thin silicon integrated circuits in flexible hybrid designs (Fig. I.3). These low-cost devices include communication ability and are central to the **Internet of Things** (Section 39.8.1).
2. Machines can be monitored at all times, using Internet-based communications protocols such as MTConnect, so that precise information is available at all times for every machine in an organization.
3. The wide application of sensors to all aspects of manufacturing has led to the development of **Big Data**, where trends and conditions of manufacturing systems can be accurately measured at all times.



**Figure I.3:** A flexible hybrid electronic wound care system (see Section 28.15). The device integrates communication ability (in this case a Bluetooth ability), sensors to detect the oxygen levels at the wound, and oxygen generating devices to increase oxygen level to optimize healing. These devices use combinations of printed electronic devices and silicon-based integrated circuits. *Source:* Courtesy of NextFlex.

4. Machine learning algorithms, and the incorporation of physics-based mathematical models of manufacturing processes and systems, has led to the ability to apply advanced controls to the manufacturing enterprise.
5. Advanced models of manufacturing processes, combined with the detailed measurement of the manufacturing and service environment of a product (Big Data), lead to the computer-based representation of the product, referred to as a *digital twin*. The digital twin represents a virtual model of the part, and accurate performance models applied to the virtual twin can predict failure or required service of the actual part.

These developments are a natural extension of the computer revolution that started in the 1990s, and developments are certain to continue.

## I.2 Product Design and Concurrent Engineering

Product design involves the creative and systematic prescription of the shape and characteristics of a product to achieve specified objectives, while simultaneously satisfying several important constraints. Design is a critical activity, because it has been estimated that as much as 80% of the cost of product development and manufacturing is determined by the decisions made in the *initial* stages of design. The product design process has been studied extensively; it is briefly introduced here because of the strong interactions among manufacturing and design activities.

Innovative approaches are essential in successful product design, as are clearly specified functions and a clear statement of the performance expected of the product. The market for a product, which may be new or a modified version of an existing product, and its anticipated use or uses, also must be clearly defined at this stage. This aspect also involves the assistance of market analysts and sales personnel who will bring valuable and timely input to the manufacturer, especially regarding market needs and trends.

**Table I.3:** Definitions of Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL).

TRL	Description	MRL	Description
1	Basic principles observed and reported	1	Manufacturing feasibility assessed
2	Technology concept and/or application formulated	2	Manufacturing concepts defined
3	Analytical and experimental critical function and/or characteristic proof of concept	3	Manufacturing concepts developed
4	Component and/or breadboard validation in a laboratory environment	4	Capability to produce the technology in a laboratory environment
5	Component or breadboard validation in a relevant environment	5	Capability to produce prototype components in a production relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment	6	Capability to produce a prototype system or subsystem in a production relevant environment
7	System prototype demonstration in an operational environment	7	Capability to produce systems, subsystems or components in a production representative environment
8	Actual system completed and qualified through test and demonstration	8	Pilot line capability demonstrated; Ready to begin low rate initial production
9	Actual system proven through successful mission operations	9	Low rate production demonstrated; capability in place to begin full rate production

**Technology Readiness Level and Manufacturing Readiness Level.** Product development generally follows the flow outlined in Table I.3. *Technology readiness level* (TRL) and *Manufacturing readiness level* (MRL) are measures of a products ability to be produced, marketed, and sold. In practice, all technologies must progress from some starting point up to a TRL and MRL of 9. A new scientific discovery or a product idea begins at a TRL of 1, and it may or may not ever be suitable for commercial application. New versions of existing products may start at some higher TRL or MRL level, but the flow of its development is always the same.

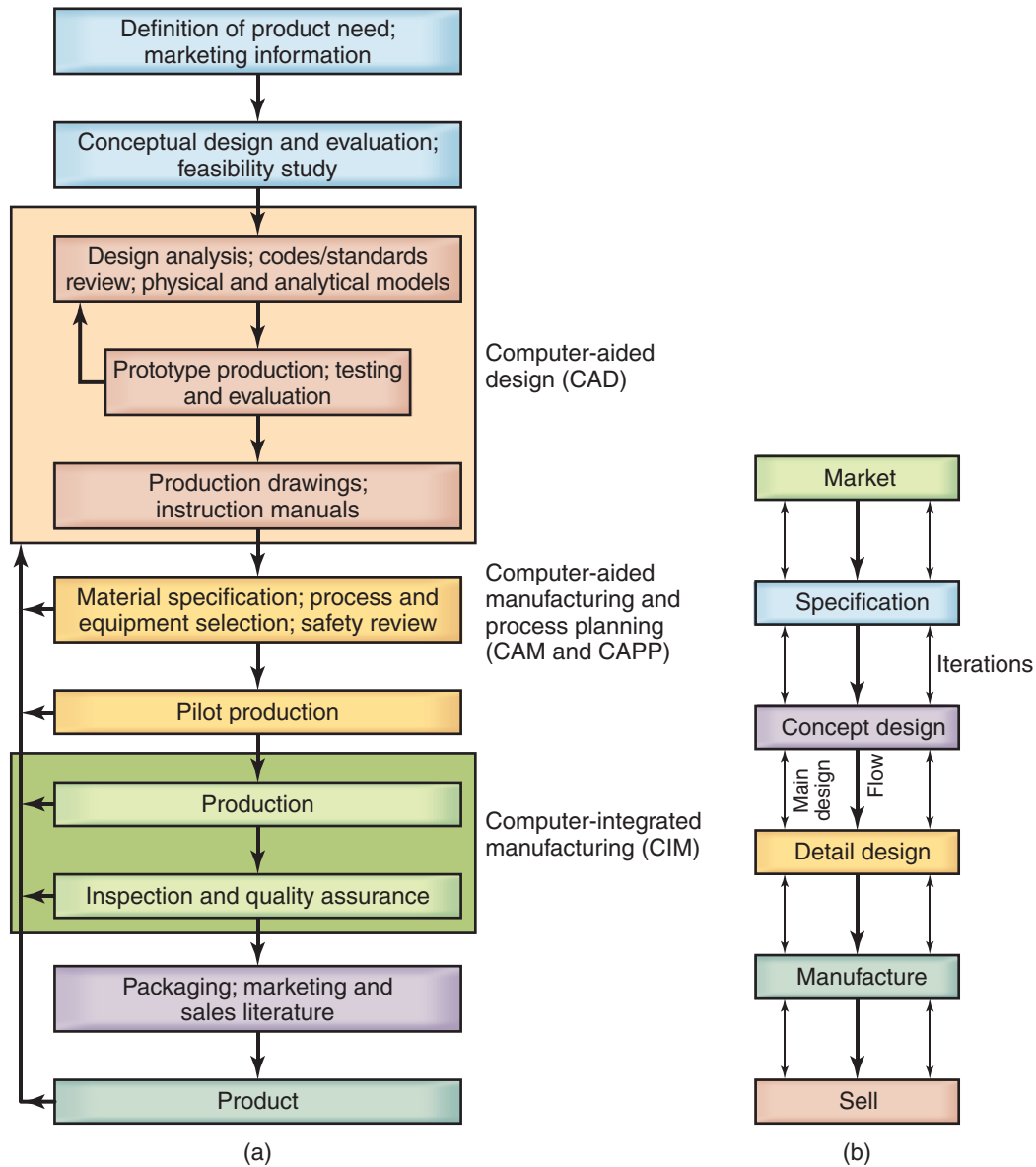
Note that each stage of a products development typically requires different skills and resources. Demonstrating a new concept in a laboratory environment (TRL 3) and demonstrating it in a new system in a real environment (TRL 7) are very different tasks. Similarly, producing a laboratory prototype (MRL 4) is very different from demonstrating manufacturing strategies for producing a product at scale (MRL 7), which is also very different from having a production facility in place.

**The Design Process.** Traditionally, design and manufacturing activities took place *sequentially*, as shown in Fig. I.4a. This methodology may, at first, appear to be straightforward and logical; in practice, however, it is wasteful of resources. Consider the case of a manufacturing engineer who, for example, determines that, for a variety of reasons, it would be more desirable to (a) use a different material, such as a polymer or a ceramic instead of metal; (b) use the same material but in a different condition, such as a softer instead of a harder or one with a smoother surface finish; or (c) modify the design of a component in order to make it easier, faster, and less costly to manufacture. Note that these decisions must take place at the material-specification stage (the sixth box from the top in Fig. I.4a).

Each of the modifications just described will necessitate a repeat of the design analysis stage (the third box from the top in Fig. I.4a) and the subsequent stages. This approach is to ensure that the product will still meet all specified requirements and will function satisfactorily. A later change from, say, a forged, cast, or machined component will, likewise, necessitate a repeat analysis. Such iterations obviously waste both time and the resources of a company.

**Concurrent Engineering.** Driven primarily by the consumer electronics industry, a continuing trend has been to bring products to the marketplace as rapidly as possible, so as to gain a higher percentage share of the market and thus higher profits. An important methodology aimed at achieving this end is *concurrent engineering*, which involves the product-development approach shown in Fig. I.4b.





**Figure I.4:** (a) Chart showing various steps involved in *traditional* design and manufacture of a product. Depending on the complexity of the product and the type of materials used, the time span between the original concept and the marketing of the product may range from a few months to several years. (b) Chart showing general product flow in *concurrent engineering*, from market analysis to marketing the product. *Source:* After S. Pugh.

Although this concept still has the same general product-flow sequence as in the traditional approach, shown in Fig. I.4a, it now includes several deliberate modifications. From the earliest stages of product design and engineering, all relevant disciplines are now *simultaneously considered*. As a result, any iterations that may have to be made will require a smaller effort, resulting in much less wasted time than occurs in the traditional approach to design. It should be apparent that a critical feature of this approach is the recognition of the importance of *communication* among and within all disciplines.

Concurrent engineering can be implemented in companies large or small, which is particularly significant because 98% of all U.S. manufacturing companies have fewer than 500 employees; the companies are generally referred to as *small businesses* or *small manufacturing enterprises* (SMEs). As an example of the benefits of concurrent engineering, one automotive company reduced the number of components in one of its engines by 30%, decreased the engine weight by 25%, and reduced its manufacturing time by 50%.

**Life Cycle.** In concurrent engineering, the design and manufacture of products are integrated, with a view toward optimizing all elements involved in the *life cycle* of the product (see Section I.4). The life cycle of a new product generally consists of four stages:

1. Product start-up
2. Rapid growth of the product in the marketplace
3. Product maturity
4. Decline.

Consequently, **life-cycle engineering** requires that the *entire life* of a product be considered, beginning with the design stage and on through production, distribution, use, and, finally, recycling or the disposal of the product.

**Role of Computers in Product Design.** Typically, product design first requires the preparation of *analytical* and *physical models* of the product, for the purposes of visualization and engineering analysis. Although the need for such models depends on product complexity, constructing and studying these models are now done using **computer-aided design** (CAD) and **computer-aided engineering** (CAE) techniques.

CAD systems are capable of rapid and complete analyses of designs, whether it is a simple part in large and complex structures. The Boeing 777 passenger airplane, for example, was designed completely by computers, in a process called **paperless design**, with 2000 workstations linked to eight design servers. Unlike previous mock-ups of aircraft, no prototypes or mock-ups were built and the 777 was built and assembled *directly* from the CAD/CAM software that had been developed.

Through computer-aided engineering, the performance of structures subjected, for example, to static or fluctuating loads or to temperature gradients also can be simulated, analyzed, and tested, rapidly and accurately. The information gathered is stored, and it can be retrieved, displayed, printed, and transferred anytime and anywhere within an organization. Design modifications can be made and optimized directly, easily, and at any time.

**Computer-aided manufacturing** involves all phases of manufacturing, by utilizing and processing large amounts of information on materials and processes gathered and stored in the organization's database. Computers greatly assist in such tasks as (a) programming for numerical-control machines and for robots for material-handling and assembly operations (Chapter 37), (b) designing tools, dies, molds, fixtures, and work-holding devices (Parts II, III, and IV), and (c) maintaining quality control throughout the total operation (Chapter 36).

On the basis of the models developed and analyzed, product designers finalize the geometric features of each of the product's components, including specifying their dimensional tolerances and surface characteristics. Because all components, regardless of their size, eventually have to be *assembled* into the final product, dimensional tolerances are a major consideration in manufacturing (Chapter 35). The models developed also allow the specification of the mechanical and physical properties required, which in turn affect the selection of materials. (Section I.5).

**Prototypes.** A *prototype* is a physical model of an individual component or product. The prototypes developed are carefully reviewed for possible modifications to the original design, materials, or production methods. An important and continuously evolving technology is **additive manufacturing** (Chapter 20). Using CAD/CAM and various specialized technologies, designers make prototypes rapidly and at low cost, from a variety of metallic or nonmetallic materials.

Additive manufacturing significantly reduces costs and associated product-development times. The technology has now advanced to such a level that it is used for low-volume economical production of a variety of *actual and functional parts*.

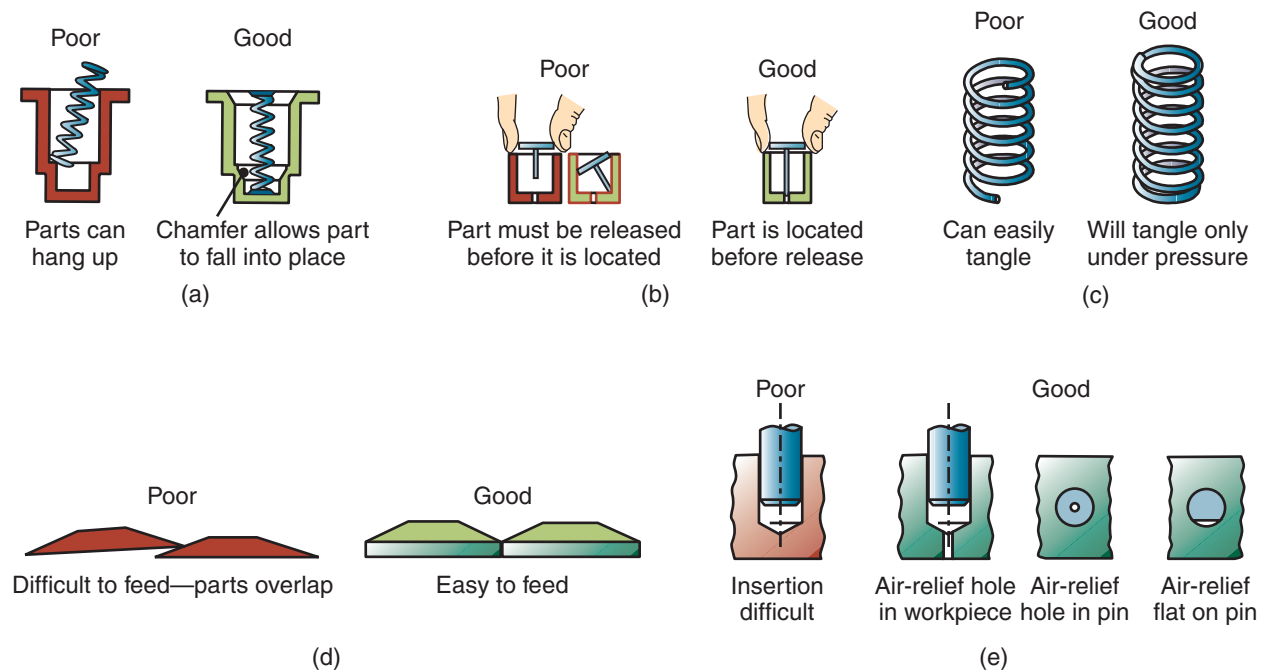


**Figure I.5:** Guitars produced through additive manufacturing. (a) Spider design being removed from a powder bed. Note that the support material, or *cake*, has some strength and needs to be carefully removed. (b) Finished Spider guitars. *Source:* Courtesy of O. Diegel.

### Case Study I.1 Three-dimensional Printing of Guitars

The design flexibility of additive manufacturing is illustrated by the custom guitars produced by ODD, Inc. These guitars are designed in CAD programs, with full artistic freedom to pursue innovative designs; those in Fig. I.5 are only a selection of the many available. The CAD file is then sent to a three-dimensional printer, using the selective laser sintering process and produced from nylon (Duraform PA). As printed, the guitars are white; they are first dyed to a new base color, then hand-painted and sprayed with a clear satin lacquer. The customer-specified hardware (pickups, bridges, necks, tuning heads, etc.) are then mounted to produce the electric guitar.

**Virtual Prototyping.** This is a software-based method that uses advanced graphics and virtual-reality environments to allow designers to view and examine a part in detail. This technology, also known as **simulation-based design**, uses CAD packages to render a part such that, in a 3-D interactive virtual environment, designers can observe and evaluate the part as it is being developed. Virtual prototyping has been gaining importance, especially because of the availability of low-cost computers and simulation and analysis tools.



**Figure I.6:** Redesign of parts to facilitate assembly. *Source:* After G. Boothroyd and P. Dewhurst.

### I.3 Design for Manufacture, Assembly, Disassembly, and Service

**Design for manufacture (DFM)** is a *comprehensive* approach to integrating the design process with production methods, materials, process planning, assembly, testing, and quality assurance. DFM requires a fundamental understanding of (a) the characteristics and capabilities of materials, manufacturing processes, machinery, equipment, and tooling, and (b) variability in machine performance, dimensional accuracy and surface finish of the workpiece, processing time, and the effect of processing methods employed on product quality. Establishing *quantitative relationships* is essential in order to be able to analyze and optimize a design, for ease of manufacturing and assembly at the lowest cost.

The concepts of **design for assembly (DFA)**, **design for manufacture and assembly (DFMA)**, and **design for disassembly (DFD)** are all important considerations in manufacturing. Methodologies and computer software are available for design for assembly, utilizing 3-D conceptual designs and solid models. Subassembly, assembly, and disassembly times and costs are minimized, while maintaining product integrity and performance. A product which is easy to assemble is usually also easy to disassemble.

*Assembly* is an important phase of manufacturing, requiring considerations of the ease, speed, and cost of putting together the numerous individual components of a product (Fig. I.6). Assembly costs in manufacturing can be substantial, typically ranging from 20% to 60% of the total product cost. *Disassembly* of a product, for such activities as maintenance, servicing, and eventual recycling of its individual components, is an equally important consideration.

As described in Part VI, there are several methods of assembly of components, including the use of a wide variety of fasteners, adhesives, or joining techniques, such as welding, brazing, or soldering. As is the case in all types of manufacturing, each of these assembly operations has its own specific characteristics, times, advantages, limitations, associated costs, and design considerations. Individual parts may be assembled by hand or by a variety of automatic equipment and industrial robots. The choice depends on several

factors, such as product complexity, number of components to be assembled, care and protection required to prevent damage to the parts, and relative cost of labor compared with the cost of machinery required for automated assembly.

**Design for Service.** In addition to design for assembly and for disassembly, *design for service* is an important aspect of product design. Products often have to be disassembled, to varying degrees, in order to service them and, if necessary, repair them. The design should take into account the concept that, for ease of access, components that are most likely to be in need of servicing be placed, as much as possible, at the *outer layers* of the product. This methodology can be appreciated by anyone who has had the experience of servicing machinery.

## I.4 Environmentally Conscious Design, Sustainable Manufacturing, and Product Life Cycle

In the United States alone, more than 30 billion kg of plastic products are discarded each year, and 62 billion kg of paper products. Every three months, U.S. industries and consumers discard enough aluminum to rebuild the country's commercial air fleet.

Globally, countless tons of automobiles, televisions, appliances, and computers are discarded each year. Metalworking fluids, such as lubricants and coolants, and fluids and solvents, such as those used in cleaning manufactured products, can pollute the air and waters, unless they are recycled or disposed of properly.

Likewise, there are numerous *byproducts* from manufacturing plants: (a) sand with additives from foundries; (b) water, oil, and various other fluids from heat-treating and facilities; (c) slag from foundries and welding operations; and (d) a wide variety of metallic and nonmetallic scrap produced in such operations as sheet forming, casting, and molding. Consider also the various effects of water and air pollution, acid rain, ozone depletion, hazardous wastes, landfill seepage, and global warming. Recycling efforts have gained increasing momentum over the years; aluminum cans, for example, are now recycled at a rate of 67% and plastics at around 9%.

Note that, as indicated below, the term *discarding* suggests that the product has reached the end of its useful life; however, it does not necessarily indicate that it has to be dumped into landfills. The particular manufacturing process and the operation of machinery can each have a significant environmental impact. Manufacturing operations generally produce some waste, such as:

1. Chips from machining and trimmed materials from sheet forming, casting, and molding operations
2. Slag from foundries and welding operations
3. Additives in sand used in sand-casting operations
4. Hazardous waste and toxic materials used in various products
5. Lubricants and coolants in metalworking and machining operations
6. Liquids from such processes as heat treating and plating
7. Solvents from cleaning operations
8. Smoke and pollutants from furnaces and gases from burning fossil fuels.

The adverse effects of these activities, their damage to the environment and to the Earth's ecosystem, and, ultimately, their effect on the quality of human life are now widely recognized. Major concerns involve global warming, greenhouse gases (carbon dioxide, methane, and nitrous oxide), acid rain, ozone depletion, hazardous wastes, water and air pollution, and contaminant seepage into water sources. One measure

of the adverse impact of human activities is called the **carbon footprint**, which quantifies the amount of greenhouse gases produced in our daily activities.

The term **sustainable design and manufacturing** has become in common usage in all industrial activities, with major emphasis on **design for the environment** (DFE). Also called **environmentally conscious design and manufacturing** and **green design**, this approach considers *all* possible adverse environmental impacts of materials, processes, operations, and products, so that they can all be taken into account at the earliest stages of their design and production.

These goals also have led to the concept of **design for recycling** (DFR). Recycling may involve one of two basic activities:

- **Biological cycle:** Organic materials degrade naturally, and in the simplest version of a biological cycle, they lead to new soil that can sustain life. Thus, product design involves the use of organic materials, as well as ensuring that products function well for their intended life and can then be safely disposed of.
- **Industrial cycle:** The materials in the product are recycled and reused continuously. To demonstrate the economic benefits of this approach, it has been estimated that producing aluminum from scrap, instead of from bauxite ore, reduces production costs by as much as 66% and reduces energy consumption and pollution by more than 90%.

A basic principle of *design for recycling* is the use of materials and product design features that facilitate biological or industrial recycling. In the U.S. automotive industry, for example, about 75% of automotive parts (mostly metal) are now recycled, and there are continuing plans to recycle the rest as well, including plastics, glass, rubber, and foam. About 80% of the 300 million discarded automobile tires are reused in various ways.

**Cradle-to-cradle Production.** Also called *cradle-to-cradle* (C2C), manufacturing considers the impact of each stage of a product's life cycle, from the time natural resources are mined and processed into raw materials, through each stage of manufacturing products, their use and, finally, recycling. *Cradle-to-grave* production, also called *womb-to-tomb* production, has a similar approach, but it does not necessarily consider or take on the responsibility of recycling.

Cradle-to-cradle production emphasizes

1. Sustainable and efficient manufacturing activities, using clean technologies
2. Waste-free production
3. Using recyclable and nonhazardous materials
4. Reducing energy consumption
5. Using renewable energy, such as wind, solar, and ocean waves
6. Maintaining ecosystems by minimizing the environmental impact of all manufacturing activities
7. Using materials and energy sources that are available locally, so as to reduce energy use associated with their transport which, by and large, has an inherently high carbon footprint
8. Continuously exploring the reuse and recycling of materials, and perpetually trying to recirculate materials; also included is investigating the composting of materials whenever appropriate or necessary, instead of dumping them into landfills.

**Guidelines for Sustainable Design and Manufacturing.** In reviewing the activities described thus far, it can be noted that there are overarching relationships among the basic concepts of DFMA, DFD, DFE, and DFR. These relationships can be summarized as guidelines, rapidly accepted worldwide:

1. Reduce waste of materials, by refining product design, reducing the amount of materials in products, and select manufacturing processes that minimize scrap (such as forming instead of machining).
2. Reduce the use of hazardous materials in products and processes.
3. Investigate manufacturing technologies that make environmentally friendly and safe products and by-products.
4. Make improvements in methods of recycling, waste treatment, and reuse of materials.
5. Minimize energy use; whenever possible, encourage the use of renewable sources of energy. Select materials can have a major impact on the latent energy in products, as described in Section 40.5.
6. Encourage recycling by using materials that are a part of either industrial or biological cycling, but not both in the same product. Ensure proper handling and disposal of all waste of materials that are used in products, but are not appropriate for industrial or biological cycling.

## I.5 Selection of Materials

An increasingly wide variety of materials are now available, each type having its own properties and manufacturing characteristics, advantages, limitations, and costs (Part I). The selection of materials for products (consumer or industrial) and their components is typically made in consultation with materials engineers; design engineers may also be sufficiently experienced and qualified to assist.

The general types of materials used, either individually or in combination with other materials, are the following:

- **Ferrous metals:** Carbon, alloy, stainless, and tool and die steels (Chapter 5)
- **Nonferrous metals:** Aluminum, magnesium, copper, nickel, titanium, superalloys, refractory metals, beryllium, zirconium, low-melting-point alloys, and precious metals (Chapter 6)
- **Plastics (polymers):** Thermoplastics, thermosets, and elastomers (Chapter 7)
- **Ceramics, glasses, glass ceramics, graphite, diamond, and diamond-like materials** (Chapter 8)
- **Composite materials:** Reinforced plastics and metal-matrix and ceramic-matrix composites (Chapter 9)
- **Nanomaterials** (Section 8.8)
- **Shape-memory alloys** (*smart materials*), **amorphous alloys, semiconductors, and superconductors** (Chapters 6, 18 and 28)

As new developments continue, selection of an appropriate material for a particular application from a very large variety of materials has become even more challenging. Furthermore, there are continuously shifting trends in the substitution of materials, driven not only by technological considerations, but also by economics.

**Properties of Materials.** *Mechanical properties* of interest in manufacturing generally include strength, ductility, hardness, toughness, elasticity, fatigue, and creep resistance (Chapter 2). *Physical properties* are density, specific heat, thermal expansion and conductivity, melting point, and electrical and magnetic properties (Chapter 3). Optimum designs often require a consideration of a combination of mechanical and physical properties. A typical example is the *strength-to-weight* and *stiffness-to-weight* ratios of materials for minimizing the weight of structural members. Weight minimization is particularly important for aerospace and automotive applications, in order to improve performance and fuel economy.



**Table I.4:** General Manufacturing Characteristics of Various Materials.

Alloy	Castability	Weldability	Machinability
Aluminum	E	F	E–G
Copper	G–F	F	G–F
Gray cast iron	E	D	G
White cast iron	G	VP	VP
Nickel	F	F	F
Steels	F	E	F
Zinc	E	D	E

*Note:* E, excellent; G, good; F, fair; D, difficult; VP, very poor. The ratings shown depend greatly on the particular material, its alloys, and its processing history.

*Chemical properties* include oxidation, corrosion, degradation, toxicity, and flammability. These properties play a significant role under both hostile (such as corrosive) and normal environments. *Manufacturing properties* indicate whether a particular material can be cast, formed, shaped, machined, joined, and heat treated with relative ease. As Table I.4 illustrates, no one material has the same manufacturing characteristics. Another important consideration is *appearance*, which includes such characteristics as surface texture, color, and feel, all of which can play a significant role in a product's acceptance by the public.

**Availability.** As emphasized throughout this book, the economic aspect of material selection is as important as technological considerations (Chapter 40). Availability of materials is a major concern in manufacturing. Furthermore, if materials are not available in the shapes needed, dimensions, surface texture, and quantities, materials substitution or additional processing of a particular material may well be required, all of which can contribute significantly to product cost.

*Reliability of supply* is important in order to meet production schedules. In automotive industries, for example, materials *must* arrive at a plant at appropriate time intervals (see also *just in time*, Section I.7). Reliability of supply is also important, considering the fact that most countries import numerous raw materials. The United States, for example, imports most of the cobalt, titanium, chromium, aluminum, nickel, natural rubber, and diamond that it needs. A country's self-reliance on resources, especially energy, is an often-expressed political goal, but challenging to achieve. Geopolitics (defined briefly as the study of the influence of a nation's physical geography on its foreign policy) also must thus be a consideration, particularly during periods of global instability or hostility.

**Service Life.** Everyone has directly experienced a shortened service life of a product, which often can be traced to one or more of the following: (a) improper selection of materials, (b) improper selection of production methods, (c) insufficient control of processing variables, (d) defective raw materials or parts, or manufacturing-induced defects, (e) poor maintenance of machinery and equipment, and (f) improper use of the product.

Generally, a product is considered to have failed when it

- stops functioning, due to the failure of one or more of its components, such as a broken shaft, gear, turbine blade, or a burned-out electric motor
- does not function properly or perform within its required specifications, due, for example, to worn gears or bearings
- becomes unreliable or unsafe for further use, as in the erratic behavior of a switch, poor connections in a printed-circuit board, or delamination of a composite material.

**Material Substitution in Products.** For a variety of reasons, numerous substitutions are often made in materials, as evidenced by a routine inspection and comparison of common products, such as home appliances,



sports equipment, and automobiles. As a measure of the challenges faced in material substitution, consider the following examples: (a) metal vs. wooden handle for a hammer, (b) aluminum vs. cast-iron lawn chair, (c) copper vs. aluminum electrical wire, and (d) alloy steel vs. titanium submarine hull.

The following two case studies describe some details of the major factors involved in material substitution in common products.

### Case Study I.2 U.S. Pennies

Billions of pennies are produced and put into circulation each year by the U.S. Mint. The materials used have undergone significant changes throughout their history, largely because of periodic material shortages and the resulting fluctuating cost of appropriate raw materials. The following table shows the chronological development of material substitutions in pennies:

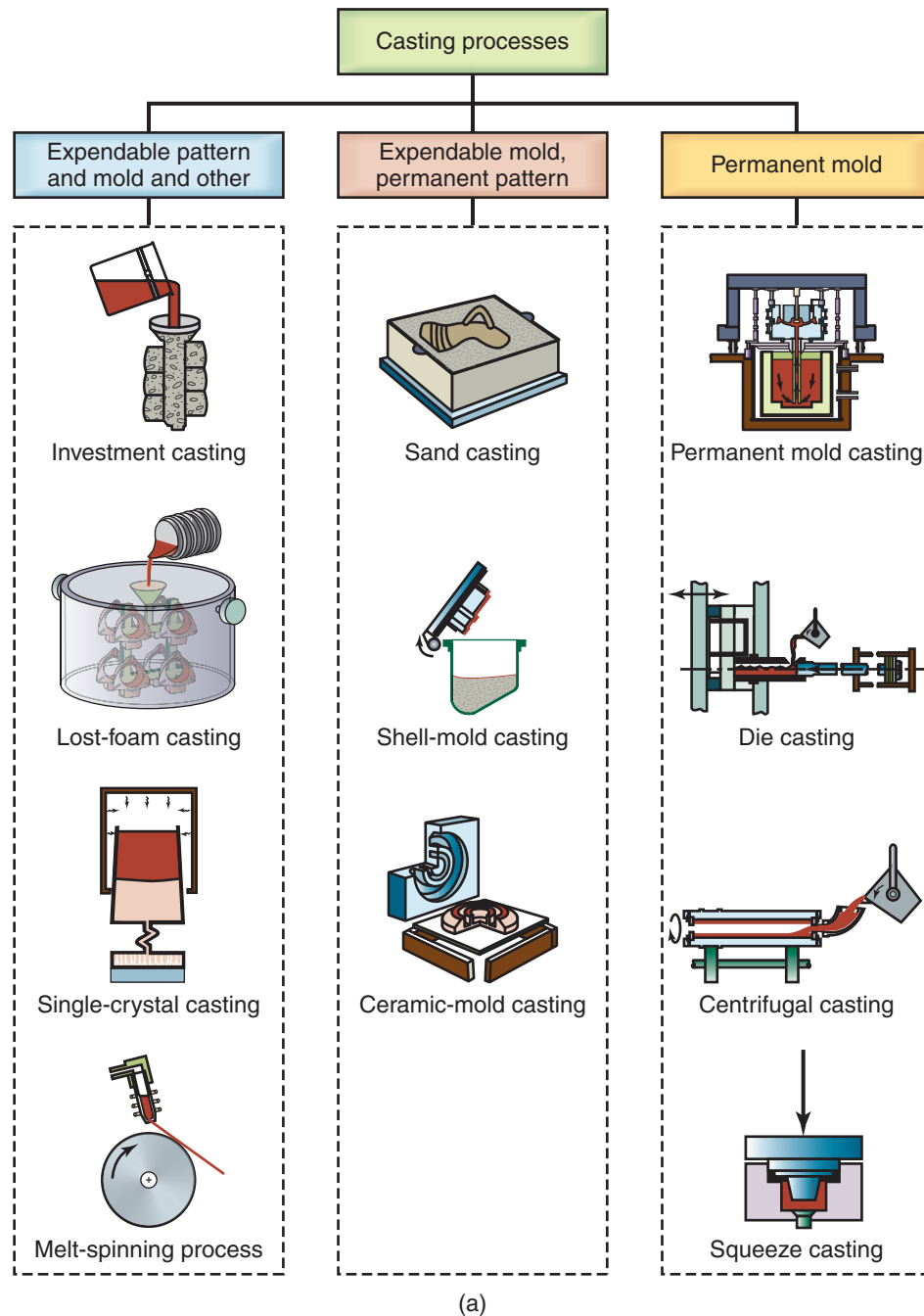
1793–1837	100% copper
1837–1857	95% copper, 5% tin and zinc
1857–1863	88% copper, 12% nickel
1864–1962	95% copper, 5% tin and zinc
1943 (WW II years)	Steel, plated with zinc
1962–1982	95% copper, 5% zinc
1982–present	97.5% zinc, plated with copper

## I.6 Selection of Manufacturing Processes

There is often more than one method that can be employed to produce a part from a given material. The following broad categories of manufacturing methods are all applicable for metallic as well as nonmetallic materials:

1. Casting (Fig. I.7a): Expendable mold and permanent mold (Part II).
2. Forming and shaping (Figs. I.7b through I.7d): Rolling, forging, extrusion, drawing, sheet forming, powder metallurgy, and molding (Part III).
3. Machining (Fig. I.7e): Turning, boring, drilling, milling, planing, shaping, broaching; grinding; ultrasonic machining; chemical, electrical, and electrochemical machining; and high-energy-beam machining (Part IV). This broad category also includes micromachining for producing ultraprecision parts (Part V).
4. Joining (Fig. I.7f): Welding, brazing, soldering, diffusion bonding, adhesive bonding, and mechanical joining (Part VI).
5. Finishing: Honing, lapping, polishing, burnishing, deburring, surface treating, coating, and plating (Chapters 26 and 34).
6. Microfabrication and nanofabrication: Technologies that are capable of producing parts with dimensions at the micro (one-millionth of a meter) and nano (one-billionth of a meter) levels; fabrication of microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS), typically involving processes such as lithography, micromachining, etching, LIGA, and various specialized processes (Chapters 28 and 29).

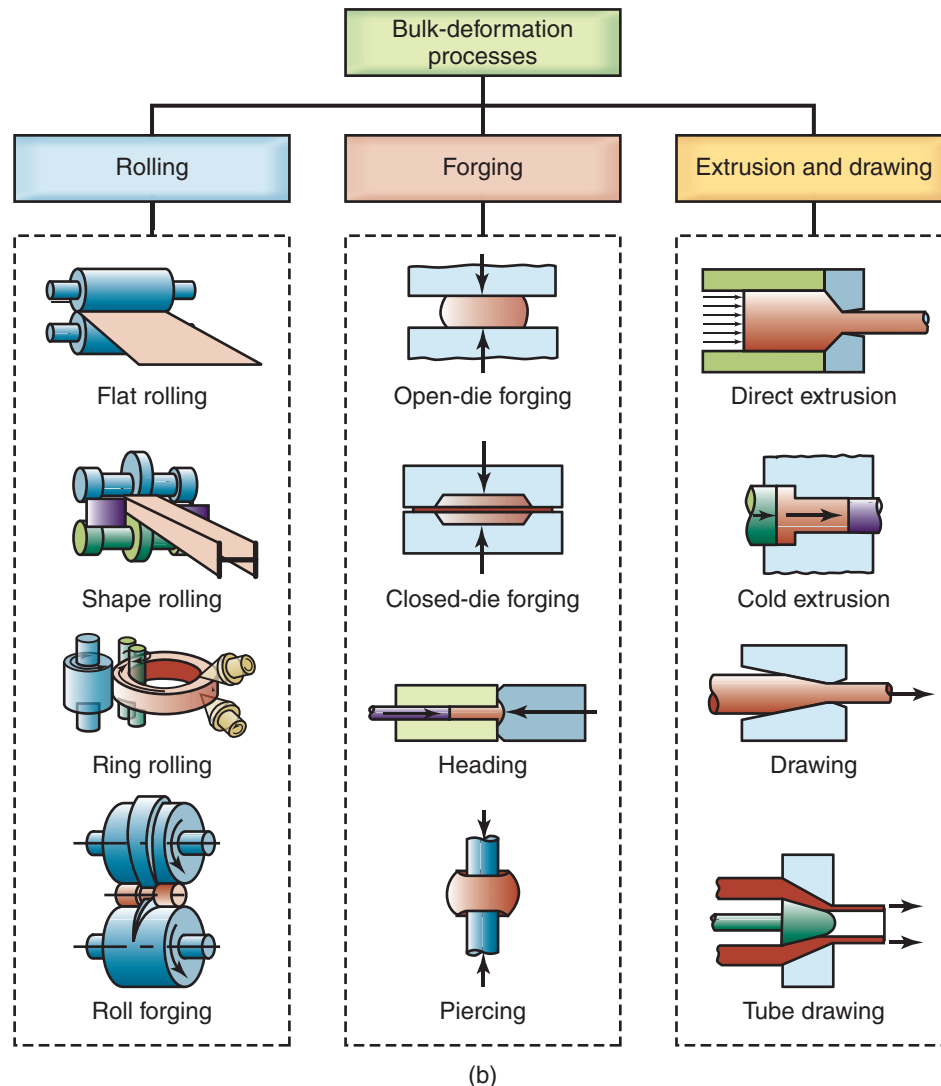
**Process Selection.** The selection of a particular manufacturing process or, more often, sequence of processes, depends on the geometric features of the parts to be made, including the dimensional tolerances



**Figure I.7:** (a) Schematic illustrations of various casting processes.

and surface texture required, and on numerous factors pertaining to the particular workpiece material and its manufacturing properties. To emphasize the challenges involved, consider the following two cases:

1. Brittle and hard materials cannot be shaped or formed without the risk of fracture, unless they performed at elevated temperatures, whereas these materials can be cast, machined, or ground with relative ease.

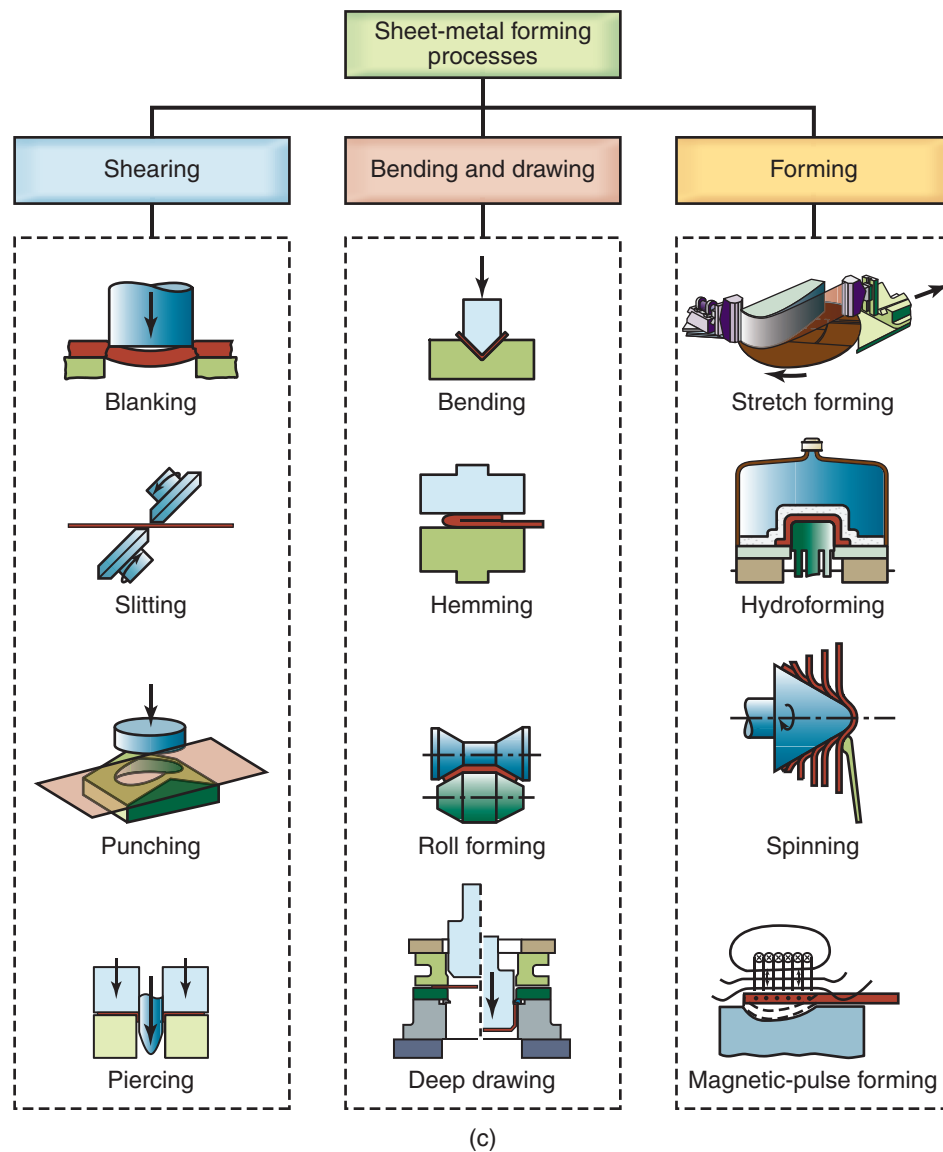


**Figure I.7:** (b) Schematic illustrations of various bulk-deformation processes.

2. Metals that have been preshaped at room temperature become less formable during subsequent processing, which, in practice, is often necessary to complete the part. This is because the metals have become stronger, harder, and less ductile than they were prior to processing them further.

There is a constant demand for new approaches to production challenges and, especially, for manufacturing cost reduction. For example, sheet-metal parts traditionally have been cut and fabricated using common mechanical tools, such as punches and dies. Although still widely used, some of these operations have been replaced by laser cutting (Fig. I.8). This method eliminates the need for hard tools, which typically have only fixed shapes, and can be expensive and time consuming to make.

The laser path in this operation is computer controlled, thereby increasing the operation's flexibility and its capability for accurately producing an infinite variety of shapes, repeatedly, and economically. Because of the high heat involved in using lasers, however, the surfaces produced have very different characteristics (such as texture and discoloration) than those produced by traditional methods. This difference can have

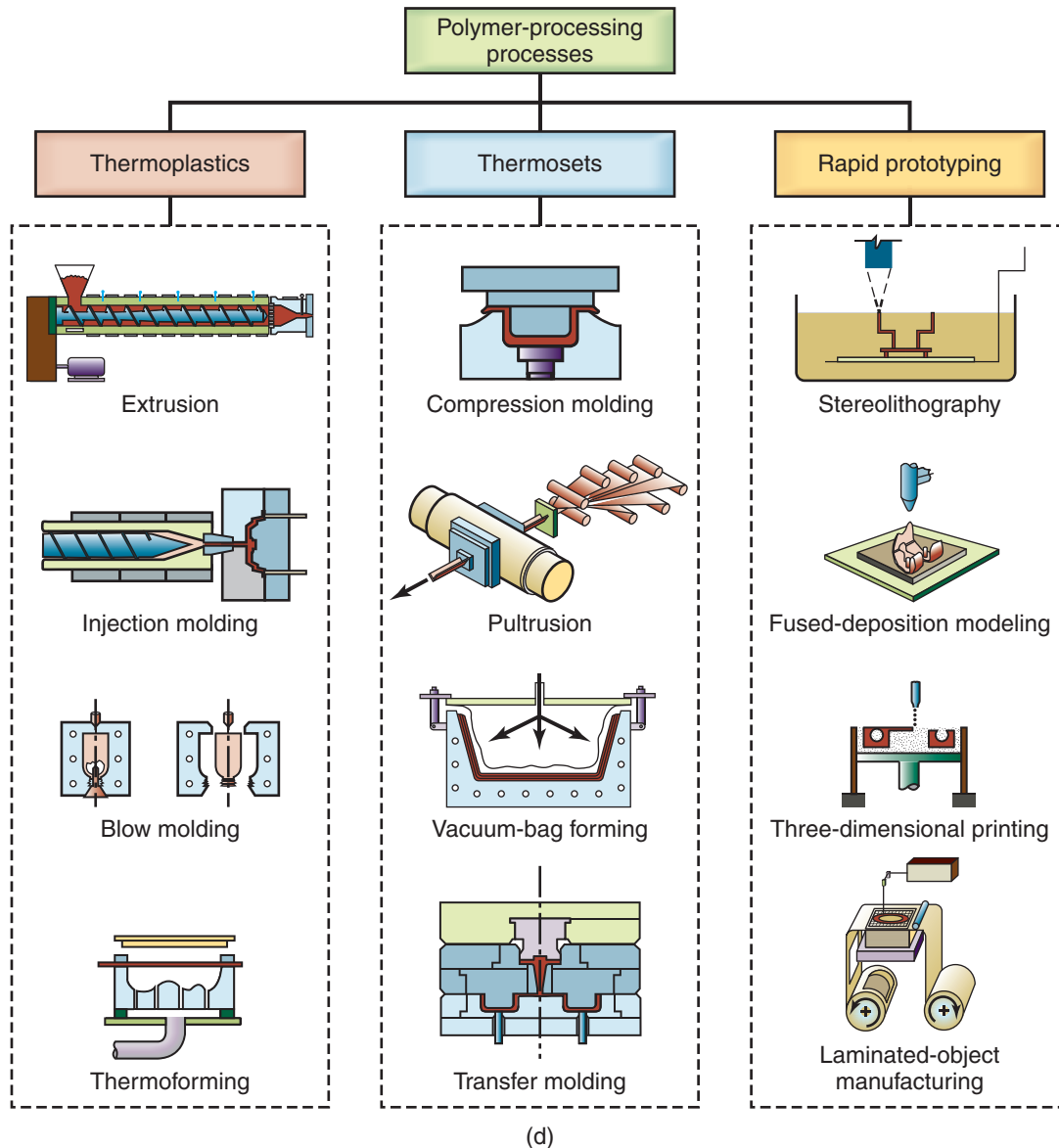


**Figure I.7:** (c) Schematic illustrations of various sheet-metal forming processes.

significant adverse effects, not only on appearance, but especially on its subsequent processing and in the service life of the product. Moreover, the inherent flexibility of the laser cutting process is countered by the fact that it is slower than traditional punching operations.

Several factors can have a major role in process selection, such as part size, shape complexity, and dimensional accuracy and surface finish required. For example:

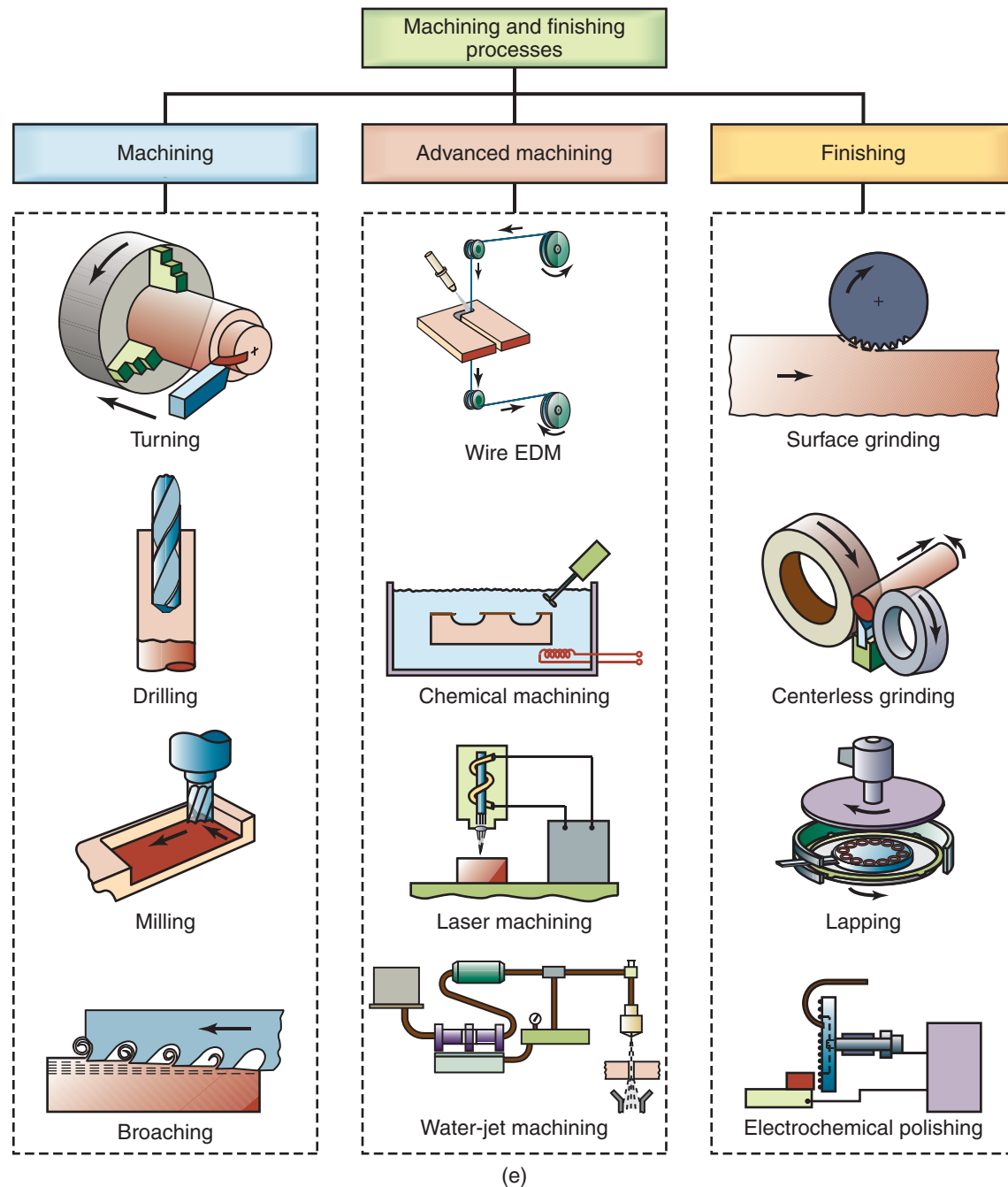
- Flat parts and thin cross sections can be difficult to cast.
- Complex parts generally cannot be shaped easily and economically by such metalworking techniques as forging, whereas, depending on part size and level of complexity, the parts may be precision cast, fabricated and assembled from individual pieces, or produced by powder-metallurgy techniques.



**Figure I.7:** (d) Schematic illustrations of various polymer-processing methods.

- Dimensional tolerances and surface finish in hot-working operations are not as fine as those obtained in operations performed at room temperature (cold working), because of the dimensional changes, distortion, warping, and surface oxidation due to elevated temperatures.

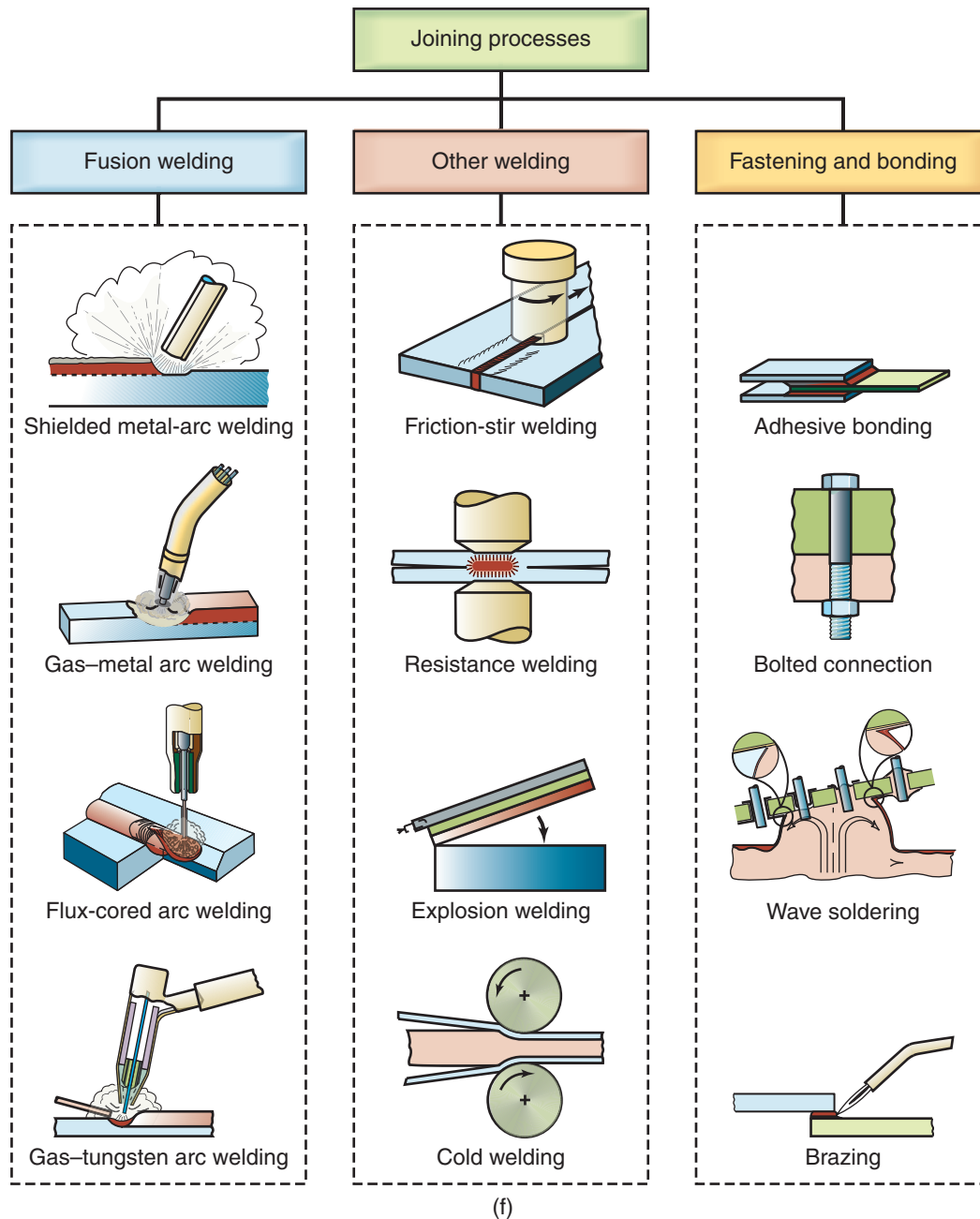
**Part size and dimensional accuracy.** The size, thickness, and shape complexity of a part have a major bearing on the process selected. Complex parts, for example, may not be formed easily and economically, whereas they may be produced by casting, injection molding, and powder metallurgy, or they may be fabricated and assembled from individual pieces. Likewise, flat parts with thin cross sections may not be cast easily. Dimensional tolerances and surface finish in hot-working operations cannot be as fine as those in cold-working operations, because dimensional changes, warping, and surface oxidation occur during processing at elevated temperatures. Also, some casting processes produce a better surface finish than others,



**Figure I.7:** (e) Schematic illustrations of various machining and finishing processes.

because of the different types of mold materials used. Moreover, the appearance of materials after they have been manufactured into products greatly influences their appeal to the consumer; color, surface texture, and feel are characteristics typically considered when making a purchasing decision.

The size and shape of manufactured products vary widely. The main landing gear for the twin-engine, 400-passenger Boeing 777 jetliner, for example, is 4.3 m (14 ft) tall, and has three axles and six wheels. The main structure of the landing gear is made by forging, followed by several machining operations



**Figure I.7:** (f) Schematic illustrations of various joining processes.

(Chapters 6, 8, and 9). At the other extreme is manufacturing microscopic parts and mechanisms. These components are produced through surface micromachining operations, typically using electron beam, laser beam, and wet and dry etching techniques, on materials such as silicon.

**Process Substitution.** It is common practice in industry that, for a variety of reasons and after a review of all appropriate and applicable processes, a particular production method, which may have been employed in the past, may well have to be substituted with another method. Consider, for example, the following



**Figure I.8:** Cutting sheet metal with a laser beam. *Source:* Courtesy of SPI Lasers UK Ltd.

products which can be produced by any of the sets of the following processes: (a) Cast vs. forged crankshaft, (b) stamped sheet-metal vs. forged or cast automobile wheels, (c) cast vs. stamped sheet-metal frying pan, (d) selective laser sintered vs. extruded or cast polymer bracket, and (e) welded vs. riveted sheet-metal safety hood for a machine.

Criteria for process selection include such factors as cost, maintenance required, whether the product is for industrial or consumer use, parameters to which the product will be subjected (such as external forces, impact, temperatures, and chemicals), environmental concerns that have to be addressed, and the product's appeal to the customer.

**Net-shape and Near-net-shape Manufacturing.** *Net-shape* and *near-net-shape manufacturing* together constitute an important methodology, by which a part is made in only one operation at or close to the final specific dimensions, tolerances, and surface finish. The difference between net shape and near net shape is a matter of degree, of how close the product is to its final dimensional surface-finish characteristics.

The necessity for and benefits of net-shape manufacturing can be appreciated from the fact that, in the majority of cases, more than one additional manufacturing operation or step is often necessary to produce the part. For example, a cast or forged crankshaft generally will not have the necessary dimensional surface finish characteristics, and will typically require additional processing, such as machining or grinding. These additional operations can contribute significantly to the cost of a product.

Typical examples of net-shape manufacturing include precision casting (Chapter 11), forging (Chapter 14), forming sheet metal (Chapter 16), powder metallurgy and injection molding of metal powders (Chapter 17), and injection molding of plastics (Chapter 19).

**Ultraprecision Manufacturing.** Dimensional accuracies for some modern equipment and instrumentation have now reached the magnitude of the atomic lattice (below 1 nm). Several techniques, including the use of highly sophisticated technologies (see *micromechanical and microelectromechanical device fabrication*, Chapter 29), are rapidly being developed to attain extreme accuracy. Also, mirror-like surfaces on metals can now be produced by machining, using a very sharp diamond with a nose radius of 250  $\mu\text{m}$  as the cutting tool. The equipment is highly specialized, with very high stiffness, to minimize deflections, as well as vibration and chatter, during machining. It is operated in a room where the ambient temperature is controlled to within 1°C, in order to avoid thermal distortions of the machine.



**Types of Production.** The number of parts to be produced (such as the annual quantity) and the rate (the number of pieces made per unit time) are important economic considerations in determining optimum processes and types of machinery required. Note, for example, that beverage cans, door locks, and spark plugs are produced in numbers and at rates that are much higher than those for jet engines ship propellers.

A brief outline of the general types of production, in increasing order of annual quantities produced, are:

1. **Job shops:** Small lot sizes, typically less than 100, using general-purpose machines, such as lathes, milling machines, drill presses, and grinders, many now typically equipped with computer controls.
2. **Small-batch production:** Quantities from about 10 to 100, using machines similar to those in job shops.
3. **Batch production:** Lot sizes typically between 100 and 5000, using more advanced machinery with computer control.
4. **Mass production:** Lot sizes generally over 100,000, using special-purpose machinery, known as dedicated machines, and various automated equipment in a plant for transferring materials and parts in progress.

### Case Study I.3 Saltshaker and Pepper Mill

The saltshaker and pepper mill set shown in Fig. I.9 consists of metallic and nonmetallic components. The main parts (the body) of the set are made by injection molding of a thermoplastic (Chapter 19), such as an acrylic, which has both transparency and other characteristics for this particular application and also is easy to mold. The round metal top of the saltshaker is made of sheet metal, has punched holes (Chapter 16), and is electroplated for improved appearance corrosion resistance (Section 34.9).

The knob on the top of the pepper mill is made by machining (Chapter 23) and is threaded on the inside to allow it to be screwed and unscrewed. The square rod connecting the top portion of the pepper mill to the two pieces shown at the bottom of the figure is made by rolling (Chapter 13). The two grinder components, shown at the bottom of the figure, are made of stainless steel. A design for manufacturing analysis indicated that casting or machining the two components would be too costly; consequently, it was determined that an appropriate and economical method would be the powder-metallurgy technique (Chapter 17).

## I.7 Computer-integrated Manufacturing

*Computer-integrated manufacturing* (CIM), as the name suggests, integrates the software and the hardware needed for computer graphics, computer-aided modeling, and computer-aided design and manufacturing activities, from initial product concept through its production and distribution in the marketplace. This comprehensive and integrated approach began in the 1970s, and has been particularly effective because of its capability of making possible the following tasks:

- Responsiveness to rapid changes in product design modifications and to varying market demands
- Better use of materials, machinery, and personnel
- Reduction in inventory
- Better control of production and management of the total manufacturing operation.



**Figure I.9:** A saltshaker and pepper mill set. The two metal pieces (at the bottom) for the pepper mill are made by powder-metallurgy techniques. *Source:* Courtesy of the Metal Powder Industries Federation.

The following is a brief outline of the various elements in CIM, all described in detail in Chapters 38 and 39:

1. **Computer numerical control (CNC).** First implemented in the early 1950s, this is a method of controlling the movements of machine components by direct insertion of coded instructions in the form of numerical data.
2. **Adaptive control (AC).** The processing parameters in an operation are automatically adjusted to optimize the production rate and product quality and to minimize manufacturing costs. For example, in machining, forces, temperature, surface finish, and dimensions of the part are constantly monitored. If they move outside the specified range, the system automatically adjusts the relevant variables until all the parameters are within the specified range.
3. **Industrial robots.** Introduced in the early 1960s, industrial robots have rapidly been replacing humans, especially in operations that are repetitive, dangerous, and boring. As a result, variability in product quality decreases and productivity is improved. Robots are particularly effective in assembly operations; *intelligent robots* have been developed with *sensory perception* capabilities and movements that simulate those of humans. Recent innovations involve *cobots*, which are designed to work and interact with humans.
4. **Automated materials handling.** Computers have made possible highly efficient handling of materials and parts in various stages of completion (*work in progress*), as in moving a part from one machine to another, and then to points of inspection, to inventory, and, finally, to shipment.
5. **Automated assembly systems.** These systems have been developed to replace assembly by human operators, although humans still have to perform some of the operations. Depending on the type of product, assembly costs can be high; thus, products must be designed such that they can be assembled more easily and faster by automated machinery.
6. **Computer-aided process planning (CAPP).** By optimizing process planning, this system is capable of improving productivity, product quality, and consistency, thus reducing costs. Functions such as cost estimating and monitoring work standards (time required to perform a certain operation) are also incorporated into the system.

7. **Group technology (GT).** The concept behind group technology is that numerous parts can be grouped and produced by classifying them into *families* according to similarities in (a) design and (b) the manufacturing processes employed to produce them. In this way, part designs and processing plans can be standardized, and new parts, based on similar parts made previously, can be produced efficiently and economically.
8. **Just-in-time production (JIT).** The principle behind JIT is that (a) supplies of raw materials and parts are delivered to the manufacturer just in time to be used, (b) parts and components are produced just in time to be made into subassemblies, and (c) products are assembled and finished just in time to be delivered to the customer. As a result, inventory carrying costs are minimal, defects in components are detected right away, productivity is increased, and high-quality products are made and at low cost.
9. **Cellular manufacturing (CM).** This system utilizes workstations that consist of a number of *manufacturing cells*, each containing various production machines, all controlled by a central robot, with each machine performing a specific operation on the part, including inspection (Fig. I.10).
10. **Flexible manufacturing systems (FMS).** These systems integrate manufacturing cells into a large production facility, in which all cells are interfaced with a central computer. Although very costly, flexible manufacturing systems are capable of producing parts efficiently (although in relatively small quantities, because hard automation is still most efficient for mass production) and of quickly changing manufacturing sequences required for making different types of parts. Flexibility enables these systems to meet rapid changes in market demand for all types of products.
11. **Expert systems (ES).** Consisting basically of complex computer programs, these systems have the capability of performing a variety of tasks and solving difficult real-life problems (much as human experts would), including expediting the traditional iterative process.
12. **Artificial intelligence (AI).** Computer-controlled systems are capable of learning from experience and of making decisions that optimize operations and minimize costs, ultimately replacing human intelligence.



**Figure I.10:** Robotic arm production line. *Source:* Shutterstock/ Andrey Armyagov.

13. **Artificial neural networks (ANN).** These networks are designed to simulate the thought processes of the human brain, with such capabilities as modeling and simulating production facilities, monitoring and controlling manufacturing operations, diagnosing problems in machine performance, and conducting financial planning and managing a company's manufacturing strategy.

## I.8 Quality Assurance and Total Quality Management

*Product quality* is one of the most critical considerations in manufacturing, because it directly influences customer satisfaction, thus playing a crucial role in determining a product's success in the marketplace (Chapter 36). The traditional approach of inspecting products after they were made has largely been replaced by the recognition that *quality must be built into the product*, from its initial design through all subsequent steps of manufacturing and assembly operations.

Even small products typically undergo several manufacturing steps, and each step involves its own variations in performance, which can occur within a relatively short time. A production machine, for example, may perform differently when it is first turned on than after it begins to warm up or when the ambient temperature in the plant fluctuates. Consequently, *continuous control of processes online monitoring* is a critical factor in maintaining product quality. The objective is to *control processes, not products*.

*Quality assurance* and *total quality management (TQM)* are widely recognized as being the responsibility of everyone involved in the design and manufacturing of products and their components. *Product integrity* is a term generally used to define the degree to which a product

- Functions reliably during its life expectancy (Table I.5)
- Is suitable for its intended purposes
- Can be maintained with relative ease.

Producing and marketing defective products can be very costly to the manufacturer, with costs varying by orders of magnitude, as shown in Table I.6.

**Table I.5:** Average Life Expectancy of Various Products.

Type of product	Life expectancy (years)
U.S. dollar bill	1.5
Personal computer	2
Car battery	4
Hair dryer	5
Automobile	8
Dishwasher	10
Kitchen disposal unit	10
Vacuum cleaner	10
Water heater (gas)	12
Clothes dryer (gas)	13
Clothes washer	13
Air-conditioning unit (central)	15
Manufacturing cell	15
Refrigerator	17
Furnace (gas)	18
Machinery	30
Nuclear reactor	40

*Note:* Significant variations can be expected, depending on the quality of the product and how well it has been maintained.

**Table I.6:** Relative Cost of Repair at Various Stages of Product Development and Sale.

Stage	Relative cost of repair
When part is being made	1
Subassembly of the product	10
Assembly of the product	100
Product at the dealership	1000
Product at the customer	10,000

Pioneers in quality control, particularly W.E. Deming (1900–1993), J.M. Juran (1904–2008), and G. Taguchi (1924–2012), all emphasized the importance of management’s commitment to (a) product quality, (b) pride of workmanship at all levels of production, and (c) the necessity of using **statistical process control** (SPC) and **control charts** (Chapter 36). They also pointed out the importance of *online monitoring* and rapidly identifying the *sources of quality problems* in production, before even another defective part is produced. The major goal of control is to *prevent* defective parts from ever being made, rather than to inspect, detect, and reject defective parts *after* they have been made.

As an example of strict quality control, computer chips are now produced with such high quality that only a few out of a million chips may be defective. The level of defects is identified in terms of **standard deviation**, denoted by the symbol  $\sigma$  (the Greek letter *sigma*). Three sigma would result in 2700 defective parts per million, which is unacceptable in modern manufacturing. In fact, it has been estimated that at this level, no modern computer would function reliably. At **six sigma**, defective parts are reduced to only 3.4 per million parts made. This level has been reached through major improvements in manufacturing *process capabilities* in order to *reduce variability* in product quality.

Important developments in quality assurance include the implementation of **experimental design**, a technique by which the factors involved in a manufacturing operation and their interactions are studied simultaneously. For example, the variables affecting dimensional accuracy or surface finish in a machining operation can readily be identified, thus making it possible for appropriate *on-time preventive adjustments* to be taken.

**Quality Standards.** Global manufacturing and competitiveness have led to an obvious need for international conformity and consensus in establishing quality control methods. This need resulted in the establishment of the ISO 9000 standards series on quality management and quality assurance standards, as well as of the QS 9000 standards (Section 36.6), introduced in 1994. A company’s registration for these standards, which is a *quality process certification* and not a product certification, means that the company conforms to consistent practices as specified by *its own* quality system. ISO 9000 and QS 9000 have permanently influenced the manner in which companies conduct business in world trade.

**Human-factors Engineering.** This topic deals with human–machine interactions, and thus it is an important aspect of manufacturing operations in a plant, as well as of products in their expected use. The human-factors approach is essential in the design and manufacture of safe products. It emphasizes **ergonomics**, defined as the study of how a workplace and the machinery and equipment in it, can best be designed and arranged for comfort, safety, efficiency, and productivity.

Examples of the need for proper ergonomic considerations are the following: (a) a mechanism that is difficult to operate manually, causing injury to the employee; (b) a poorly designed keyboard that causes pain to the user’s hands and arms during its normal use (*repetitive stress syndrome*); and (c) a control panel on a machine which is difficult to reach or use safely and comfortably.

**Product Liability.** Designing and manufacturing safe products is an essential responsibility of the manufacturer. All those involved with product design, manufacture, and marketing must fully recognize the consequences of a product’s failure, including failure due to foreseeable misuse of the product.

A product's malfunction or failure can cause bodily injury or even death, as well as financial loss to an individual, a bystander, or an organization. Known as *product liability*, the laws governing it vary from state to state and from country to country. Among numerous examples of products that could involve liability are the following:

- A grinding wheel that shatters and causes injury to a worker.
- A cable supporting a platform snaps, allowing the platform to drop, causing bodily harm or death.
- Automotive brakes that suddenly become inoperative, because of the failure of a particular component of the braking system.
- Production machinery that lacks appropriate safety guards.
- Electric and pneumatic tools that lack appropriate warnings and instructions for their safe use.

## I.9 Lean Production and Agile Manufacturing

*Lean production* (Section 39.7) is a methodology that involves thorough assessment of each activity of a company. Its basic purpose is to minimize waste at *all* levels, and calling for the elimination of unnecessary operations that do not provide any added value to the product being made. This approach, also called *lean manufacturing*, identifies all of a manufacturer's activities and optimizes the processes used in order to *maximize added value*.

Lean production focuses on (a) the efficiency and effectiveness of each and every manufacturing step, (b) the efficiency of the machinery and equipment used, and (c) the activities of the personnel involved in each operation. This methodology also includes a comprehensive analysis of the *costs* incurred in each activity and the costs of productive and for nonproductive labor.

The lean production strategy requires a fundamental change in corporate culture, as well as having an understanding of the importance of *cooperation and teamwork* among a company's workforce and management. Lean production does not necessarily require cutting back on a company's physical or human resources. It aims at *continually* improving efficiency and profitability by removing all waste in the company's operations and dealing with any problems as soon as they arise.

## I.10 Manufacturing Costs and Global Competition

Always critically important, economics of manufacturing has become even more so with (a) ever-increasing global competition and (b) the demand for high-quality products, generally referred to as *world-class manufacturing*, and at low prices. Typically, the *manufacturing cost* of a product represents about 40% of its *selling price*, which often is the overriding consideration in a product's marketability and general customer satisfaction. An approximate, but typical, breakdown of costs in modern manufacturing is given in Table I.7. As to be expected, the percentages indicated can vary significantly depending on product type.

**Table I.7:** Typical Cost Breakdown in Manufacturing.

Design	5%
Materials	50%
Manufacturing	
Direct labor	15%
Indirect labor	30%



The *total cost* of manufacturing a product generally consists of the following components:

1. **Materials.** Raw-material costs depend on the material itself and on supply and demand for that material. Low cost may not be the deciding factor if the cost of processing a particular material is higher than that for a more expensive material. For example, a low-cost piece of metal may require more time to machine or to shape than one of higher cost.
2. **Tooling.** Tooling costs include those for cutting tools, dies, molds, workholding devices, and fixtures. Some cutting tools cost as little as \$2, others as much as \$100 for cubic boron nitride and diamond. Depending on their size and the materials involved in making them, molds and dies can cost from only a few hundred dollars to over \$2 million for a set of dies for stamping large sheet metal parts.
3. **Fixed.** Fixed costs include costs for energy, rent for facilities, insurance, and real-estate taxes.
4. **Capital.** Production machinery, equipment, buildings, and land are typical capital costs. Machinery costs can range from a few hundred to millions of dollars. Although the cost of computer-controlled machinery can be very high, such an expenditure may well be warranted if it reduces labor costs.
5. **Labor.** Labor costs consist of direct and indirect costs. *Direct labor*, also called *productive labor*, concerns the labor that is directly involved in manufacturing products. *Indirect labor*, also called *nonproductive labor* or *overhead*, pertains to servicing of the total manufacturing operation.

Direct-labor costs may be only 10% to 15% of the total cost (Table I.7), but it can be as much as 60% for labor-intensive products, such as clothing and other textiles, and products assembled from components such as toys and musical instruments. Reductions in the direct-labor share of manufacturing costs can be achieved by such means as extensive use of automation, computer control of all aspects of manufacturing, implementation of modern technologies, and increased efficiency of operations.

As expected and as shown in Table I.8, there continues to be a worldwide disparity in labor costs, by an order of magnitude. Today, numerous consumer products are manufactured or assembled in the Pacific Rim countries, especially China. Likewise, software and information technologies are often much less costly to develop in such countries as India and China than in the United States or Europe. As living standards continue to rise, however, labor costs, too, are beginning to rise significantly in these countries.

**Table I.8:** Approximate Relative Hourly Compensation for Workers in Manufacturing in 2010 (United States = 100).

Norway	166	Italy	96
Switzerland	153	Japan	92
Belgium	146	Spain	76
Denmark	131	New Zealand	59
Germany	126	Israel	58
Sweden	126	Singapore	55
Finland	122	Korea (South)	48
Austria	118	Argentina, Slovakia	36
Netherlands, Australia	118	Portugal	34
France,	117	Czech Republic	33
Ireland	104	Poland	23
United States	100	Mexico	18
Canada	97	China, India, Philippines	6

*Note:* Compensation can vary significantly with benefits. Data for China and India are estimates, use different statistical measures of compensation, and are provided for comparison purposes only. *Source:* U.S. Department of Labor.