

CHAPTER 6

Selecting Manufacturing Processes

LEARNING OBJECTIVES

When you have completed this chapter you will be able to

- Characterize basic manufacturing processes
- Differentiate primary, secondary, and tertiary processes
- Select appropriate manufacturing processes
- Estimate the costs of manufacturing a product
- Describe and use manufacturing terms and concepts

6.1 INTRODUCTION

Regardless of the type of material, even the simplest product involves many manufacturing processes. Let's examine that Trek mountain bicycle shown in Figure 6.1.

The Trek model 4300 includes a frame, rear-wheel assembly, front-wheel assembly, steering fork with suspension, handlebar, hand controls, seat post with saddle, pedal crank subassembly, and Derailleur system.

The product is shipped as a few subassemblies. Before the product is displayed, the retailer attaches the front wheel, handlebar, seat post, and saddle. The retailer also checks for proper operation of the 24-speed shifter, and adjusts the spoke tension of each wheel. We note that assembling components is an important manufacturing process whether the components are assembled by the retailer or at the factory.

A number of manufacturing processes are used to make the frame subassembly. To start with, standard lengths of aluminum tubing are cut to approximate lengths for the top tube, down tube, seat tube, and rear stays. The rear stays are then formed in a bending process. The ends of each tube are shaped and cleaned. The tubes and stays are then welded together using the Gas Tungsten Arc welding process. The welded frame is then cleaned and finally painted. Quality inspections are also completed in between. Note that the type



FIGURE 6.1 Trek mountain bicycle. (Courtesy of Trek Bicycle Corporation.)

of process and its sequence is important. Part of production planning, in fact, is determining the appropriate sequence of primary, secondary, and tertiary manufacturing processes.

Other processes are used in making bicycles, including: molding (tires), chrome plating or anodizing (handlebars, wheel rims), swaging (seat posts), stamping (sprockets), and casting (hand controls).

As we plan the manufacture of any product, we need to answer the following questions:

- How do we choose the specific manufacturing processes?
- How do the materials selected influence the choice of manufacturing processes?
- Would product function or performance issues influence our choice of processes?
- What criteria should we use to select processes?
- Which criteria are most important?
- Who will make the final decisions?

In the remaining sections we will examine some of the more widely used manufacturing processes. We will investigate their: compatibility with alternative materials, ability to generate complex shapes, limitations as to the maximum or minimum part size, feasible production quantities, and overall economic viability. Then we will present a general method that will help us select appropriate manufacturing processes.

6.2 MANUFACTURING PROCESSES

Manufacturing processes transform raw materials into products. Processes are used to change a material's form as in metal casting, sheet metal bending, or machining. Processes can alter the microstructure and properties of a material such as increasing the yield strength of steel by cold rolling, or heat treatment. Some processes change the chemical composition of a material such as in chrome plating or galvanizing steel.

Manufacturing processes can be categorized as bulk deformation, casting, sheet metalworking, polymer processing, machining, finishing, and assembly, as shown in Figure 6.2.

Primary manufacturing processes are used principally to alter the material's shape or form. We use casting, for example, to transform rectangular ingots of steel into cylindrical brake drums. Injection molding is used to convert pellets of thermoplastic polyethylene into telephone handsets. Rolling is used to flatten slabs of steel. And, sheet metalworking is used to bend steel sheets into refrigerator housings.

Secondary manufacturing processes are used to add or remove geometric features from the basic forms. The brake drum casting, for example, undergoes

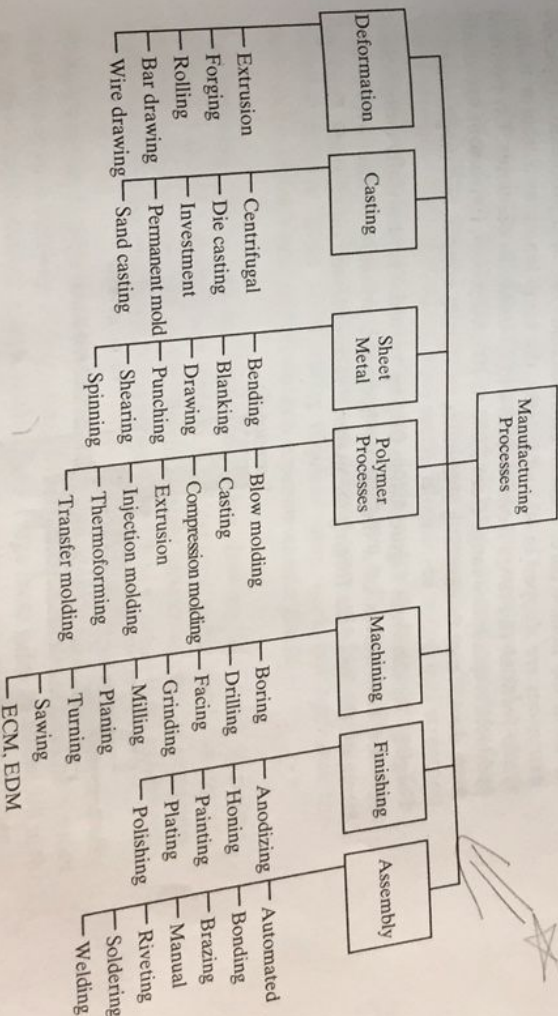


FIGURE 6.2 Types of manufacturing processes.

secondary machining operations such as turning and grinding of the friction surface. Refrigerator housings are frequently flash trimmed.

tion molded parts usually will have surplus flash trimmed. Injection molding parts usually will have surplus flash trimmed. Injection molding parts usually will have surplus flash trimmed. Injection molding parts usually will have surplus flash trimmed.

Tertiary manufacturing processes relate to surface treatments such as polishing, painting, heat treating, and joining. A part, such as the bike frame, can undergo a sequence of many processes, including cleaning and painting before it is assembled as the final product.

6.2.1 Bulk Deformation

Bulk deformation changes the shape or form of bulk raw materials caused by compressive or tensile yielding. Bulk materials include billets, blooms, and slabs, as compared to sheet materials. Ore is initially processed into solidified ingots. Ingots are subsequently rolled into small rectangular blooms, billets and slabs. Some of the more common bulk deformation processes are described below.

Extrusion As shown in Figure 6.3, in **extrusion**, heated metal plastically yields as it is pushed through a **die**, producing long pieces with a constant cross-section. Rectangular, circular, triangular, L-shaped, and U-shaped cross-sections are common. Tubing and piping can also be extruded using a mandrel to form the hollow core. Custom cross sections are also produced. Typically extrusions are shipped in 40-foot lengths, the same length as a tractor trailer. Cross-sections can range from about 1/4 to 12 inches in diameter. Economical production quantities range from 1,000 to 100,000 pieces. Extrusions are made from ductile metals including aluminum, steel, zinc, copper, and magnesium.

Forging As shown in Figure 6.4, in **forging**, material is plastically compressed between two halves of a die set by hydraulic pressure or the stroke of a hammer. In closed die forging the material is compressed on all sides. During

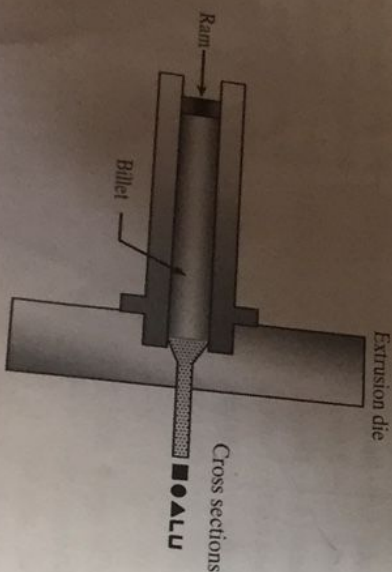


FIGURE 6.3
Extrusion of metals.

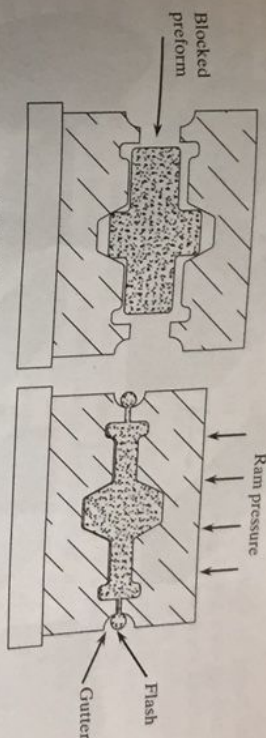


FIGURE 6.4 Closed-die forging.

open die forging the workpiece is hammered between two die halves that do not restrict the side flow of material. Often bulk material is preformed in blockier dies. Forging is typically done when the metal is hot, requiring less work. Moderately complex shapes can be forged with a maximum size limited to roughly 36 inches. Economic production quantities range from 1,000 to 100,000 pieces.

Rolling Two or more cylindrical rollers plastically compress material, forming sheets, bars, or rods. **Rolling** is used to produce billets, blooms, and slabs from ingots. The billets are subsequently rolled into rectangular or circular bars. Slabs are rolled into plates and sheet metal. Blooms are rolled into structural shapes including I-beams, channel beams, angle, and wide-flange beams. The processing of ingots into the various shapes is shown in Figure 6.5. Hot rolling requires less work than cold rolling to deform materials but produces an oxidized surface finish. Cold rolling requires more work but increases the material's yield strength and produces a superior surface finish.

Bar Drawing As shown in Figure 6.6, in **bar drawing**, bar stock is pulled through a die of reduced cross section. Cold drawing increases the material's strength and improves the surface finish. Straight lengths of circular or rectangular bar stock are produced. Sizes range from 1/8 to 6 inches in cross section.

Wire Drawing In **wire drawing**, bar stock is pulled through a set of successively narrowing dies, forming a long strand of wire that is usually wound on a spool as a continuous process. Cross section sizes range from 0.001 to about 3/8 inches. Drawing is used with ductile metals such as aluminum, steel, and copper.

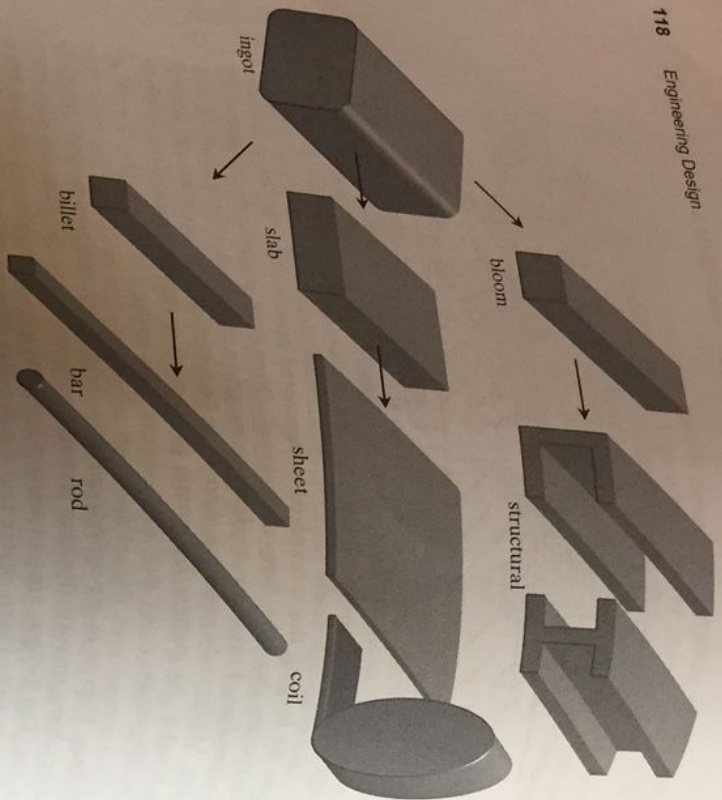


FIGURE 6.5 The rolling deformation process initially produces blooms, slabs, and billets. These are subsequently rolled into structural, sheet, coil, bar, and rod shapes.

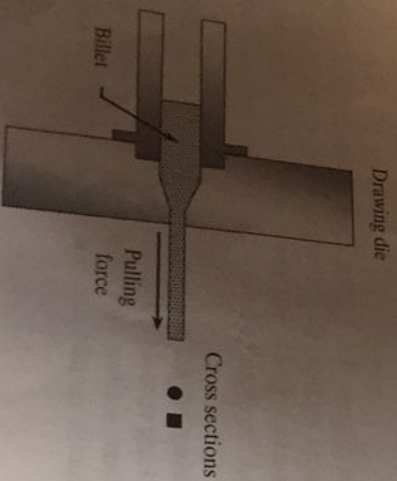


FIGURE 6.6
Drawing of bar stock.

6.2.2 Casting

Casting is one of the oldest processes, dating back thousands of years, in which molten metal is poured into a cast to solidify. Casting can produce complex geometries within broad tolerances. For dimensional accuracy castings are typically machined in secondary operations. Three of the most commonly used casting processes are sand casting, die casting, and investment cast-

Sand Casting. In sand casting, molten metal solidifies in a sand mold. The standard mold is formed by packing damp sand around a pattern with the same external shape as the part to be cast. The pattern is removed before casting and later reused. As shown in Figure 6-7, molten metal flows down the sprue into the runner, through the opening to the part, called a gate and into the part cavity forming. The riser is a small reservoir of liquid metal that feeds material into the part as the part cools and shrinks. Performed cores can be placed in the mold to create voids, such as cylindrical holes. Open-mold casting is used for parts with a flat surface on one side (e.g., manhole covers, jewelry). Closed-mold casting uses a cope half and a drag half, enclosed in a flask. When the metal has solidified and cooled the mold is destroyed in order to remove the part. The parting line is where the two mold halves meet. Sizes for sand castings can range from inches to feet. Some industrial engine blocks have been cast as large as 12 feet in cross section and 30 feet long. Economical production quantities can be very small, for example between 1 and 10. All nonferrous and ferrous metals are used. Moderately complex shapes are possible. Sand cores can be used to produce internal and external undercuts. Parts made by sand casting have a granular surface finish.

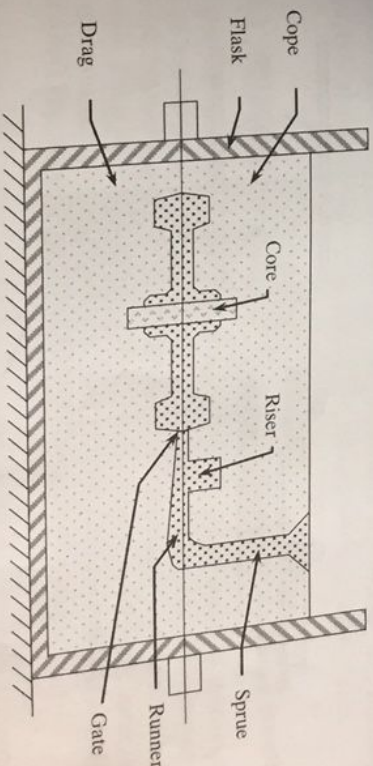


FIGURE 6.7 Closed-mold sand casting.

Die Casting In **die casting**, molten material is injected under pressure into permanent die set (i.e., mold halves) usually made of steel. Because the steel

mold is reused, die casting is faster than sand casting. But, the steel die set is often more expensive to machine.

The surface finish of die-cast parts is smoother than sand-cast parts. As shown in Figure 6.8, a shot of molten metal is ladled into the opening, and then hydraulically rammed into the process even further, after the die set is solidified part is pushed out of the mold by **ejector pins**, after the die set is separated. Maximum part sizes are typically around 30 inches by 30 inches. Small parts, less than an inch, can be die-cast. Moderately complex shapes are possible. Economically, injection machines are generally over 10,000 pieces. In order not to melt the steel mold, common die-casting materials are low melting-point metals, including alloys of aluminum, zinc, magnesium, and brass.

Investment Casting (Lost-Wax Process) In investment casting, molten metal solidifies in a ceramic cast made by coating a wax pattern with liquid slurry, then dried. The wax is melted out prior to casting. As shown in Figure 6.9, the wax pattern is made in a metal mold. Multiple parts can be combined on the pattern tree. The wax is melted and drained from the ceramic mold. Molten

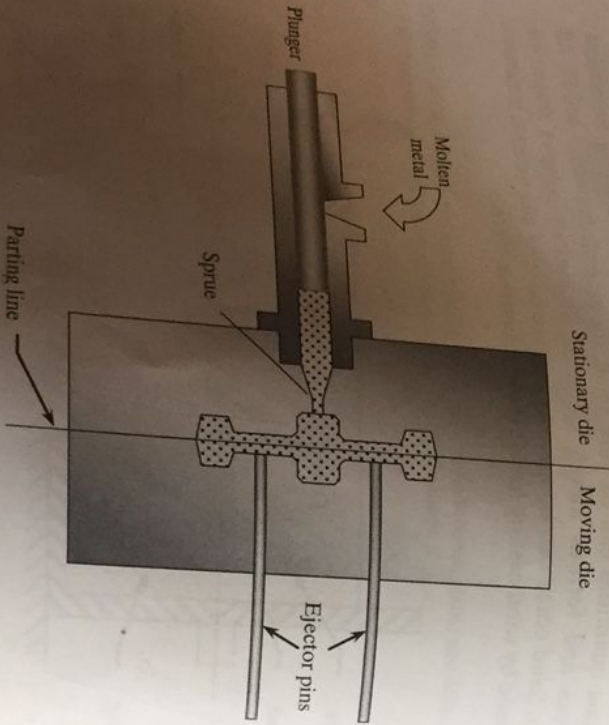


FIGURE 6.8 Cold-chamber die casting.

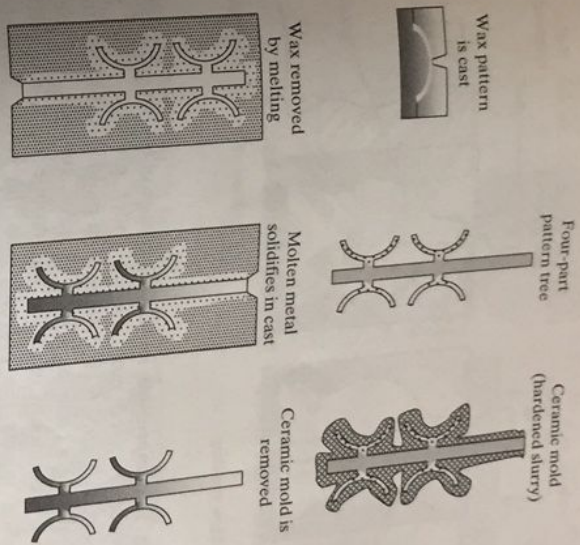


FIGURE 6.9 Investment casting.

metal is poured into the ceramic mold that is destroyed after the part solidifies. Shape complexity and production volume are similar to die casting. Casting materials include alloys of aluminum, zinc, magnesium, brass, steel, and stainless steel. Investment casting is typically used for runs of less than 10,000 pieces.

6.2.3 Polymer Processing

In **polymer processing**, part shapes are created by solidification of thermoplastic polymers or curing of thermosetting polymers. Parts made of thermoplastic and thermosetting materials can be made in many shapes and sizes, with little waste of raw material, requiring few, if any, finishing operations. Some of the more common processes include: blow molding, injection molding, compression molding, transfer molding, thermoforming, and casting.

Blow Molding In **blow molding**, as shown in Figure 6.10, a molten parison of thermoplastic material is extruded then injected with air, then expands to the shape of the mold. Blow molding is frequently used to produce hollow parts with thin walls. Captured cavities shapes are possible, such as a bottle. Sizes are limited to about three feet in diameter.

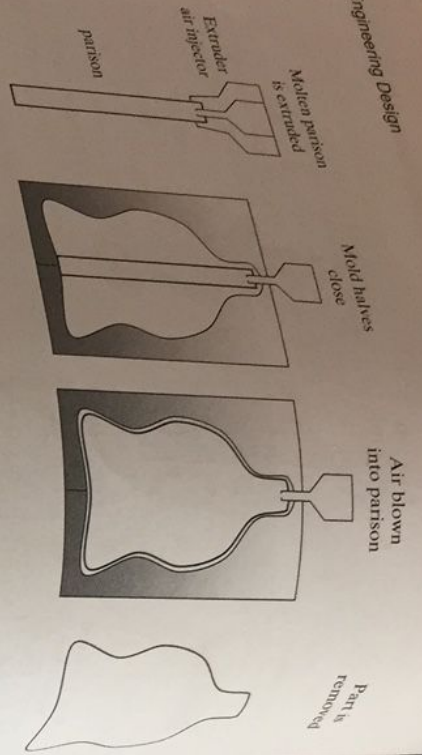


FIGURE 6.10 Extrusion blow molding.

Compression Molding In compression molding, a charge of thermoset or elastomer is formed between heated mold halves under pressure. While the polymer cures, As shown in Figure 6.11, compression molds are simpler than injection molds, not requiring a complex system of sprue, runners, and gates. Compression molding is commonly used for automobile tires and resin albums. Transfer molding injects the polymer into the cavity permitting compression molding. However, the thermoset or elastomer sprues and runners, as molded inserts. However, the thermoset or elastomer sprues and runners, as shown in Figure 6.12, are not reground and reused as with thermoplastic. Maximum part sizes are typically less than 24 inches by 24 inches. Minimum part sizes can be on the order of 1/8 to 1/4 inch in cross section. Economic production volumes start at about 10,000 pieces.

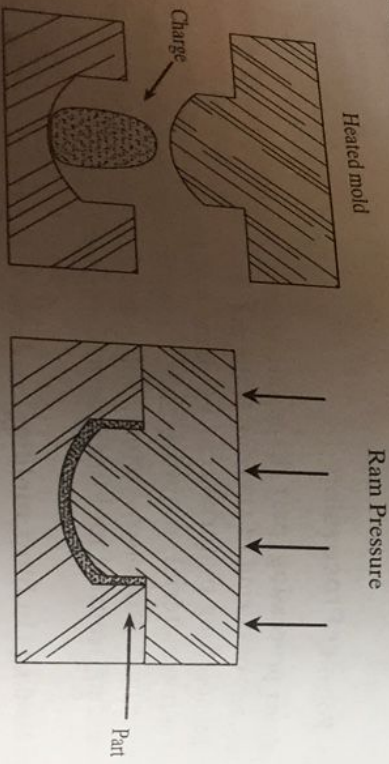


FIGURE 6.11 Compression molding.

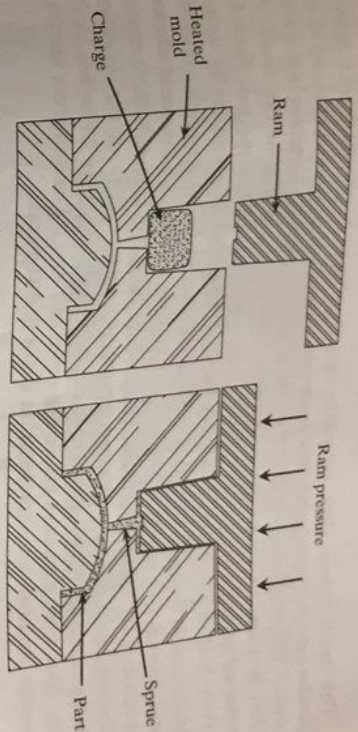


FIGURE 6.12 Transfer molding.

Injection Molding In injection molding, thermoplastic pellets are melted and then injected under high pressure into a metal mold. As shown in Figure 6.13, the pellets of thermoplastic are placed into the hopper. As the pellets auger into the barrel, the pellets begin to rub against each other, causing enough heat to ultimately melt the pellets. The auger then rams the molten plastic into the mold via the sprue, runner, and gate network. The auger then rams the molten plastic into the mold via the sprue, runner, and gate network. The core half of the mold forms the inside of the part. The cavity half of the mold forms the outside. As the part cools, it shrinks onto the core, requiring ejector pins to remove the part.

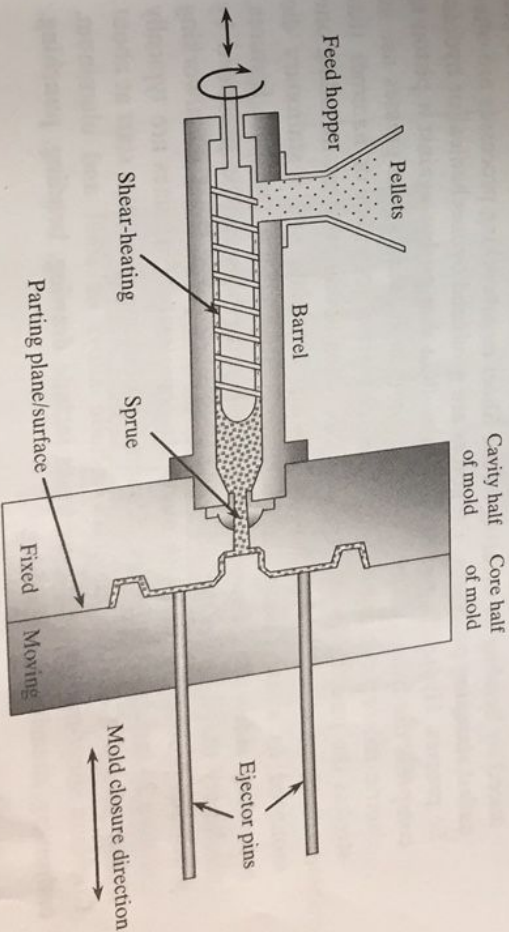


FIGURE 6.13 Injection molding of thermoplastic materials.

The mold halves slide on guideposts (not shown). External and internal undercuts can be formed. **Side cores** are shaped metal parts that move in and out of the mold to form external undercuts. An **internal undercut** is a feature that restricts the removal of the part from the mold. A **parting line** separates the core and cavity halves. An **external undercut** is a feature that restricts the removal of the part from the cavity half of the mold. A **parting line** separates the core and cavity halves. Undercuts are shown in Figure 6.14. A system of liquid channels cools the mold halves. The mold halves move along an axis called the **mold close direction**. Very complex shapes are possible including internal and external undercuts. Part sizes are limited by the planing capacity of the injection molding machine. Maximum part sizes are typically less than 24 inches by 24 inches. Minimum part sizes are on the order of 1/8 to 1/4 inch in cross section. Economic production volumes start at about 10,000 pieces.

Thermal Forming Thermal forming includes vacuum-forming thin sheets of thermoplastic. A vacuum is drawn sucking the molten sheet onto the pattern forming the part. Parts as large as 6 feet by 6 feet have been vacuum-formed.

Casting (Polymers) Gravity casting of polyurethane materials is done using silicone or rubber molds. Complex shapes can be cast, including internal and external undercuts, since the mold will flex upon part removal.

6.2.4 Sheet Metalworking

In **sheet metalworking**, permanent deformation of thin metal sheets is produced by bending or shearing forces. Sheet metalworking processes are often called **stamping** processes. The forces are produced by mechanical or hydraulic presses. Hydraulic presses pressurize fluid that pushes against a piston to compress die halves. Faster, but less controllable, mechanical presses use an electric motor to energize a flywheel, connected to a ram or hammer that strokes the punch. Die sets include a collection of components, including one or more moving **punches** fastened to a punch plate and a stationary die mounted to a die holder. In addition to bending and punched features, secondary **side-action features** such as a hole or boss can be produced by machinery that acts on the sides of the stamped parts. Sheet metalworking processes produce shapes with moderate complexity. Part sizes are typically less than 24 inches by 24 inches. Economic production quantities start at about 10,000 pieces. Common materials include alloys of steel and aluminum. Common sheet-metalworking processes include **drawing, bending, punching, embossing, shearing, and blanking**.

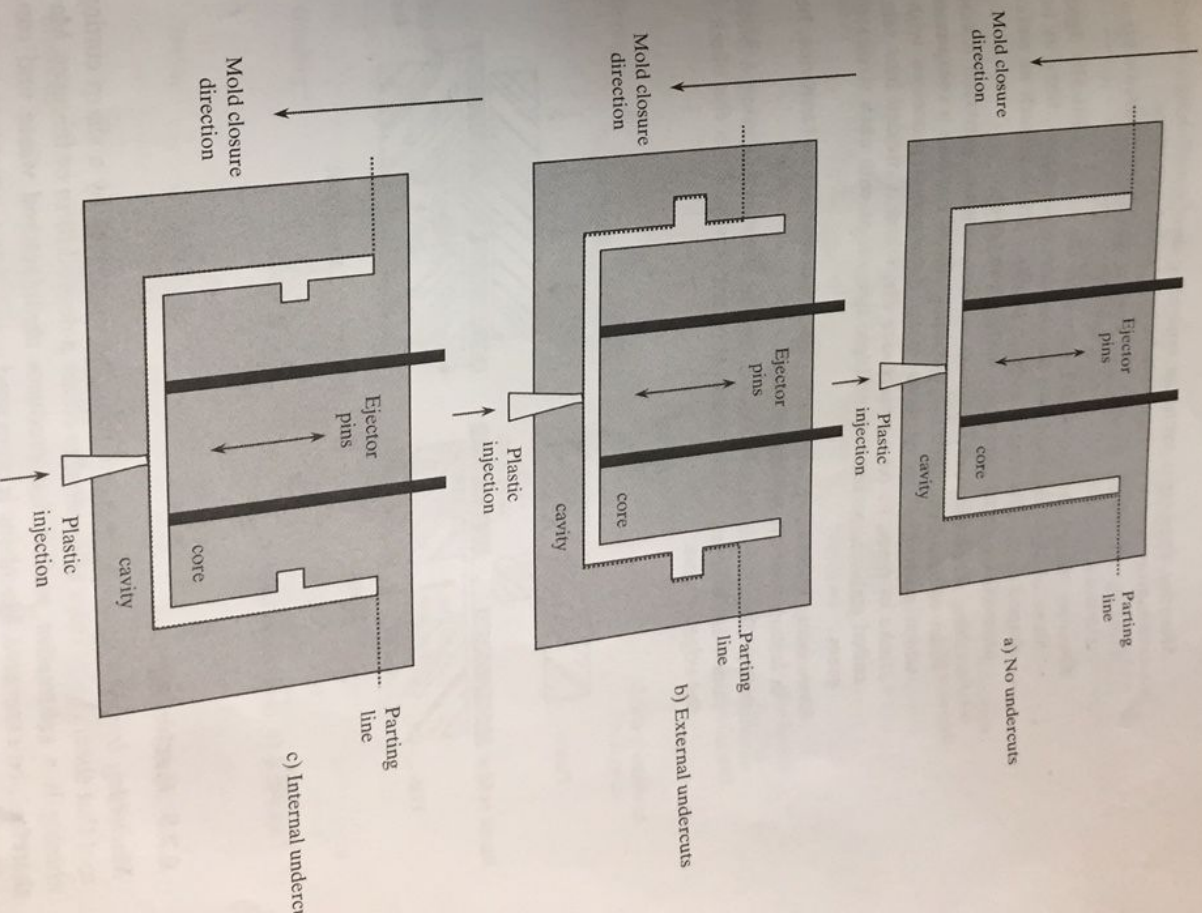


FIGURE 6.14 The boss features create external undercuts that restrict the removal of the part from the cavity half of the mold in (b), and an internal undercut that restricts removal of the part from the core half of the mold, as in (c).

Shearing. Shearing is cutting or separating sheet metal along a straight line. Shearing is used to size sheets for subsequent operations.

Blanking. Blanking is shearing of a smaller, shaped piece, called a blank, from the stock. Blanks are used in deep drawing.

Drawing (sheet). As shown in Figure 6.15, the punch plastically deforms a blank of sheet material into the die, forming cupped-, box-, or hollow-shaped parts. Drawing is used to produce products such as soda cans, ammunition cartridge casings, and pots and pans.

Punching. Producing features such as slots, notches, extruded holes, and holes using a punch and die, punching can be done on a **compound die**, which performs two or more metal deformation processes with the stroke of press, or on a **progressive die**, which is divided into sections, called stations, performing multiple operations with each stroke of the press.

Embossing. Embossing is forming plastic indentations to form ribs, beads, or lettering on the surface of metal.

Bending. Bending is plastic deformation of sheet metal using a matched punch-and-die set, or a descending punch to wipe-form the blank over the edge of a die.

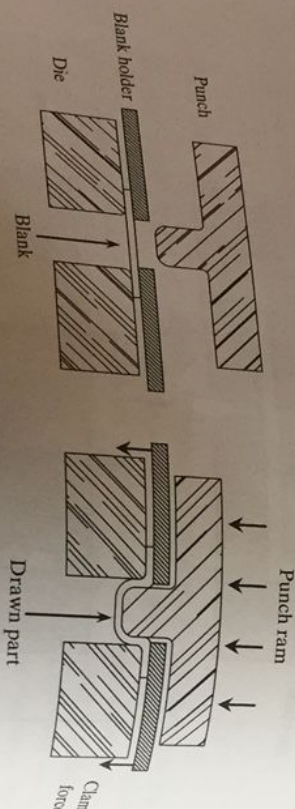


FIGURE 6.15 Sheet metal drawing.

6.2.5 Machining

Machining involves removing material from the workpiece by a sharp cutting tool that shears away chips of material to create a desired form or features. Machining is a **subtractive process** that produces **manufactured waste** and can, therefore, be expensive. Machining is often used as secondary process to true-up critical dimensions or surfaces or to smooth the surface finish. Even though machining is an expensive process, it is often used for low-volume production since an expensive mold or die-set need not be prepared. Some of the more common machining processes are listed below and shown in Figures 6.16 and 6.17.

Operation	Block diagram	Most commonly used machines	Machines less frequently used	Machines seldom used
Turning		Lathe turning control	Boring mill	
Grinding		Cylindrical grinder		Lathe (with special attachment)
Sawing (of plates)		Contour or band saw	Laser flame cutting Plasma arc	
Drilling		Drill press Machining center Vert. milling machine	Lathe horizontal boring machine	Horizontal milling machine Boring mill
Boring		Lathe Boring mill Horizontal boring machine Machining center		Milling machine Drill press
Reaming		Lathe Drill press Boring mill Horizontal boring machine Machining center	Milling machine	
Grinding		Cylindrical grinder		Lathe (with special attachment)
Sawing		Contour or band saw		
Broaching		Broaching machine		Arbor press (keyway broaching)

FIGURE 6.16 Machining cylindrical surfaces. (Materials and Processes in Manufacturing, 8th ed.; E. P. DeGarmo, J. T. Black, and R. Kohser. Copyright © 1997. This material is used by permission of John Wiley & Sons, Inc.)

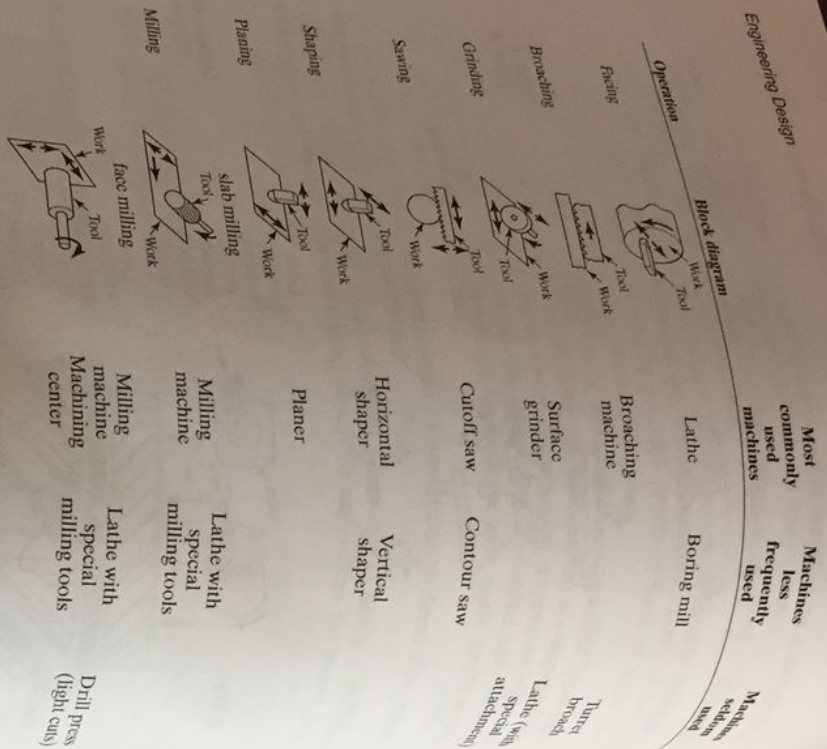


FIGURE 6.17 Machining flat surfaces. (Materials and Processes in Manufacturing, 8th ed.; E. P. DeGarmo, J. T. Black, and R. Kohser; Copyright © 1997. This material is used by permission of John Wiley & Sons, Inc.)

Sawing involves removing material with a toothed blade.

Milling involves removing material from a flat surface by a rotating cutter tool.

Planing involves removing material using a translating cutter as the work-piece feeds.

Shaping involves removing material from a translating workpiece and a stationary cutter.

Boring is increasing the diameter of an existing hole with a cutting tool by rotating the workpiece.

Drilling is removing material using a rotating bit to form a cylindrical hole.

Reaming is refining the diameter of an existing hole.

Turning is removal of material from a rotating workpiece.

Facing is material removal from a turning workpiece using a radially fed tool.

Grinding is removal of material from a surface using an abrasive spinning wheel.

Electric discharge machining is removal of material by means of a spark.

6.2.6 Finishing

Finishing is preparing the final surface for aesthetics and protection from the environment. Machining processes produce different **surface roughness**, as shown in Table 6.1. Fine grinding is sometimes used to reduce the surface roughness of parts to between 8 and 16 micro-inches (Dieter, 2002). However, for superior smoothness, surfaces are often polished between 1 and 32 micro-inches. Polishing uses abrasive powders embedded in rotating leather or felt wheel. Honing is used for interior cylindrical surfaces. Lapping is used for flat surfaces. Buffing can produce roughness approximating 0.5–16 micro-inches.

Cleaning. Wire brushing is used to remove grit and scale, and chemical solutions, including acid baths, are used to remove oily films.

Protection. Polymers and ceramics require little protection from the environment. Metals, however, require some surface treatment. Oil- and water-based painting is perhaps the least expensive coating. Steels are often plated with chrome, cadmium, or zinc (galvanizing). Aluminum alloys are usually anodized, which is a chemical surface treatment.

6.2.7 Assembly

Assembly is the process of putting together all the product's components before shipping. Products that have subassemblies will have undergone some

TABLE 6.1 Surface Roughness (adapted from SME, 1992)

Process	Roughness (μ inch)
Machining	
Turning	32-250
Boring	16-250
Milling	32-250
Drilling	63-250
Reaming	16-125
Broaching	16-125
Finishing	
Precision grinding	2-16
Lapping / honing	2-16
Super finishing	1-8

assembly operations prior to final assembly. Assembly operations include the assembly operations, and/or attachment of parts. Handling includes grasping, handling, insertion, and placing parts, before insertion or attachment. Attached parts are usually either permanent, or temporary as in the case of servicing parts. Permanent-attachment methods include welding, brazing, soldering, rivets, cyclets, staples, shrink fits, and press fits, and adhesive bonding. Temporary-attachment methods include threaded fasteners such as screws, nuts and bolts, and snap fits. Polymer materials sometimes use metallic threaded inserts. Metals, of course, can be machined to form threads.

6.3 COSTS OF MANUFACTURING

The cost to manufacture a product depends on the chosen materials and manufacturing processes. If we plan to produce 50,000 or more pieces of the same part, we will want to consider investing in processes with more automated tooling such as die casting and/or injection molding, to reduce labor costs and have little material waste. On the other hand, if we are making a custom, one-off part for a special customer (e.g., the U.S. Navy), the high cost of automated tooling will not likely be economical. Therefore, we will likely consider machining, even though labor costs would be higher.

The customer pays the selling price, less any discounts. The company's net income results from deducting selling costs, administrative costs, and manufacturing costs from the total sales revenues. When a company is profitable, it will have cash available to replace worn-out manufacturing equipment and buildings, in addition to paying dividends to stockholders. We can help, of course, by making economical design and manufacturing decisions that keep total manufacturing costs low.

Let's examine the total manufacturing costs (TMC) for making a production run of quantity, q , pieces and see how some manufacturing processes differ. The three major components are total material costs, M , total tooling costs, T , and total processing costs, P . Other breakdowns of costs can be made, but the one proposed will work well for illustration purposes.

Total Manufacturing Cost = Material + Tooling + Processing

$$TMC = M + T + P$$

(6.1)

Let

c_m = material cost per part

c_p = material cost per unit weight, and

w_p = weight of finished part

w_w = weight of wasted material, scrap

α = wasted material weight / finished weight = w_w / w_p

Then the **material cost** per part is a function of weight and waste:

$$\text{Material cost per part, } c_M = M/q = c_m(w_p + w_w) = c_m(w_p + \alpha w_p) \quad (6.2)$$

$$c_M = c_m w_p (1 + \alpha) \quad (6.3)$$

The total **tooling cost**, T , is composed of the total material and labor costs to make the part patterns, or die-casting molds, or sheet metal punch-and-die sets, or jigs and fixtures used in machining. Once the tooling is made, however, the tooling cost is fixed. Consequently, the more parts made with the same tooling, the more economical it becomes. The tooling cost per part is therefore:

$$\text{Tooling cost per part, } c_T = T/q \quad (6.4)$$

The total **processing cost**, P , includes the cost of: labor, energy, floor space, and machine usage. For example, a machine shop might estimate their cost per hour, c_i , to run a milling machine at \$150/hr. to pay for the machine operator, electricity usage, floor space (building depreciation or rent), and machine depreciation (or rent). Then, if the cycle time to make a part is t (hours per part), the processing cost per part, c_P is:

$$\text{Processing cost per part, } c_P = c_i t \quad (6.5)$$

The total cost per part is therefore:

$$\text{Cost per part, } c = c_M w_p (1 + \alpha) + T/q + c_i t \quad (6.6)$$

Examining equation (6.6), we see that to reduce part costs we should:

- purchase less expensive materials
- keep our finished part weight low
- produce little manufactured waste
- make many parts per production run (i.e., batch)
- design simple parts and tools that result in less expensive tooling
- choose a manufacturing process that has a low cycle time

Unfortunately, the material selection and the choice of manufacturing process are coupled. Choosing a material for its low material cost, for example, may result in larger processing costs. Some inexpensive plastics, for example, require longer freezing/solidification cycle, increasing processing cycle time and costs, actually raising the total cost per part. Therefore, we need to make our decisions based on the total costs, as we shall see in the following example.

Example

Assume that our company is considering making a part out of low-strength metals or thermoplastics. Three processes appear compatible with the required feature shapes: sand casting, injection molding, and machining. Data gathered to select the least expensive sand casting, injection molding, and machining processes are shown in Table 6.2. Determine the material and manufacturing process are shown in Table 6.2. Determine the cost per part.

TABLE 6.2 Manufacturing Data for Cost Estimates

Mfg. Process	Alternative		
	A	B	C
Sand casting	Aluminum alloy	Injection molding	Machining
Material	1	3	2
Part weight (lb)	0.05	0.01	0.2
Alpha	1	0.25	0.75
Material cost (\$/lb), c_M	10000	35000	1500
Tooling cost (\$), T	5000	5000	5000
Production quantity, q	0.3	0.03	0.6
Cycle time (hrs/part), t	30	100	75
Machine rate (\$/hr)			

We use equation (6.3) to calculate the material cost per part as $c_M = c_M w_p (1 + \alpha)$.

- A: $c_{MA} = \$1.00/\text{lb} (1 \text{ lb/part}) (1 + 0.05) = \$1.050/\text{part}$
 B: $c_{MB} = \$0.25/\text{lb} (3 \text{ lb/part}) (1 + 0.01) = \$0.758/\text{part}$
 C: $c_{MC} = \$0.75/\text{lb} (2 \text{ lb/part}) (1 + 0.20) = \$1.800/\text{part}$

Using equation (6.4) we calculate the tooling cost as $c_T = T/q$.

- A: $c_{TA} = \$10,000 / 5000 \text{ parts} = \$2.00/\text{part}$
 B: $c_{TB} = \$35,000 / 5000 \text{ parts} = \$7.00/\text{part}$
 C: $c_{TC} = \$1,500 / 5000 \text{ parts} = \$0.30/\text{part}$

Using equation (6.5) we calculate the processing cost per part as $c_P = c_P t$.

- A: $c_{PA} = \$30/\text{hr} (0.30 \text{ hrs/part}) = \$9.00/\text{part}$
 B: $c_{PB} = \$100/\text{hr} (0.03 \text{ hrs/part}) = \$3.00/\text{part}$
 C: $c_{PC} = \$75/\text{hr} (0.60 \text{ hrs/part}) = \$45.00/\text{part}$

Summing the material, tooling and processing cost for each part we obtain:

- A: $c_{MA} + c_{TA} + c_{PA} = \$1.050 + 2.00 + 9.00 = \$12.050/\text{part}$
 B: $c_{MB} + c_{TB} + c_{PB} = \$0.758 + 7.00 + 3.00 = \$10.758/\text{part}$
 C: $c_{MC} + c_{TC} + c_{PC} = \$1.800 + 0.30 + 45.00 = \$47.100/\text{part}$

Therefore, based on the marketing department's 5,000-run estimate, injection molding would be the least expensive process.

The alternatives are plotted as a function of production volume, as shown in Figure 6.18. Note that for very small quantities, machining would produce the lowest cost per part (up to pt. a). And from about 200 to about 4,000 per run (between pt. a and pt. b), sand casting would be the least expensive. After about 4,000 parts per run (pt. b) injection molding would be the least expensive.

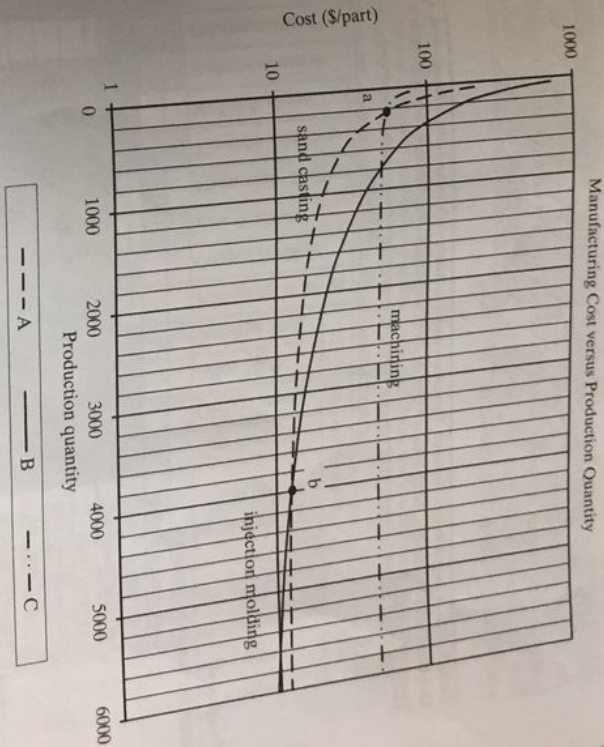


FIGURE 6.18 Manufacturing cost/part as a function of production volume.

Example

Determine the production quantity for which the manufacturing costs for alternative A and B are the same.

We can let $c_A = c_B$ and use equation (6.6) such that

$$c = c_M w_p (1 + \alpha) + T/q + c_P t$$

$$\$01.050/\text{part} + \$10,000/q + \$9/\text{part} = \$0.758/\text{part} + \$35,000/q + \$3/\text{part}$$

$$\$10.050/\text{part} + \$10,000/q = \$3.758/\text{part} + \$35,000/q$$

100-0-4

6.4 PROCESS SELECTION

Most parts undergo primary, secondary, and tertiary manufacturing processes. As a part design evolves, a variety of processes are not economically feasible. As we have learned in previous sections, some processes are not compatible with certain materials. As a part design evolves, a variety of processes are not economically feasible. As we have learned in previous sections, some processes are not compatible with certain materials. As a part design evolves, a variety of processes are not economically feasible. As we have learned in previous sections, some processes are not compatible with certain materials.

TABLE 6.3 Compatibility Between Processes and Materials (Adapted from Boothroyd, G. P., Dewhurst, and W. Knight, 2002, *Product Design for Manufacture and Assembly* with permission from Taylor & Francis)

Processes	Materials												
	Cast Iron	Carbon Steel	Alloy Steel	Stainless Steel	Aluminum & alloys	Copper & alloys	Zinc & alloys	Magnesium & alloys	Titanium and alloys	Nickel & alloys	Refractory metals	Thermoplastics	Thermosets
Solidification	Sand casting												
	Investment casting												
	Die casting												
	Injection molding												
	Structural foam												
	Blow molding - extr												
	Blow molding - inj												
	Rotational molding												
	Impact extrusion												
	Cold heading												
Bulk Deformation	Closed die forging												
	Powder metal												
	Hot extrusion												
	Rotary swaging												
	Machined from stock												
Metal Removal	ECM												
	EDM												
	Wire EDM												
	Sheet stamp bend												
	Thermoforming												
Forming	Metal spinning												

Normal practice ☐ Less common ☐ Not applicable ☐

Some processes are not capable of producing large part sizes. Other processes cannot produce the desired geometric complexity, such as: the type and number of features, including: holes, notches, bosses, rotational symmetry, enclosed cavities, and uniformity of walls and/or cross sections as shown in Table 6.4.

Manufacturing process and materials selection decisions occur in every phase of a part's design. As more and more information becomes available, revised cost estimates can also be made, ultimately affecting prior decisions. During conceptual design, for example, little is known about the part sizes or dimensions. Also, design is iterative. During the configuration design phase, some features may be combined to improve functionality, but demand a specialized manufacturing process or material, not previously considered. When we use the *manufacturing-processes-first approach*, we first screen out manufacturing processes that will not satisfy part considerations, such as:

TABLE 6.4 Shape Generation Capabilities of Processes, Y=Yes, N=no, M=must, Y=easier, a=higher cost, b=shallow undercut, c=requires special equipment, d=only continuous, open ended. (Adapted from Boothroyd, G. P., Dewhurst, and W. Knight, 2002, *Product Design for Manufacture and Assembly*, with permission from Taylor & Francis).

Processes	Shapes / Features													DFA
	Depressions 1D	Depressions >1D	Uniform-Wall	Uniform-Section	Axis of Rotation	Regular Cross Section	Captured Cavities	Enclosed	Draft Free Surfaces	Part consolidation	Alignment Features	Integral Fasteners		
Solidification	Sand casting	Y	Y	Y	Y	Y	Y	Y	N	4	3	1		
	Investment casting	Y	Y	Y	Y	Y	Y	Y	N	5	5	2		
	Die casting	Y	Y ^a	Y	Y	Y	Y	Y	N	4	5	3		
	Injection molding	Y	Y ^a	Y	Y	Y	Y	N ^b	N	5	5	5		
	Structural foam	Y	Y ^a	Y	Y	Y	Y	N	N	4	4	3		
	Blow molding - extr	Y	Y ^a	M	N	Y	Y	M	Y	3	4	3		
	Blow molding - inj	Y	Y ^a	M	N	Y	Y	M	N	3	4	3		
	Rotational molding	Y	Y ^a	M	N	Y	Y	M	N	2	2	1		
	Impact extrusion	Y	N	Y	N	Y	Y	N	Y	3	3	1		
	Cold heading	Y	N	Y	N	Y	Y	N	Y	3	3	1		
Bulk Deformation	Closed die forging	Y	Y ^a	Y	Y	Y	Y	N	N	3	2	1		
	Powder metal	Y	N	Y	Y	Y	Y	N	N	3	3	1		
	Hot extrusion	Y ^d	N	Y	M	Y	Y	N	N	2	2	3		
	Rotary swaging	N ^c	N	N	N	M	N ^c	N	N	1	1	1		
	Machined from stock	Y	Y	Y	Y	Y	Y	Y	Y	2	3	2		
Metal Removal	ECM	Y	Y ^c	Y	Y	Y	Y	N	N	3	4	1		
	EDM	Y	Y ^c	Y	Y	Y	Y	N	N	3	4	1		
	Wire EDM	Y ^d	N	Y	Y	Y	Y	N	N	2	2	3		
	Sheet metal bending	Y	Y	M	Y	Y	Y	N	N	4	3	4		
	Thermoforming	Y	Y ^a	M	Y	Y	Y	N	N	3	3	3		
Forming	Metal spinning	N	N	M	N	M	N	M	N	Y	Y	1		

production quantities, part size, or shape capability, as shown in Table 6.5. The remaining feasible processes will be compatible with some material classes. The next screen out materials that will not satisfy the functional classes.

We next screen out materials to the mechanical and physical properties requirements of the part. Namely, we compare application informational requirements against design specification to the mechanical and physical properties requirements of the part. We typically include criteria regarding the nature of the material classes, the operating environment. This screening will eliminate some material classes, and the remaining sub-classes.

As mentioned in Chapter 5, either approach will lead to the same subset of material classes and compatible manufacturing process since we are doing the same thing: eliminating material classes or screenings based on the same criteria. Also noted in Chapter 5, the first approach first screens out manufacturing processes that will further help us refine our manufacturing design-for-manufacture guidelines that will determine secondary and tertiary processes, such as determining secondary and tertiary processes.

TABLE 6.5 Process-first approach first screens out manufacturing processes that are incompatible with the desired production run quantity, part size, and geometric shape capability.

1. Product (overall)
2. Part size (geometric features)
3. Shape capability (in one dimension)
 - boss or depression in more than one dimension
 - boss or depression in one dimension
 - holes
 - undercuts (internal/external)
 - uniform wall thickness
 - cross sections – uniform/regular
 - rotational symmetry
 - captured cavities (e.g., bottles)

Example

In chapter 5 we concluded that carbon steels and aluminum alloys would be prospective materials for our lawn mower wheel rim design. A 50,000 unit production run is anticipated. Complete a process screening.

Examining Table 6.3 we find that sand casting, investment casting, die casting, closed die forging, machining, and sheet metalworking are compatible manufacturing processes (normal practice). Considering both part-size and production run quantity, machining and investment casting are eliminated at this point. We will revisit Table 6.4 during configuration design to screen out processes that are not capable in generating the features defined at that time.

At this point we have narrowed our materials to carbon steels and aluminum alloys which are compatible with sand casting, die casting, forging and sheet metalworking processes.

6.5 SUMMARY

- Most parts undergo primary, secondary, and tertiary manufacturing processes.
- Fundamental manufacturing processes include: bulk deformation, casting, sheet metal working, polymer processes, machining, finishing, and assembly.
- Manufacturing costs include material, tooling, and processing costs.
- Material cost per part is directly related to manufactured waste.
- Manufacturing costs are influenced by planned production quantities.
- Some processes are more compatible with certain materials.
- Some processes are more capable at generating certain geometric features.
- Preliminary process selection considerations include: part size, geometric complexity, and production quantities.

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KEY TERMS

- | | | |
|------------------|---------------------|--------------------|
| Assembly | Compression molding | Embossing |
| Bar drawing | Core (mold) | External undercut |
| Bending | Cycle time | Extrusion |
| Blanking | Die | Facing |
| Blow molding | Die casting | Finishing |
| Boring | Drawing (metal) | Forging |
| Bulk deformation | Drilling | Grinding |
| Casting | Ejector pins | Injection molding |
| Cavity | Electric discharge | Internal undercut |
| Compound die | machining | Investment casting |

CHAPTER 14

Projects, Teamwork, and Ethics

LEARNING OBJECTIVES

When you have completed this chapter you will be able to

- Develop a project problem and mission statement
- Prepare a project plan, including a work scope, schedule and budget
- Prepare a work breakdown structure diagram and responsibilities table
- Complete an earned-value analysis
- Describe and utilize the elements of successful teamwork
- Describe the forming, storming, norming, and performing stages
- Develop and execute an effective meeting
- Explain and apply the fundamental canons of a code of ethics
- Identify and resolve ethical dilemmas

14.1 INTRODUCTION

The design and manufacture of a product is often accomplished as a project performed by a concurrent engineering team. As the group members participate in the development of a project plan, including a problem statement, mission statement, scope of work, schedule, budget, and responsibilities table, they begin to work as a team. Successful projects can often be traced back to effective teamwork. Similarly, effective teamwork can be traced back to thorough project planning.

We can draw an analogy between project planning and a football team during practice sessions, learning new plays on the board during the "chalk-talk," and then taking the field to drill individual assignments and hone timing. When athletes know what they are supposed to do, and how to do it, they have a good chance at being successful. Similarly, project teams can establish effective teamwork through communication, decision making, collaboration, and self-management.

Finally, we will examine the fundamentals of professional ethics and how they relate to our project work tasks and everyday decision making.

14.2 PROJECTS

A **project** is a unique sequence of work tasks, undertaken once, to achieve a specific set of objectives. Design projects, in particular, focus on solving a specific design problem. Other projects include construction or software development. We perform work tasks only once in a project. This aspect helps to distinguish a project from daily work routines. A design engineer may invent a new paper handler for a laser printer as a unique work task. A sales engineer, on the other hand, performs the same routine by contacting a dozen customer prospects as part of his or her normal daily responsibilities.

The four major elements of a project are the scope of work (i.e., set of work tasks to be performed), the cost for labor, materials, and other resources to accomplish the scope, the time allotted, and the quality of the work performed (Lewis, 2002). The four elements are usually interdependent. We can illustrate the coupling of the four elements as three legs and area of a triangle as shown in Figure 14.1. If, for example, the scope of work is expanded to include more work tasks, the costs, quality, or time allotted will be affected. If we expand the scope without changing the cost or time, quality will usually suffer. Whenever a change in one of the four elements needs to be made, a project team would be well advised to consider making revisions to the other three elements.

A project has three main phases: planning, executing, and closing. During planning we determine the what, who, how much, and when. We determine what the work tasks are, who the team members are, which tasks they will complete, how much time, money, and other resources are needed, and when the tasks need to be completed. As we execute our work tasks, we also monitor and control our progress to determine if and when any corrective measures need to be taken. During the closing of a project we reflect and document on our successes and failures, such that we and others in the company can benefit.

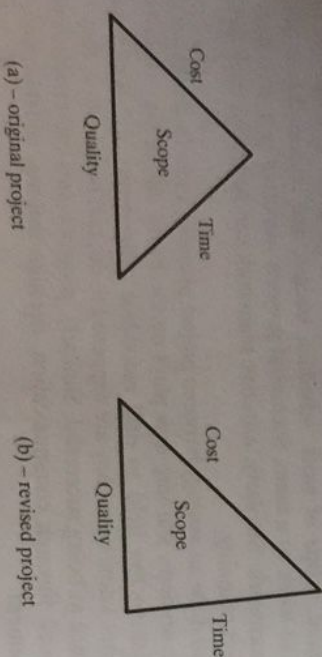


FIGURE 14.1 Scope, cost, time, and quality are interrelated. Change any leg of the triangle or the area of the triangle and the others change also.

14.2.1 Planning a Project

During the project-planning phase, team members prepare a package of items collectively called the **project plan**. The amount of effort that a team spends preparing a project plan usually depends on the extent and type of project. Some design problems require hundreds or thousands of man-hours and take weeks, months, or years to solve such as designing a hydroelectric power plant. On the other hand, a simple selection design problem that is expected to take three man-hours would hardly require a project plan.

A fundamental principle of project management is that those who will work on a project should participate in planning it. Those who will do the work usually know best which specific tasks and deliverables need to be completed. They also know how much time and/or other resources may be needed. A project plan typically includes:

1. Problem statement
2. Mission statement
3. Project objectives
4. Work breakdown structure
5. Scope of work (work scope)
6. Responsibilities table
7. Organization chart
8. Budget
9. Schedule
10. Risk assessment

1. **Problem Statement.** A problem statement is a simple sentence or two describing a. what the problem is, b. what the desired end state is, c. what currently prevents it, and d. how we know when we have achieved the desired outcome.

2. **Mission Statement.** A mission statement is a paragraph of two or three sentences that states what we are going to do, for whom, and how we will go about doing it.

3. **Project Objectives.** To better understand the amount of work in a project we need to develop **project objectives**, which are specific outcomes that we expect to produce. In a design project, for example, we expect to complete a package of "deliverables," including production drawings, prototype test reports, bills of materials, manufacturing process specifications, and performance simulation reports. Project outcomes should be specific as to quantity and quality. Also, outcomes should be realistic in that they consider available time, personnel, and equipment. An example of some project objectives is shown in Table 14.1. By detailing project objectives, we are determining specific "whats" that will be completed, not the "how." The "how" is determined when the work tasks are detailed, as discussed later.

Example

Bob Bear, Inc. successfully produces a garden tractor, selling about 50,000 units per year. However, the company does not make a snow blower attachment for its garden tractor product. A project is needed to design, prototype, and test a new snow blower attachment that is easy to use, safe, and cost-effective.

Problem Statement

The project team will design, prototype, and test a new snow blower attachment for its existing tractor line. The team will formulate customer and company requirements, develop alternative snow blower concepts, configure snow blower attachments alternatives, establish feasible design variable values, prototype components, and test the final production assembly.

Mission Statement

The project team will design, prototype, and test a new snow blower attachment for its existing tractor line. The team will formulate customer and company requirements, develop alternative snow blower concepts, configure snow blower attachments alternatives, establish feasible design variable values, prototype components, and test the final production assembly.

TABLE 14.1 Partial List of Project Objectives for a Design Project.

1. Obtain detailed understanding of customer and company requirements
 - 1.1 Completed survey of 1,000 customers
 - 1.2 Benchmark study of 5 competitive or substitute products
 - 1.3 House-of-quality diagram
 - 1.4 Engineering design specifications
2. Establish alternative concept designs
 - 2.1 Minimum of five feasible concept designs
 - 2.2 Sketches illustrating physical principles, working geometry, and material
 - 2.3 Completed product function decomposition diagrams
 - 2.4 Completed morphological structure table
 - 2.5 Weighted-rating evaluation table
3. Develop alternative configuration designs
 - 3.1 Three feasible product architecture diagrams
 - 3.2 Special-purpose configuration sketches
 - 3.3 Completed design for assembly checklist
 - 3.4 Completed design for manufacture checklist

4. Work Breakdown Structure. A work breakdown structure (WBS) is a project. It is a graphical "outline" of sorts. The primary work task categories are shown at the top level, with subordinate tasks underneath each major task. In one glance, the reader gains an overview of the work to be completed. An example is shown in Figure 14.2.

5. Scope of Work. A scope of work is a written detailed list of tasks to be completed during the project. Each level 1 task is subdivided into level 2 tasks. For large projects, level 3 and level 4 task descriptions can be used. Alternatively, the list can be expanded into narrative sentences and paragraphs. Alternatively, progress reports, test reports, physical prototypes, and computer programs, are also mentioned, in addition to the task description. Successful teams use the opportunity to jointly develop the work scope and clarify and resolve potential misunderstandings before the project begins. An example work scope is shown in Table 14.2.

6. Responsibilities Table. The individuals responsible for each task, as well as others who will be assisting, are listed in a project responsibilities table. Those in charge of a task have "R" next to their work time estimate. The table helps to coordinate key team members and those that assist. An example responsibilities table is given in Table 14.3.

7. Organization Chart. An organization chart includes the name and function of each team member. The chart helps to facilitate communications and foster accountability. An example chart for a concurrent engineering design team is shown in Figure 14.3.

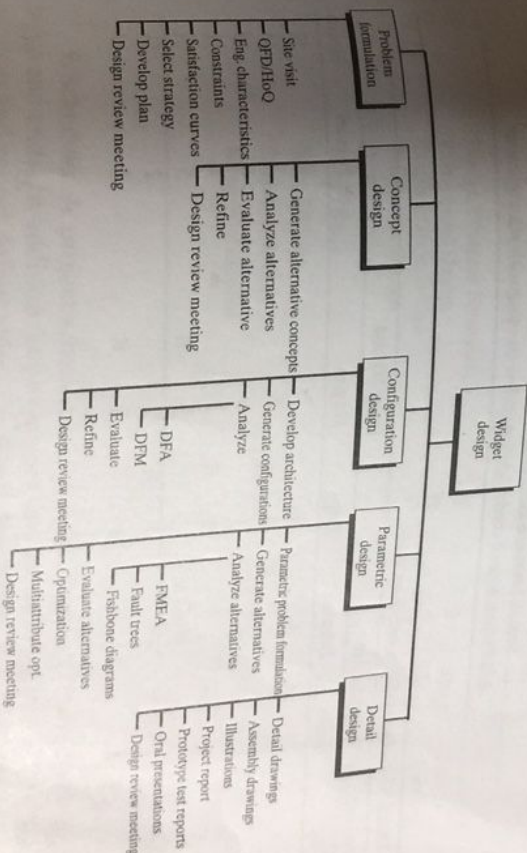


FIGURE 14.2 Work breakdown structure for a typical new product design project.

TABLE 14.2 Example Scope of Work for Section 1

1.0 Design problem formulation	
1.1	Visit site
1.2	Meet with management/clients to discuss design problem
1.3	Make phone calls to determine pros and cons of current unit
1.4	Set an appointment time to witness existing product in operation
1.5	Conduct benchmarking
1.6	Research existing products that are currently available
1.7	Conduct benchmarking
1.8	Conduct benchmarking
1.9	Analyze the competition for functionality and performance
1.10	Complete QFD/HOO
1.11	Determine requirements, engineering characteristics
1.12	Determine parameters
1.13	Define problem definition parameters/performance parameters
1.14	Define solution evaluation levels
1.15	Estimate satisfaction levels for performance parameter
1.16	Estimate satisfaction levels for performance parameter
1.17	Prepare engineering design specifications
1.18	List in-use purposes for the product
1.19	List customer and company requirements
1.20	Finalize scope of work
1.21	Refine work breakdown structure
1.22	Determine schedule
1.23	Assign a time value to each task
1.24	Prepare Gantt chart
1.25	Prepare budget
1.26	Determine total number of engineering hours
1.27	Determine total number of expert faculty hours
1.28	Sum all hours and material cost
1.29	Prepare for and conduct design review meeting with management

TABLE 14.3 Project Responsibilities Table

Project Name: Widget Design		Date: 7/11/04		n-th Person		Hours	
Task	Smith	Johnson	Tully	Hughes	n-th Person	Hours	
1.1	6	R	1	1	2	2	12
1.2	3	3	R	2	3	3	14
1.3	1	2	3	6	6	R	18
1.4	2	1	2	R	2	4	11
1.5	4	1	1	3	R	5	14
1.6	3	2	2	R	2	2	11
1.7	2	1	2	5	R	3	13
m-th task	21	11	13	23	25	93	
Total hours	21	11	13	23	25	93	
R - Responsible engineer in-charge							

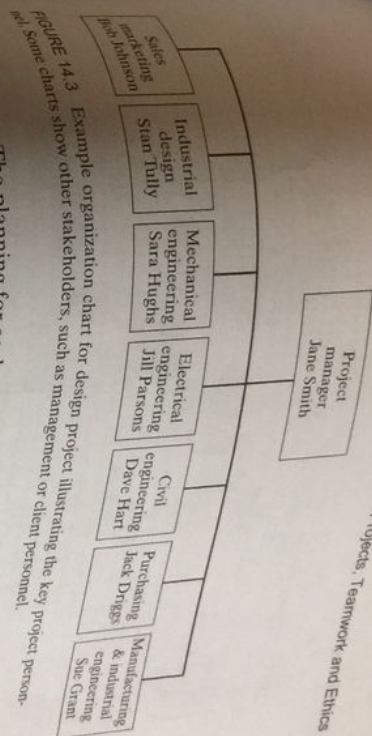


FIGURE 14.3 Example organization chart for design project illustrating the key project personnel. Some charts show other stakeholders, such as management or client personnel.

8. Budget. The planning for each work task is assigned to one or more individuals. They, in turn, estimate the man-hours, and other resources, necessary to complete the assigned task and are summarized in the project budget. An example budget is shown in Table 14.4.

TABLE 14.4 Example Project Budget Listing Major Work Tasks, Time, and Expenses Required to Complete the Project Tasks

Project Name: Snow Blower Attachment Design		Date: 2/7/04		
Project Budget				
Task	Description	Sr. Engineers	Admin. Hours	\$
1.0	Design Problem Formulation	91	2	93
2.0	Conceptual Design	96	6	102
3.0	Configuration Design	97	8	105
4.0	Parametric Design	160	9	169
5.0	Detail Design	202	10	212
	Total Hours	646	35	681
	Rate: \$/Hour	20	40	
	Total Labor Cost	\$ 12,920	\$ 1,400	\$ 14,320
	Materials/Supplies			\$200
	Total Costs:			\$ 14,520.00

9. Schedule. A project schedule is a chart that illustrates when each task begins and ends. In addition, key events are denoted, including interim review meetings and report deliverables. The Gantt chart format shows work tasks as horizontal bars as shown in Figure 14.4. Special events, called milestones and deliverables are often shown as small diamonds, triangles, or circles.

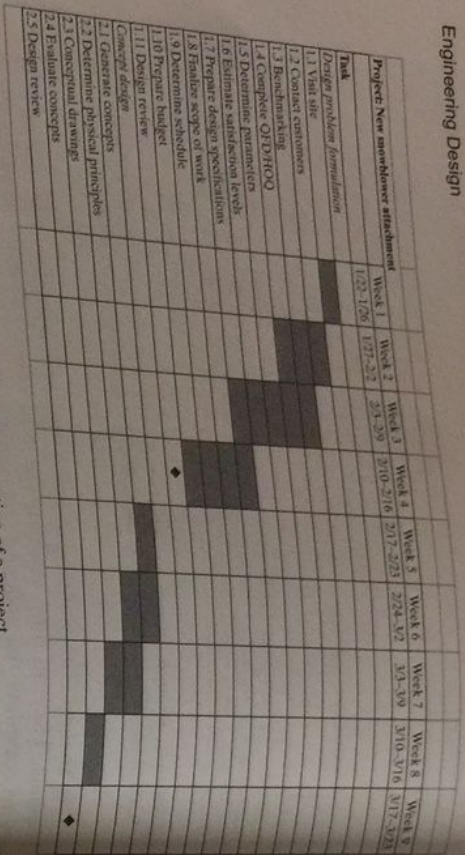


FIGURE 14.4 Example project schedule showing a portion of a project.

The major drawback of the Gantt chart is that succeeding tasks are not "connected" to preceding tasks. It is difficult to determine what effect a delay in a preceding task will have on succeeding tasks and the overall project completion date.

An advanced method, called activity network diagramming, overcomes Gantt chart drawbacks. Project activities are connected by arrows illustrating the network of dependencies. Combinations of parallel and sequential activities are thereby effectively managed. A critical path through the network can be also identified using some simple rules and basic arithmetic. The critical path determines the shortest time to complete the whole network of activities. The program evaluation and review technique (PERT) is an extension of the critical path method and uses quantitative measures to enhance project scheduling. Activity network diagramming is beyond the scope of this book. More information on this method and other aspects of project management can be found in Badiru and Pulat (1995) and Stub et al. (1994).

10. Risk Assessment. The last section of a project plan involves an assessment of the likely risks that face the project and possible contingency plans to overcome such situations. We call this activity risk assessment. First, we determine what risks might exist. Two questions that we might ask are "What is likely to go wrong with the project?" and "What could prevent us from achieving our objectives?" Construction projects, for example face considerable risks, such as building-permit-approval delays, inclement weather, construction-material-delivery delays, and worker strikes. Design projects face risks such as the accidental death or sickness of key personnel, glitches with computer software, delays with fabricating prototypes, testing accidents, and

Chapter 14 Projects, Teamwork and Ethics

major quote delays. The second aspect of the risk assessment is to consider and recommend a variety of contingency plans. Recognizing key risks in a project and having a couple of ready fallback plans is just smart business.

The project plan is a road map of what the team should be working on, when it should have tasks completed, and how much time and resources to devote to each, or ahead or behind schedule. The plan helps the team to keep over budget. Without a plan the team has no idea if it is "on-track" or not, under control. Without a road map the team may not know where it is going, or where it should reach its destination.

During the project planning phase a significant amount of information is generated and collected. Project notebooks can organize and protect data, analyses, and observations. It behooves each team member to protect data, analyses, and observations. In addition, a team notebook or file cabinet is sometimes used to store originals of key documents. Notebooks and file cabinets should be organized into convenient sections as suggested in Table 14.5.

TABLE 14.5 Example Project Notebook/File Cabinet Sections

Project name
Team member name
Telephone/e-mail addresses
Design problem formulation
Engineering design specifications
Customer notes
House of quality
Prior art (library research, Web)/benchmarks
Alternative generation, analyses, and evaluation
Analysis plan
Computations, experiments
Citations for equations, data
Spreadsheets
Sketches, figures, schematics, drawings
Evaluation plan
Evaluations/computations
References/bibliography
Project engineering
Project meeting notes
Work breakdown structure
Scope of work
Project schedule and updates
Budget, earned-value analyses
Risk assessments
Time sheet—log of work/team meeting hours
Punch lists of things to be done
Vendor information
Telephone numbers, addresses
Phone conversations notes
Web site printouts
Product/vendor literature

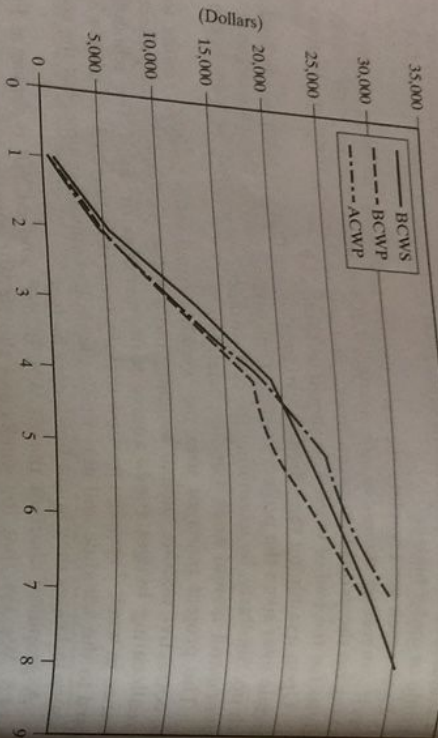


FIGURE 14.5 Earned-value Analysis Graphs of the BCWS, BCWP, and ACWP. The gap between the BCWP and BCWS lines is the schedule variance. The gap between the BCWP and ACWP is the cost variance.

14.2.3 Closing a Project

At the conclusion of a project we perform a project review. We reflect back what we learned, what we did well, and what we could have done better. We record and archive these findings for future use. Archival information can give future project teams a head start and hopefully prevent them from making similar mistakes. An official closing of the project signifies that our project team is no longer working or spending resources on it and is available for reassignment.

14.3 TEAMWORK

A **team** is a group of people who have complementary skills and knowledge, work together toward common goals, and hold each other mutually accountable. A product development team, for example, will have members with special skills and knowledge in areas such as sales, marketing, engineering design, purchasing, manufacturing engineering, production, and distribution. They share the goal of developing a successful product. They also are mutually accountable for the performance of the fellow team members.

Not all teams have **teamwork**, however. In team sports, for example, we routinely witness examples where teamwork breaks down, with personality issues, poor timing, or not paying attention to the game. Engineering design and manufacturing teams are quite similar.

14.3.1 Elements of Teamwork

Let's examine a well-executed offensive play in football to identify some of the necessary ingredients for teamwork. The quarterback receives the ball and initiates the defensive lineup, spots an opportunity to run a different play, and initiates the new play in a coordinated fashion. Individual team members perform separate roles, but with a common purpose of scoring. Blockers protect the quarterback as he drops back into the pocket for a pass. A halfback splits forward to a fake a running play. As one receiver sprints from the scrimmage line he sees an opening and adapts his running pattern. The quarterback lofts the football in his direction. The receiver successfully catches the ball and runs toward the goal line with his teammates blocking a path in front of him. Using his well-conditioned running skills he dodges the last tackler and scores a touchdown. Now that was teamwork!

Successful project teams and sports teams exhibit a number of common behaviors which can be classified into four major categories (McGourry and DeMeuse, 2001): communication, decision making, collaboration, and self-management.

Communication Communication is the means by which we exchange information between team members. The quarterback communicated his observation to the offensive line, thereby taking advantage of an opportunity. He also effectively communicated the timing of the hike, preventing an offside penalty. Downfield team members were watching and listening and came to the aid of the receiver.

Principal forms of communication include spoken and written messages. An effective communicator will spend time in preparing better oral presentations, written documents such as e-mails, memoranda, and reports. And an effective communicator will take specific actions to make himself or herself understood.

Listening skills are an important aspect of good communication. The downfield teammates had their "heads up," watching and listening to the play as it unfolded. Without their "listening" the play might have ended differently. Whether in professional football or business, we can find people who "miss the call" because they are not listening carefully or paying attention.

Listening is an individual skill, something that we have control over, and something that we can improve. Listening guidelines include:

Stop talking. Hear "the play?" Engage in only one discussion at a time.
Show respect. Empathize with the speaker. Show interest in what is being said, respond with appropriate body language, and refrain from interrupting.

Concentrate on what is being said. Do we understand the message completely? Is there something missing?

Stay calm. Keep control of our emotions. React to the ideas or facts not to the speaker presenting them. Try not to jump to any conclusions.

Ask questions. Take responsibility for some of the communication. Paraphrase the speaker's main points until we understand them. We should first try to understand the speaker before trying to have our views understood.

Decision Making Effective decision making begins with having a clear understanding of the problem. It also involves activities for generating, analyzing, evaluating, and refining alternatives, and then implementing the best one in a timely fashion.

Team decision making takes effort. For example, when we make "individual" decisions we don't necessarily need to communicate with, or understand, others. We can use our own criteria and selection process to decide the best alternative. We rarely have to compromise or consider other options if we don't want to. Team decision making, on the other hand, requires subordinating our own individual desires for the good of the team.

Assuming that the team has gathered the pertinent data and established evaluation criteria and importance weights, they can prepare a weighted rating evaluation to prioritize the alternatives. The final decision, however, comes down to the team making its final selection. Various approaches include a handoff to management, voting, and consensus.

The handoff to management is an abrogation of the team's responsibility to find the best solution for the company. Non-effective teams will pass decisions up the chain of command, especially if the team is concerned about personal retribution. Effective teams will be decisive and recommend action plans for management review and approval.

Voting is a seemingly democratic process, which can lead to some less-than-desirable consequences. If the team decides to use a "unanimous vote required" criterion one team member has the power to veto all choices, such that everyone loses. If the team uses a "majority vote wins" criterion then as the majority wins, the minority loses. Ignoring the minority's issues may put the company at risk.

A **consensus decision** occurs when the team thoughtfully examines all of the issues and agrees upon a course of action that does not compromise any strong convictions of a team member. The approach gives everyone an opportunity to present his case, while recognizing that in some circumstances a "command decision" has to be made. While a team member may not get the choice he favors, at least he knows why, and moreover, agrees that the decision has to be made.

Collaboration Teams that exhibit effective collaboration have members that are committed to the goals of the team, work cooperatively and constructively, actively participate in team activities, and support fellow team members. In our example, the blockers protected the quarterback. And the receiver got blocking help from his teammates when they realized the opportunity for a team score. Collaboration requires subordination of individual desires so that the team can benefit.

Self-Management Effective teams have members that manage themselves. They monitor their own progress to meet established goals, stay focused on their tasks, use meeting time effectively, solicit constructive feedback on their performance, involve others in all the decision making, and put top priority on getting results.

By improving our collaboration, communication, decision-making and management skills we can become better team members. Fifteen team-building skills are presented in Table 14.10. Informally, we can regularly evaluate our own teamwork skills. We could also ask our fellow team members, team forms: paper, computer, or internet-based, to survey team members and use the results to improve our teamwork. More formally, we can use forms: paper, computer, or internet-based, to survey team members and to evaluate ourselves (Eggert, 2008; Loughry et al. 2007; McGourty and DeMeuse, 2001). The forms are distributed to team members for completion, collected and forwarded to an independent person, thereby protecting anonymity. A summary report is then prepared and returned to each team member. Frequent feedback and self-reflection are potent tools that help to build teamwork skills.

TABLE 14.10 Teamwork skills

Collaboration	1.	Understands and commits to team goals
	2.	Participates actively in team activities
	3.	Respects individual viewpoints/differences
	4.	Accepts criticism
	5.	Assists other teammates
Communication	6.	Listens attentively to others on team
	7.	Provides constructive feedback
	8.	Communicates clearly and concisely
Decision Making	9.	Makes decisions based on facts
	10.	Anticipates problems
	11.	Contributes to meetings
Self-Management	12.	Monitors self-progress
	13.	Completes individual tasks thoroughly
	14.	Completes individual tasks on time
	15.	Asks for help when needed

14.3.2 Stages of Team Development

Teamwork develops over time. We don't expect a group of football players to exhibit teamwork the first day of practice. Neither can we expect a business team to do the same. A professional team will practice their skills until they are ready for the game. Unfortunately, few business teams have the same opportunity. Business team members usually develop their skills of communication, decision making, collaboration, and self-management on-the-job.