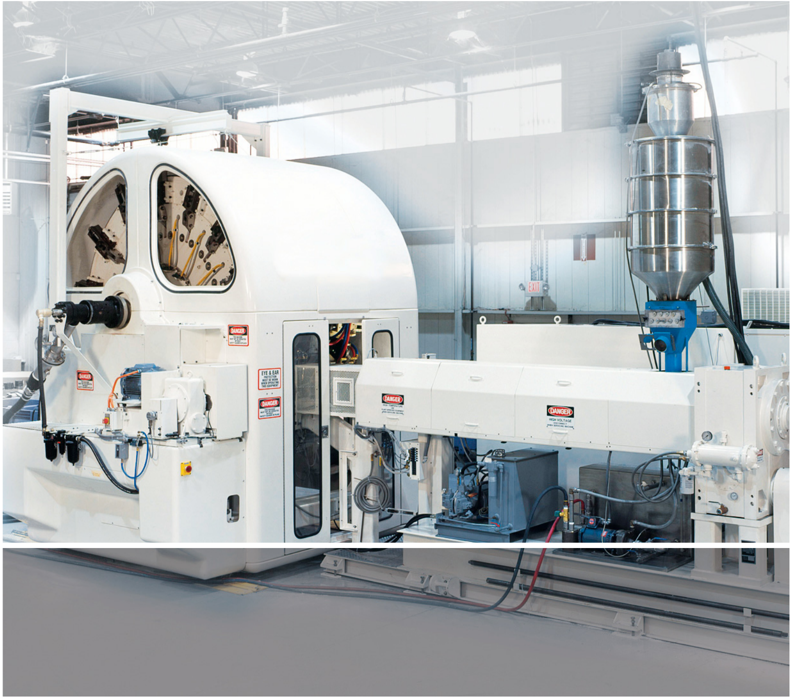
David O. Kazmer

Plastics Manufacturing Systems Engineering

A Systems Approach



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Dedication

The word “educate” is derived from the Latin word “educare”, literally translated as “to bring out of” or “to lead forth”. This book is dedicated to my father, Andrew James Kazmer, who has brought out the best in me.

Acknowledgement

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Prof. K. K. Wang of Cornell University; Prof. Phil Barkan & Prof. Kos Ishii of Stanford University; Prof. Francis Lai, Prof. Nick Schott, and Dr. Stephen Johnston of Univ. Mass. Lowell; Dan Hazen of MKS Instruments; Brian Dowler of Graham Engineering, and Joe Dziedzic of AEC, Inc.

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Preface

Plastics manufacturing is a highly interdisciplinary field integrating materials science, physics, engineering, and management. Because of this diversity, the plastics engineer interacts with many stakeholders: customers, designers, materials suppliers, machine builders, mold/die suppliers, systems integrators, operators, quality engineers, managers, and others. Yet, many plastics manufacturing systems are poorly engineered and require too much investment to achieve too little productivity.

This book was written to support plastics and manufacturing engineers as well as others who are performing process development, research, and design. The physics of these processes are not treated here at an advanced level given the availability of many more specific reference texts. Instead, a systems engineering approach was adopted to provide guidance about plastics manufacturing as an integrated system with broadly applicable analysis of the underlying subsystems.

The book begins with a high level review of plastics manufacturing strategy from a management perspective followed by a review of plastics manufacturing systems from a technical perspective. The remaining twelve chapters of the book are evenly divided into three parts related to 1) machine elements, 2) controls, and 3) operations. More specifically, the chapters of the book are outlined as follows:

- Chapter 1 opens with cost and productivity data of the plastics industry. Manufacturing planning and strategy are then discussed to provide a basis for plastics manufacturing systems engineering. To economically efficient engineering, a review of engineering economics is also provided.
- Chapter 2 provides a brief overview of the most common plastics manufacturing processes including extrusion, injection molding, thermoforming, and blow molding. The goal is not to provide detailed analysis of these processes, but indicate the common characteristics of their design and operation.
- Chapter 3 provides design and analysis of heating and cooling systems commonly integrated within plastics manufacturing processes. The chapter also provides a discussion of specifications applicable to all actuators.
- Chapter 4 covers hydraulics and pneumatics including not only cylinders and motors but also pumps and the supporting fluid conditioning systems. Design and operation of directional and metering valves is supported by dynamic analysis of the integrated fluid power system.
- Chapter 5 supports the increasing use of electric drives in plastics manufacturing. While the book focuses on the design of DC and AC motors, basic analysis of electromagnetism and electromotive forces are provided. A comparison of these and other motors is developed with respect to efficient, power output, and other performance measurements.
- Chapter 6 discusses sensors used for feedback control of the process states such as force, pressure, position, and temperature. Common transducer specifications are also discussed.

- Chapter 7 delves into signal conditioners used for signal conversion, amplification, filtering, and digital signal processing. The chapter also provides some very practical programs for implementing filtering in control software or post-processing.
- Chapter 8 deals with data acquisition: analog to digital, digital to analog, and digital input/output. Performance specifications related to resolution, response time, and bandwidth are analyzed to support the selection and use of commercial products.
- Chapter 9 discusses the integration of these subsystems with modern control system architectures including programmable logic controllers, virtualized PC controllers, and embedded controllers.
- Closed loop control and tuning are discussed in Chapter 10. The chapter has been written to be highly accessible without the use of Laplace transform yet still provide significant insight into PID control laws and tuning.
- Chapter 11 provides a process characterization methodology based on statistical modeling of variation, design of experiments, and regression methods.
- Chapter 12 uses the developed process models for process optimization, providing a treatment of both process window mapping and multiobjective optimization.
- Chapter 13 covers quality control with gage R&R, acceptance sampling, and statistical process control.
- Finally, Chapter 14 discusses various process and plant automation technologies that can be implemented after the plastics manufacturing processes are developed, optimized, and consistent.

It is my intention for the book to cover the essence of plastics manufacturing systems engineering. I hope you find it useful and are encouraged to advance your applications and improve our world's prosperity.

Sincerely,

David Kazmer
Lowell, Massachusetts
April, 2009

1 Background

Plastics are a class of materials with diverse characteristics, low cost per unit volume, and relative ease of conversion into finished goods. In industry practice, value engineering techniques have consistently found that plastic components provide high function per unit cost [1], motivate further materials development [2], and have undergone “explosive” growth [3]. Such commercial growth, however, has permitted inefficiencies in plastics manufacturing that are no longer acceptable in the marketplace. Current issues now threatening plastics manufacturers include continued global competition [4], increases in feedstock and commodity prices [5], and surging environmental awareness [6]. As a result, plastics manufacturing systems need to be well engineered, make optimal use of human and natural resources, and provide competitive yet socially responsible solutions.

1.1 Plastics Industry Review

1.1.1 Manufacturing Productivity

Global economic growth has fueled the development of international supply chains. Plastics manufacturing has grown more quickly overseas than in more developed markets for at least three reasons. First, plastics manufacturing has traditionally required semi-skilled machine operators who are available at lower cost overseas [7] (see also the labor cost comparison in Appendix A). Second, overseas plastics manufacturing has been required to supply growing local demand of plastic components [8]. Third, overseas plastics manufacturing is tightly integrated into the supply chain with other overseas manufacturers for production of complex products exported back to the United States and other developed nations [9].

The demise of manufacturing in the United States and other developed countries is grossly overstated. As shown in Figure 1-1, it is true that employment in the manufacturing sector has declined from roughly 1 in 3 workers during the 1950s to roughly 1 in 10 workers today. Some analysts point to this decline of manufacturing employment as a percentage of the workforce as evidence that developed countries can not compete given an abundance of lower cost labor in less developed nations [10]. Other issues that are claimed to undermine manufacturing competitiveness include lax regulation of environmental protection and worker safety, theft of intellectual property, unfair currency valuations, and other indirect cost disadvantages [11]. It would be understandable if one were to believe that manufacturers in developed nations have no hope of competing with offshore manufacturers.

However, the decline of manufacturing employment shown in Figure 1-1 is somewhat misleading since it does not consider that the size of the workforce has increased with population growth. When this factor is taken into account, the number of workers employed in manufacturing has remained nearly constant. Furthermore, the “demise” of manufacturing is directly countered by the sustained growth of manufacturing output shown in Figure 1-2.

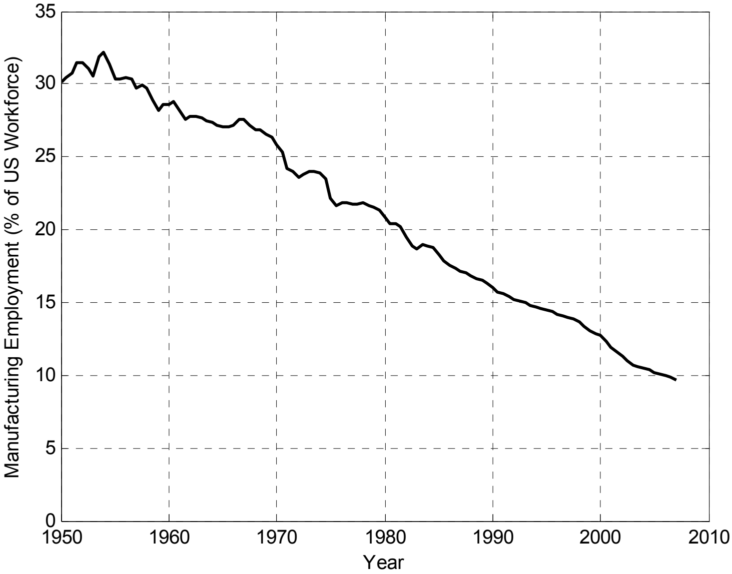

Figure 1-1: Decline in manufacturing employment

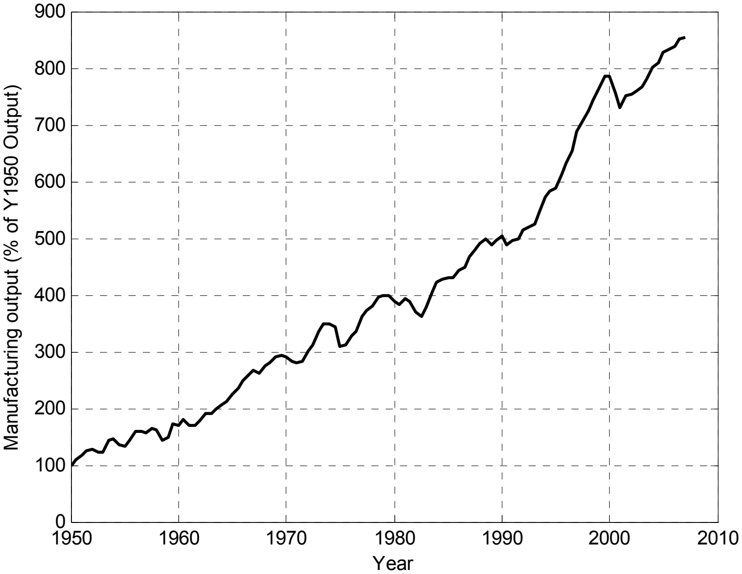

Figure 1-2: Growth in manufacturing output

Specifically, sales of products manufactured in the United States has seen more than an eight-fold increase since the "golden" year of 1950 [12]. In fact, the growth in manufacturing output has accelerated in the past twenty years, a period during which many analysts suggested that US manufacturing was in decline.

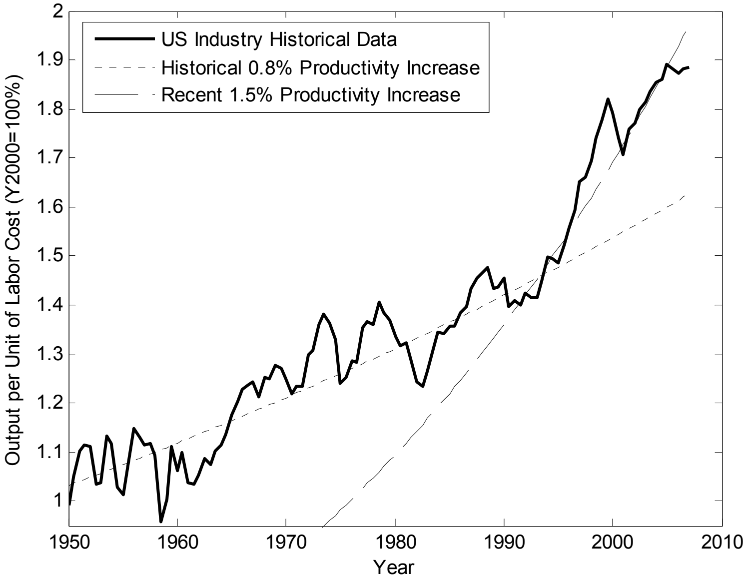

Figure 1-3: Net increase in plastics manufacturing productivity

Even though manufacturing output has grown in the United States, plastics manufacturers continue their focus on cost reduction and productivity increases. The US Department of Labor's Bureau of Labor Statistics indicated that plastics production per worker increased 2.6% per year from 1987 to 2006, a net 67% increase in labor productivity over that period. However, labor costs rose by 3.5% per year during that same period, or a 99% increase in labor costs. The net result is that labor costs increased at an annual rate of 0.9% per unit of production [13]. When this historical data about the workforce size and labor costs is factored into the analysis, the change in plastics manufacturing productivity can be estimated as shown in Figure 1-3. Manufacturing output per dollar of labor cost has roughly doubled over the span of sixty years, which corresponds to productivity growth of 1.1% per year.

There appears to be a breakpoint in the productivity data of Figure 1-3 around 1990. Between 1950 and 1990, manufacturing productivity per labor dollar increased at a rate of 0.8% per year. After 1990, manufacturing productivity appears to increase at a higher annual rate of 1.5%. There are many potential reasons for the more recent increase in manufacturing productivity including:

- Improved manufacturing system designs through the use of total quality management (TQM, [14]), lean principles [15], Six Sigma initiatives [16], etc.,
- Higher levels of automation provided through robots and other information technology [17], and
- Manufacturers reducing their number of employees in response to lower labor costs available in the global marketplace.

The net result of this analysis is that plastics manufacturers need to increase their productivity at a rate of 1 to 2% per year or risk jeopardizing their long term profitability and competitiveness. In a global marketplace, other manufacturers are likely to offer similar products at more competitive prices. If a company does not continually reduce their manufacturing costs in response to competitor pricing, then that company's profit margins will eventually be eroded to a point where their business is no longer viable.

1.1.2 Manufacturing Cost Breakdown

The preceding manufacturing productivity analysis is macroeconomic in nature, meaning that it aggregates the manufacturing output and labor cost statistics of many different manufacturers. As such, the analysis provides little guidance as to how a plastics manufacturer can increase their manufacturing productivity. One approach is to breakdown the costs of goods sold into individual categories, and then consider alternative strategies to reducing the cost components. The cost of goods sold is generally referred to as "COGS", and is well defined in most accounting systems [18]. The cost of goods sold typically includes the direct materials and labor required to produce the goods sold by a company. The gross profit margin of a company is the difference between the sales revenue and the cost of goods sold. To increase profitability without changing pricing, companies continually seek to reduce the cost of goods sold by reducing the underlying cost components.

An approximate breakdown of cost of goods sold for various plastics manufacturers is provided in Table 1-1. For a typical manufacturer, the cost of the materials used to make the product is the single largest cost driver and often represents 50 to 60% of the production costs. These "direct materials" most often include resin, sheeting, fasteners, colorant, packaging, and other materials that are directly incorporated into the finished goods. Other "indirect materials" are also used in production, including supplies, lubricants, cleaners, solvents, adhesives, and others that are purchased by the manufacturer but not used exclusively for production of one type of good. Because these materials are directly incorporated into the product, increases in material costs have direct adverse effects on the cost of goods sold. Some strategies for cost reduction include standardization of materials and buying in bulk to negotiate better delivery terms with suppliers, substituting lower cost materials or switching to lower cost suppliers, reducing the amount of material used in the product, and reducing or recycling the amount of scrap generated during production.

The second largest cost driver for most plastics manufacturers is the cost of the labor directly used in production. The direct labor includes the set-up technicians, machine operators, assembly workers, material handlers, production supervisors, and other workers who are directly involved in the manufacturing operations. For a typical plastics manufacturer, the cost of direct labor represents about 25% of the cost of goods sold. Plastics manufacturers also incur indirect labor costs for workers who perform maintenance, janitorial, and other services that are required to keep the manufacturing lines running. These workers are referred to as "indirect labor" since their services are not dedicated directly to the production of manufactured goods. The previous analysis of Figure 1-3 indicates that the combined cost of direct and indirect labor per unit of manufactured output should decrease at roughly 1.5% per year due to productivity improvements.

Table 1-1: Cost of goods sold (COGS) for typical plastics manufacturer

Cost category	Typical plant	Overseas plant	Automated plant
Direct materials (resin, sheet, fasteners, etc.)	0.50	0.48	0.50
Indirect material (supplies, lubricants, etc.)	0.03	0.03	0.03
Direct labor (operators, set-up, supervisors, etc.)	0.25	0.08	0.05
Indirect labor (maintenance, janitorial, etc.)	0.05	0.05	0.02
Fringe benefits (insurance, retirement, vacation, etc.)	0.07	0.03	0.03
Other manufacturing overhead (rent, utilities, machine depreciation, etc.)	0.10	0.08	0.10
Shipping (sea, rail, truck, etc.)	0.00	0.05	0.00
"Landed" product cost	1.00	0.80	0.73

Most manufacturers tightly control labor utilization since it is a significant expense that can be adjusted in response to production levels. In particular, manufacturers carefully control the number of full time employees (FTEs) since employers are required by law to provide full time employees with health insurance, retirement, vacation, and other fringe benefits. These fringe benefits represent 5 to 15% of the cost of goods sold [11]. Some strategies for reducing labor related costs include hiring part time employees with fewer benefits to work more flexible shifts in response to varying production levels, cross-training employees to work different roles within the factory in response to varying production levels, redesigning products to reduce the number of components per assembly or reduce the product assembly time, increasing production output per machine line, increasing production consistency and automation to reduce the number of workers per line, outsourcing component production to lower cost suppliers, and others.

The cost of materials and labor together typically represent more than two-thirds of the cost of goods sold for plastics manufacturers. Other manufacturing costs may include rent, utilities, machine and mold depreciation, insurance, inventory spoilage, interest expenses, and other items. Though a smaller contributor to the cost of goods sold, these "overhead" costs directly reduce profitability and are often reduced by increasing the number of shifts worked per week, water and energy conservation programs, just in time inventory programs, improved maintenance programs provide to extended equipment usage, slower depreciation rates, and others.

Some manufacturers are drawn overseas to reduce their manufacturing costs. As indicated in Table 1-1, a typical overseas plant may reduce the cost of their "landed" products by up to 20% compared to a typical domestic plant. In some cases, plastics manufacturers are driven overseas to support their customer's supply chains. For instance, suppose that an automobile manufacturer wishes to sell their vehicles to the Chinese public. China and many countries dictate limitations on the proportion of a product that must be domestically produced [19]. The easiest way to ensure compliance and avoid high tariffs is to produce and assemble the product in the country where the product is sold. Once an automotive supplier decides to assemble cars in a foreign country, the supporting plastics manufacturers must also deploy on foreign soil to meet the customer's just in time delivery requirements.

The cost breakdown of the overseas plastics manufacturing plant is somewhat different than that of the domestic plant. Clearly, the costs of direct labor and fringe benefits in plants located in developing countries are much lower in the overseas plant due to lower labor rates and reduced standard of living. The cost of direct materials is also sometimes lower due to local availability of these materials. Even so, plastics manufactures utilizing overseas manufacturing are often disappointed due to the increased cost to support and qualify the overseas suppliers, lag in communications, reduced flexibility, greater inventory exposure, risk of intellectual property theft, and increased shipping costs. As such, the best product candidates to be outsourced to overseas suppliers are those that have a stable production schedule, require significant labor, and do not require or disclose valuable technology [20].

1.1.3 Characteristics of Productive Plastics Manufacturers

Regardless of where the plastics manufacturing plant is located, manufacturing costs are reduced by maximizing material, machine, and labor productivity. Consider a molder annually producing two hundred million 15 g parts molded from polypropylene with 1990 era molding technology.[1] To meet production requirements, this molder would need 48 molding machines, 48 operators (24 operators for each of two shifts), four production supervisors, and 6 million kilowatt hours of energy per year. If operating today in the United States with current labor, material, and energy rates, the cost of goods sold would be about $0.025 per piece. For comparison, a highly automated molder[2] with the same production requirements would need only 8 molding machines, 6 operators, one production supervisor, and 2 million kilowatt hours of energy per year. With the same labor, material, and energy costs, the cost of goods sold would be about $0.016 per piece, a reduction of more than 30%.

Further analysis shows that a highly productive domestic plant can compete with highly productive foreign plants when shipping and other transaction costs are considered. Unfortunately, the transition to a modern, highly automated factory is not trivial. Plant tours through "lights out" and other highly productive facilities indicate some significant commonalities. First, productive plastics manufacturing are highly systematized. The term "systematized" does not necessarily mean "automated". Rather, a highly systematized facility has an excellent layout, consistent (and often unidirectional) flow of materials, and formal production planning, and stringent quality control processes. To support the systematization, most highly productive facilities use only one primary supplier of plastics machinery and many facilities use only a single model.

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[1] 1990 era technology in a commodity application may be considred 16 cavity molds (50% with hot runner systems) with well selected hydraulic molding machines (30 kW), 45 seconds per average cycle, 98% quality level, one operator per two machines, one supervisor per fifteen operators, running two shifts per day for five days per week, and performing a two hour setup per batch of ten thousand pieces.

[2] Modern highly automated technology may be considered 32 cavity molds with hot runners, all electric molding machines (22 kW), 35 seconds per average cycle, fully automatic materials handling, 99.9% quality level, 1 operator per four machines, one supervisor per fifteen operators, running twenty four hours per day for seven days per week, and performing a thirty minute setup per batch of ten thousand pieces.

Table 1-2: Plastics manufacturer characteristics

Cost category	Typical plant	Efficient plant
Machines or lines	48	8
Operators	48	6
Production supervisors	4	1
Factory size	10,000 m^2	500 m^2
Energy use	6 GWhr	3 GWhr
Piece manufacturing cost	$0.025	$0.016

A second common trait of highly productive facilities is that the machines are highly utilized, with a majority of machines being used over 90% of the time. Most competitive plastics manufacturers run these machines 24 hours per day, seven days a week, with an occasional weekend day used for maintenance. Production schedules are often set on Friday for the following week. Typically, production schedules are developed to fully utilize a given set of machines. If the plant utilization is low due to a drop in demand, then a smaller set of the best machines is continuously operated rather than running all machines for fewer shifts. This strategy keeps the plant and manufacturing lines continuously operating, which thereby reduced operator and plant inconsistencies related to shut downs.

A third common trait is that yields are high, typically above 95%, but not as high as might be expected according to a Six Sigma philosophy that would dictate only a few defects per million. While defects and waste are undesirable, a fairly high level of defects can be tolerated internal to the plastics manufacturing plant without jeopardizing overall manufacturing profitability. Any defective products, however, must be automatically and consistently prohibited from leaving the factory since shipping defective products can result in high costs related to warranty and liability. As such, most highly productive plastics manufacturers do not rely exclusively on manual inspection by operators or acceptance sampling of finished goods. Rather, highly productive facilities use 100% quality assurance through automatic vision, part weight, metrology, or other statistical process monitoring of critical production variables. The control limits on these quality systems are typically set quite tight, so that any questionable products are discarded rather than accepted. The fundamental premise of this strategy is that the automatic quality assurance is so central to achieving high productivity that it is better to reject a small proportion of dubious manufactured products in an automated manner than require manual inspection to reduce the number of rejected products.

The fourth and final common trait to be discussed is that most highly productive facilities serve a single industry sector and application. The reason is that the development of robust manufacturing processes and automatic quality control systems requires significant experience and a long term commitment. As such, highly productive manufacturing systems tend to be developed at captive and custom plastics manufacturers who produce a single type of product, such as gears, electrical connectors, lenses, tubing, sheet, etc. By contrast, it would be difficult if not impossible to develop a single facility that could produce all of these plastic products as efficiently.

1.2 Manufacturing and Strategic Planning

Manufacturing is a critical determinant of how a company competes, and yet many manufacturing and process engineers do not understand how manufacturing processes are developed or scheduled. In many plastics manufacturing companies, the plant is provided a new manufacturing project but required (or assumed to require) that the new project must be implemented with the old manufacturing systems and policies. The result is that disconnects may develop over time between the current mix of products and the available set of processes and expertise within the plant. This disconnect can lead to poor quality, long lead times, low yields, high cost, low employee morale, limitations in product performance, and eventually corporate demise.

1.2.1 Manufacturing Planning

The engineering of a plastics manufacturing system depends upon the role of the process in the larger organization. Figure 1-4 provides a typical manufacturing planning process. Customer

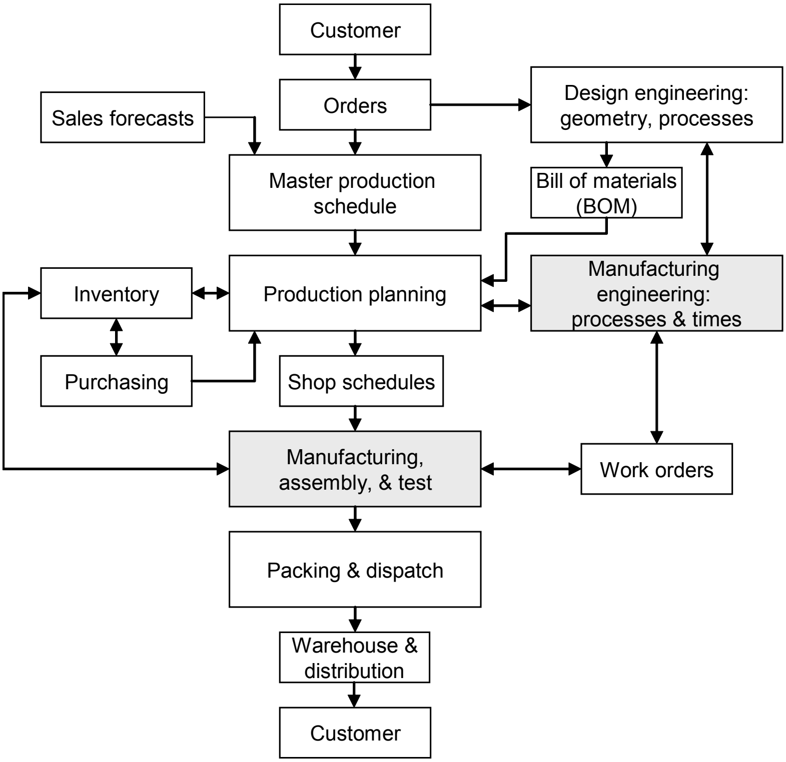

Figure 1-4: Manufacturing resource planning (MRP) process

orders and sales forecasts are provided to develop a master production schedule, which lists the products to be manufactured together with their quantities and dates. In those plastics manufacturing facilities whose piece parts are the final products, the master production schedule can directly drive the scheduling of the shop's labor and machinery given the machine availability, order quantities, and processing times.

In other manufacturing operations, the final product is assembled from multiple components that are either manufactured or purchased from suppliers. In these cases, the bills of materials from all products to be manufactured are examined and aggregated to determine the type and number of components required to assemble each product. A materials resource planning (MRP) program compares the required number of components with the inventory availability [21]. If the required number of components can be pulled from inventory, then the inventory is allocated and no component production is scheduled.

Example 1-1: A medical device manufacturer sells three similar products, each requiring a varying number of components as listed in the following table. Provide the aggregate demand for the underlying components.

Table 1-3: Materials requirements planning example

	Product A	**Product B**	**Product C**	**Inventory level**
Projected demand	400	800	200	n/a
Couplers	1	2	3	2,000
Lumens	1	1	2	2,000
Tubing length	10	15	18	20,000

Solution: The demand, D, for each of the components can be calculated as

$$D = \sum_j P_j \cdot n_j \tag{1-1}$$

where P_j is the projected demand for product j and n_j is the quantity of components required per finished product. Using this formula, the projected demand for each type of component is as follows:

	Projected demand	**Inventory level**
Couplers	$400 \cdot 1 + 800 \cdot 2 + 200 \cdot 3 = 2{,}300$	2,000
Lumens	$400 \cdot 1 + 800 \cdot 1 + 200 \cdot 2 = 1{,}600$	5,000
Tubing length	$400 \cdot 10 + 800 \cdot 15 + 200 \cdot 18 = 19{,}600$	20,000

In the previous example, a comparison of the projected demand against the inventory level indicates that more couplers are required and more lumens are not. However, the projected demand for the tubing is very close to the inventory level. Should more tubing be procured? The answer depends on many factors including the expected variability in demand, cost of stocking out, production lead times, potential for product obsolescence or inventory spoilage, and other issues. If more components are needed, then the MRP program calculates a suitable batch size that balances the cost of setting up the manufacturing process against the holding cost of carrying the inventory. This optimal quantity is frequently called the economic order quantity (EOQ) and is estimated as [22]:

$$EOQ = \sqrt{\frac{2\,k\,\lambda}{i\,C}} \qquad 1\text{-}2$$

where k is the cost of planning and setting up the process, λ is the rate of demand, C is the manufacturing cost per unit of demand, and i is an internal interest rate charged to the inventory holding cost. Most companies wish to avoid holding inventory, so the interest rate, i, is set higher than the desired rate of return on capital. Interest rates of 15 to 50% per year are typical depending on the application and manufacturer preferences.

Example 1-2: A pipe extrusion manufacturer produces a variety of different pipes with one particular schedule 40, 10 cm diameter pipe costing \$2.80 per meter in materials, labor, and processing time. The manufacturer estimates the setup cost to be \$120 including materials, labor, and extruder down time. Estimate the optimal batch size if weekly demand is 2,000 m and an annual interest rate of 25% is charged to inventory.

Solution: Equation 1-2 may be used to estimate the optimal batch size, but the annual rate of demand should be calculated since an annual interest rate is applied. A demand of 2,000 m/week equals 104,000 m/yr. Then, the optimal batch size is:

$$EOQ = \sqrt{\frac{2 \cdot 120\,\$ \cdot 104{,}000\,\text{m/yr}}{25\%/\text{yr} \cdot 2.80\,\$/\text{m}}} = 5{,}970\,\text{m}$$

The annual inventory holding costs and manufacturing setup costs can be compared to check the solution. The number of set-ups per year is 104,000 meters per year divided by 5,970 meters per setup, which equals an average of 17.4 setups per year for a total cost of \$2,090 per year. Assuming constant demand, the average inventory level will be one-half the batch size. The average value of the inventory is equal to one-half of the 5,970 meters times the 2.80 \$/meter, which equals \$8,358. The annual inventory holding costs is equal to the value of the inventory times the 25% interest rate per year, which equals \$2,090. The fact that the annual inventory holding costs equals the manufacturing setup costs indicates that the batch size is optimal. A larger batch size would reduce the number of setups and the total setup costs per year, but incur higher inventory holding costs.

To summarize the preceding discussion, the production quantities are estimated from the master production schedule, bills of materials aggregation, inventory allocation, and EOQ analysis. Once the production quantities are known, the production planning provides detailed schedules for each machine and worker in the shop as indicated in Figure 1-4. The production plan must consider the availability and throughput of each process as specified by manufacturing engineers. If multiple components are being produced on a single machine, then the order in which the jobs are processed is often determined by various scheduling heuristics [23]. The most common heuristics are first in first out (FIFO), earliest due date (EDD), and shortest processing time (SPT):

- FIFO schedules the jobs in the order by which they are received by the factory. FIFO is considered to be “fair” since each order maintains its place in line waiting to be fulfilled, but it often results in poor plant productivity.
- EDD schedules the jobs according to which job is due the soonest (or most overdue). EDD will tend to minimize the number of orders that are fulfilled late, and thereby minimizes the amount of expediting required in a plant.
- SPT schedules the jobs according to which jobs will require the least amount of time. SPT tends to minimize the average tact time in the plant as well as the average number of jobs on the docket, but can result in some very late jobs.

The production plan also computes the resource utilization given the setup times, processing times, and production quantities. The utilization levels are then compared to the available capacity to determine if additional shifts or overtime is needed to satisfy demand. Similarly, low utilization levels may be used to reduce the number of shifts or consolidate production into a fewer number of manufacturing lines. Since product demand and inventory levels vary over time, the production planning process is repeated on a weekly or daily basis to provide updated shop schedules. The resulting utilization and productivity levels are less frequently examined to indicate if a different manufacturing system design is necessary.

1.2.2 Manufacturing System Design

The foregoing manufacturing resource planning process is widely used, but is also widely disputed [24]. One reason for contention is that many of the planning inputs (such as the setup costs, inventory interest rate, inventory levels, lead times, and demand) are often difficult to estimate or expensive to track. Significant errors in these inputs can lead to incorrect inventory levels and production plans, idle machines and operators, and significant losses in manufacturing productivity and profitability. For instance, over-estimating the demand can result in scheduling overtime at a cost premium only to produce excess inventory that incurs additional inventory carrying costs. As another example, under-estimating the setup time or inventory interest rate can result in very large batch sizes and inventory that is never consumed due to obsolescence or spoilage.

A second and even more fundamental contention about centralized manufacturing planning systems is that they “push” components through the manufacturing and assembly processes, resulting ultimately in components and products that reside in inventory. Components and finished goods may remain in inventory for a very long period of time, such that any quality issues are not instantaneously discovered when the components were manufactured. As such, quality issues can be difficult to diagnose and correct with “push” type systems. Furthermore, management may also make pricing and manufacturing decisions based upon the current inventory levels rather than the fundamental market demand, leading to a poor product portfolio and lower profits.

Interestingly, manufacturing processes and facilities can be designed to operate with minimal or even no inventory at all. Such a lean system was first successfully developed by Toyota [25] and is referred to as a “kanban”, “pull”, or Toyota Production System (TPS). The kanban is essentially an empty bin that is sent from an almost starved downstream manufacturing

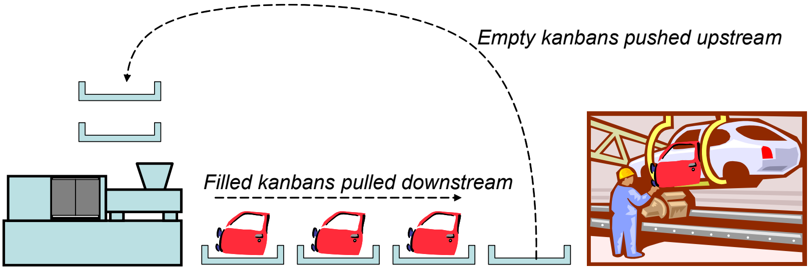

Figure 1-5: Pull type system with six kanbans

process that uses a given component to an upstream manufacturing process where the needed component is produced. The arrival of the kanban at the upstream process provides a signal to make parts and acts as the carrier of those parts back to the downstream process. As shown in Figure 1-5, a molding process and an assembly process may be separated by a couple of pieces of work in progress (WIP). As the upstream worker performs their task, they draw the work in process from the kanbans and send the empty kanbans back to the upstream process. The existence of kanbans at the upstream process signals that the upsteam process may continue production. If no kanbans are at the downstream process, then the downstream process already has several filled kanbans waiting to be processed and so "blocks" further production at the upstream process.

With very limited work in process between the upstream and downstream processes, any quality issues are continuously identified and resolved. Furthermore, the amount of inventory in the plant is purposefully determined by the number of kanbans and so eliminates the need for production planning based on inventory levels. Such pull system designs, however, do have some significant issues. First, problems with the supplying upstream processes can quickly starve the downstream process and the entire plant in a matter of minutes since there is no spare inventory from which to draw. For this reason, the manufacturing processes in a pull system must be very reliable. Second, the tight coupling of processes in a pull type system can limit the mix of finished goods that the system can produce. For this reason, many pull type systems and Toyota in particular have implemented flexible manufacturing processes that have minimal setup times and can produce a variety of components and subassemblies. Cross trained workers often are able to alter assembly processes within an assembly station to provide different product customizations. The result, at least for Toyota, has been a very lean production system that provides high quality vehicles in response to dynamic customer demand.

Designing a plastics manufacturing system to best meet product demand is no easy task, yet is a great opportunity for manufacturing engineers and their employers. Hayes and Wheelwright [26] recognized that the best manufacturing system is closely related to the complexity of the product design and the required production volume. As shown in Figure 1-6, there are many types of manufacturing systems. A job shop is a facility with various types of machines, such as lathes, mills, prototyping equipment, and hand assembly. Low volumes of custom products can be manually routed through the shop to perform the necessary production steps to produce the finished product. The variety of machines and flexibility in product routing provides a capability to make a wide range of products. However, the multiple process setups and relatively long processing times in job shops incur high manufacturing costs.

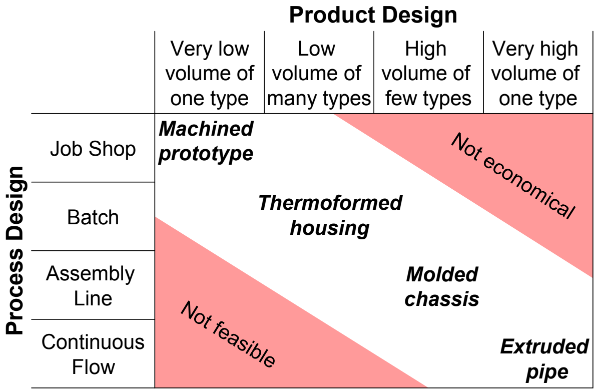

Figure 1-6: Product-process matrix

With higher production volumes, job shops are uneconomical leading to a preference for batch and assembly line processes. In a batch process, costs are reduced by using a more productive manufacturing process and producing a quantity of parts in a batch with a single setup. The same batch of parts is routed through the job shop in a flexible manner, but setup and processing times are reduced by processing all parts in the batch at the same time. Assembly line processes further reduce costs by linking all processes in a linear flow to eliminate setups, reduce part handling times, and increase the production throughput. A continuous flow process builds on the assembly line concept by specifically designing all manufacturing processes specific to a single product, and hard wiring the processes into a single continuous process.

Continuous flow processes tend to have the highest throughput and lowest marginal production cost. Unfortunately, continuous flow processes also tend to have the highest upfront implementation cost and least flexibility in the types of products that can be produced. As such, there are constraints on the manufacturing system design as shown by the diagonals in Figure 1-6. The upper right corner corresponds to products with high production volumes that are made with job shop or batch processes. While providing good manufacturing flexibility, these processes should be avoided due to high costs. Conversely, the lower left corner corresponds to products with low production volumes that are made with assembly line or continuous flow processes. These processes would result in low marginal costs, but will require upfront investment in manufacturing technology that is not feasible given the limited production volume or lifetime.

1.2.3 Strategic Planning

Hayes and Wheelright also suggest that there are different levels of manufacturing support within a company [26]. At the lowest level, in which management is said to be “internally neutral”, management simply wishes to minimize manufacturing’s negative potential on product quality and pricing. An example of this lowest level of support would be a company that does not see any advantage in their manufacturing and is seeking to outsource their production to a lower cost supplier. Such a low level of support can be reckless in the long term since their competitors also have access to the same supplier network. At the second level, “externally neutral”, management’s goal is to support manufacturing to achieve price parity with competitors. At the highest level of support, “externally supportive”, management bases much of their competitive strategy on their manufacturing unit’s unique capabilities.

There are four common competitive strategies pursued by companies [27]: 1) cost, 2) speed, 3) quality, and 4) performance. In a cost-based strategythe company seeks to minimize the manufacturing cost to provide the lowest product pricing in the marketplace. If costs are sufficiently low, then production quantities should increase with demand drawn to lower prices. Increased production quantities in turn support economies of scale. Material costs are reduced through supplier discounts related to buying in bulk. Furthermore, the same manufacturing overhead costs are levied across a larger production quantity. Yet, cost-based strategies can be detrimental to speed, quality, and performance. The reason is that costs are often minimized by using lower cost materials and labor, avoiding investments in technology, and limiting production capabilities. As such, companies focused solely on cost may not respond well to changes in the marketplace that demand different product offerings. The result is that the production volumes may decline, and eliminate any advantages of a cost-based manufacturing strategy.

A performance-based strategy seeks to provide a competitive advantage through the sale of products with unique attributes that are enabled by advanced product designs or manufacturing processes. By providing a unique product to the marketplace, the product pricing can be set much higher than those of competing products with lesser properties. However, the time and cost required to develop these unique products are typically greater than those of competitive offerings, so an increased price is required to maintain profitability. Furthermore, highly successful products tend to be reverse engineered by competitors and offered at a lower price unless the product and process designs are protected through patents or tightly held trade secrets. Companies with performance-based strategies are often undermined by companies using a speed-based strategy to quickly emulate and sell clones of other companies’ products.

Some companies seek to compete with a quality-based strategy in which a price premium is assessed for products having higher quality. If a product has a high failure rate or poor quality, then the customer will tend to avoid purchasing that company’s products in the future even at reduced prices. Conversely, higher product quality may provide some price premium if the product’s quality and reliability can be quantitatively shown to provide a longer term value proposition to the customer. However, such life cycle costing decisions are not always accounted for in many plastics applications. As such, high quality should be considered a manufacturing requirement while trying to reduce cost, maximize speed, and provide performance.

Manufacturing is critical to competitiveness, so manufacturing processes and technologies should be periodically reviewed [28]. Figure 1-7 depicts one manufacturing strategic planning process. In this process, the corporate executives are charged with providing a long-term vision based on their strategic mission, values, and industry data. The long-term vision is periodically but infrequently updated based on feedback from the company’s annual performance review and competitive information. A mid-term plan is usually updated annually that includes product offerings, resource allocations, and other policies in response to performance reviews and budget requests arising from the managerial level.

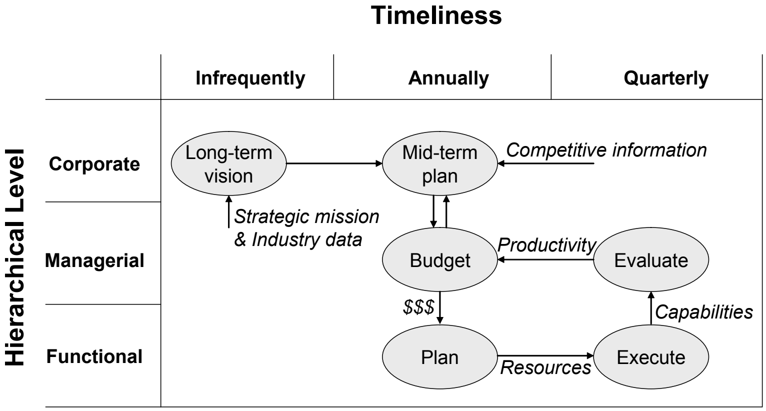

Figure 1-7: Manufacturing strategic planning process

At the managerial level, manufacturing managers are tasked with the allocation of resources, such as number of employees and budgets for procurement of new equipment. At the functional level, group leaders or individual contributors are provided these resources in response to their proposed activities. The acquired resources are used to execute the functional plan and generate manufacturing capabilities such as increased production diversity, increased production output, increased quality, or reduced costs. The managers will evaluate the productivity of the implemented processes relative to the proposed targets. Increased productivity will improve the competitiveness of the entire company and with it the fates of the managers and individual contributors. However, disconnects between the corporate plan and the functional activities can lead to misspent resources and poor productivity.

Table 1-4: Manufacturing strategic objectives and decisions

Strategy and objectives		Scope and decisions
Costs: marginal costs, capital costs, overhead rate, total costs **Speed**: delivery times, responsiveness to design or volume changes, fraction of on-time shipments, manufacturing flexibility **Quality**: consistency of product relative to specifications, product reliability, return rate, warranty costs **Performance**: product innovativeness, time to market, product longevity, product price premium	⇔	**Process technologies**: equipment type, level of automation, throughput, size, flexibility, interconnectedness **Work force**: wage and scheduling policies, skill levels, turnover **Logistics**: scheduling and inventory policies, vendor coordination, production planning **Capacity**: production volumes, lead times, product mixes **Facilities**: size, location, capabilities **Organizational**: structure, reporting policies, role of staff, reward policies, cost structures

Major changes to the manufacturing facility are sometimes required to resolve issues arising from corporate, managerial, and functional review. Table 1-4 lists the four fundamental strategies and some related performance objectives [29]. Once a given performance objective is targeted for improvement, the manufacturer must then decide how the objective is to be fulfilled. Unfortunately, not all objectives can be met due to the scope of the decisions and solutions to be implemented. The individual contributor at a functional level typically has a limited decision making scope, such as the type of process technology on a given manufacturing line or other logistics issues. To effect larger changes throughout the facility or company, the individual must percolate their vision up through the managerial levels until the idea is appropriately resourced. With higher level support, organizational changes can be implemented including changes to the product mix, personnel policies, and facility design. Decisions at all levels must be appropriate to the manufacturer's strategy and objectives to sustain economic viability.

1.3 Engineering Economics

Regardless of which manufacturing strategy is being pursued, decisions at the managerial and corporate levels are frequently based on the results of financial analysis. Increased manufacturing capability and productivity usually comes at a cost, including cost of machinery, cost of installation and validation, cost of training, and on-going support costs. As such, there is a trade-off between the investment that must be made now and the increased profitability that will be recouped later. The first step in evaluating the financial outcome of a potential manufacturing decision is to develop a series of cash flows representing the investment and expected revenues.

Example 1-3: A blow molder is considering the installation of an auxiliary control system on one of their manufacturing lines to monitor their manufacturing process and quality. The manufacturing line is operated 6,000 hours per year and costs $120 per hour to operate including labor, materials, machinery, and overhead. The auxiliary system costs $15,000 with on-going support costs of $5,000 per year but is expected to increase manufacturing productivity by 2% due to more optimal process settings and lower defect rates. Determine the cash flow for this project assuming the auxiliary control system has a lifetime of four years.

Solution: Cash flow is typically plotted on a quarterly or annual basis. In this example, the $15,000 investment in the system is considered an expense at the very start, referred to here as year 0. In each of the subsequent four years, an increased revenue of $14,400 is expected from the use of the system. This $14,400 was calculated as the productivity increase of 2% times the 6,000 hours per year of operating the line at a cost of $120 per hour. However, the on-going support cost of $5,000 must also be considered. The resulting cash flow is provided in Figure 1-8.

The cash flow projection of Figure 1-8 should be determined in a manner as realistically as possible. Managers and individual contributors should agree upon the assumptions, since the realization of those assumptions will be expected when the project is implemented. However,

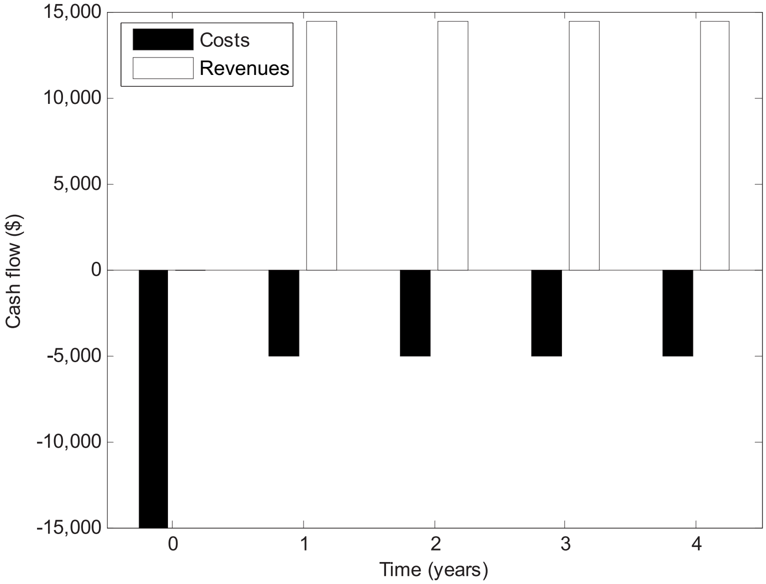

Figure 1-8: Cash flow diagram

determining the cash flow for a project is fraught with risk. While the initial investment may be quantified precisely, the revenue resulting from the project is closely tied to gains in productivity, yields, and production volume. These factors may be difficult to quantify and subsequently change with the business climate or manufacturing requirements. Furthermore, projects may incur unforeseen costs after the initial investment, such as training or hiring of personnel, higher maintenance, and higher overhead.

To reduce the amount of risk due to uncertain performance, manufacturers should contemplate a profit sharing strategy with suppliers on particularly large or risky projects. In a profit sharing strategy, the supplier and manufacturer jointly set target productivity and profitability levels. The manufacturer typically pays a reduced initial fee to the supplier but a larger quarterly or annual fee once the system is meeting productivity targets. Such profit sharing reduces the risk to the manufacturer implementing new systems, but also transfers some of the manufacturer's increased profitability directly to the supplier. If a profit sharing strategy is not available or desired, then manufacturers should consider leasing the equipment from suppliers. While leasing can increase the system implementation cost, it does provide other benefits including better supplier support and upgrades to new technologies when available [30].

Once a cash flow is estimated for a given project, the cash flow is analyzed to verify its acceptability. One manufacturer may review the cash flow of Figure 1-8 and determine that the project should be implemented, while another manufacturer may review a similar cash flow but determine that the project should not be implemented. These different outcomes stem from different methods of economic analysis and financial requirements. The three most common methods for analysis are payback period, net present value, and return on investment [31].

1.3.1 Payback Period

The payback period (PP) is the amount of time required for the return on an investment to recoup the original investment. The payback period, *PP*, is calculated according to the formula:

$$PP = \frac{C_{\text{investment}}}{\mathrm{d}R/\mathrm{d}t} \quad \text{1-3}$$

where $C_{\text{investment}}$ is the cost of the initial investment and $\mathrm{d}R/\mathrm{d}t$ is the rate at which the revenue is returned per unit time.

Example 1-4: In Example 1-3, an initial investment of \$15,000 is required to purchase an auxiliary control system. Calculate the payback period if the system provides annual revenues of \$14,400 but also incurs annual maintenance costs of \$5,000.

Solution: The rate of revenue, $\mathrm{d}R/\mathrm{d}t$, is \$9,400 resulting from the \$14,400 annual revenue from increased manufacturing productivity less the \$5,000 annual maintenance costs. The payback period is then calculated as:

$$PP = \frac{C_{\text{investment}}}{\mathrm{d}R/\mathrm{d}t} = \frac{\$15{,}000}{9{,}400\$/\text{year}} = 1.6 \text{ years}$$

The payback period is widely used in industry. The payback period is simple to calculate and intuitively measures how long the project will take to pay for itself. Projects with shorter payback periods are generally preferred to projects with longer payback periods for at least two reasons. First, a project with a shorter payback period will necessarily provide a higher rate of revenue relative to the initial investment, which should result in greater long term profitability than a project with a longer payback period. Second, individual contributors and managers are typically measured on an annual basis for their accomplishments in their current job assignment; employees may be best rewarded for those project implementations which are profitable in the short term.

Some companies rely extensively on the use of payback periods in project cost analysis, requiring projects to pay for themselves within a certain amount of time, say one or two years. As a counter example, consider a large project that may return substantial revenue but with a payback period of four years. A manager may decide against the project due to the longer payback period and instead choose a smaller project with lower revenue and a one year payback period. In this case, the manager's short term focus may have reduced the long term profitability of the company. As such, engineers and managers should consider not only the payback period but the total dollar return on the project as provided by the net present value analysis discussed next.

1.3.2 Net Present Value

One deficiency of the payback period analysis is that it emphasizes short term returns without considering the total amount of revenue returned from a project. A second deficiency of the payback period analysis is that it does not consider the time value of money, meaning that revenue recouped from a project in the future is worth less than the same amount of revenue today. The reason for the time value of money is that money today can be invested to return the principal with interest in the future. As such, future revenue, F, is discounted to a lesser present value, P, according to the formula:

$$P = \frac{F}{(1+i)^n} \qquad 1\text{-}4$$

where P is the present value of a future payment F, i is the interest rate, and n is the number of time periods in which the future payment would be received and over which the interest rate is applied.

Example 1-5: A company discounts their future cash flow at a rate of 0.4% per week. What is the present value of a \$50,000 payment they expect to receive in two years?

Solution: The \$50,000 will be received in 104 weeks, but discounted at a rate of 0.4% per week. The present value is:

$$P = \frac{F}{(1+i)^n} = \frac{\$50{,}000}{(1+0.004)^{104}} = \$33{,}011$$

The discounting in the previous example indicates that the company views a payment of \$50,000 in two years equal to a payment of \$33,011 today. The discounting of 0.4% per week is equivalent to an annual interest rate of $(1.004)^{52}$ or 23%. Such a high interest rate may seem exorbitant to us as consumers. After all, neither the bank nor stock market indices provide such high rates of return. However, companies typically use very high discount rates between 15% and 30% to reflect the risk related to their projects and protect the value of their capital. In the previous example, for instance, there is the risk that the company will never actually be provided with the \$50,000 payment in two years or that the actual payment amount will be less than expected.

If the discount rate is known, then the net present value of a project may be evaluated as the sum of all future costs and revenues discounted back to today's currency. Specifically, the net present value, NPV, is calculated according to the formula:

$$NPV = \sum_{j=0}^{n} \left[\frac{F_j}{(1+i)^j} \right] \qquad 1\text{-}5$$

where F_j is the future value of the revenue or cost in the j-th time period, i is the interest rate, and n is the number of periods across which the net present value is evaluated. The "present" time period, j equal to zero, reflects any revenue received or costs incurred at the start of the project.

Example 1-6: Consider Example 1-3 in which an auxiliary control system is purchased for \$15,000. Calculate the net present value if the system has a life of four years and provides annual revenues of \$14,400 but also incurs annual maintenance costs of \$5,000. Assume a discount rate, i, of 20%.

Solution: The cash flow is shown in Figure 1-8. Accordingly, F_0 is a negative \$15,000 to represent the cost of the investment. F_1, F_2, F_3, and F_4 are all equal to \$9,400. These future values are then discounted as shown in Table 1-5.

Table 1-5: Present value of future payments

Year, *j*	F_j	P_j
0	-\$15,000	$\frac{-\$15,000}{(1+0.2)^0} = -\$15,000$
1	\$9,400	$\frac{\$9,400}{(1+0.2)^1} = \$7,833$
2	\$9,400	$\frac{\$9,400}{(1+0.2)^2} = \$6,528$
3	\$9,400	$\frac{\$9,400}{(1+0.2)^3} = \$5,440$
4	\$,9400	$\frac{\$9,400}{(1+0.2)^4} = \$4,533$

The net present value is then calculated as the sum of these present values:

$$NPV = \sum_{j=0}^{n} \frac{F_j}{(1+i)^j} = -\$15,000 + \$7,833 + \$6,528 + \$5,440 + \$4,533 = \$9,334$$

Since the net present value is positive, the project can be considered viable compared to doing nothing, which would return zero profit. Alternatively, the net present value of this and other projects can be compared to determine which project is preferred.

One advantage of the net present value analysis is that it discounts the contribution of future revenues and expenses. These future values are worth less given the time value of money, and so the net present value analysis will tend to favor projects that return revenues sooner over projects that may return the same or higher revenues at a later time. While this behavior is similar to the payback period analysis, the net present value is more precise and allows a more direct comparison of different projects with respect to the magnitude of profitability. The primary issue with calculating the net present value is the determination of the interest rate at which future values are discounted. To eliminate the need for this assumption, some companies use a third type of economic analysis to calculate the internal rate of return (IRR).

1.3.3 Internal Rate of Return

The internal rate of return, *IRR*, is the effective interest rate that a project provides across its life. Given a cash flow, the internal rate of return is calculated as:

$$\text{choose } IRR \text{ such that } NPV = \sum_{j=0}^{n} \frac{F_j}{(1+IRR)^j} = 0 \qquad \text{1-6}$$

While the internal rate of return can be solved analytically for very simple cash flows, the net present values are iteratively calculated for different internal rates of return until the net present value equals zero. At this internal rate of return, the sum of the present value of all revenues exactly equals the sum of the present values of all costs. The internal rate of return then represents the compounding interest rate provided by the revenues given the costs. The internal rate of return represents the annual percentage return on investment (ROI). The term IRR is preferred over the term ROI since it more clearly delineates the interest rate that is returned internal to the project. The term ROI can be ambiguous in that it is sometimes used in reference to the magnitude of revenue returned from an investment calculated according to a net present value type of analysis.

Example 1-7: Consider Example 1-3 in which an auxiliary control system purchased for \$15,000. Calculate the internal rate of return if the system has a life of four years and provides annual revenues of \$14,400 but also incurs annual maintenance costs of \$5,000.

Solution: The cash flow is the same as in the previous example. As shown in Table 1-6, an interest rate of 20% provides a net present value of \$9,334. This positive net present value means that the future revenues have not been discounted sufficiently to bring the net present value to zero. As such, the internal rate of return is higher than 20%. Applying an interest rate of 30% provides a net present value of \$5,363, so the internal rate of return is higher than 30%. An interest rate of 50% results in a net present value of \$86, which is very close to zero. A few more iterations will return the actual internal rate of return of 50.43%. At this rate of return, the present value of the future revenues equals the \$15,000 investment.

Table 1-6: Net present value assuming different rates of return

Year, *j*	**F_j**	**P_j for *i* = 20%**	**P_j for *i* = 30%**	**P_j for *i* = 50%**
0	–\$15,000	$\frac{-\$15,000}{(1+0.2)^0} = -\$15,000$	$\frac{-\$15,000}{(1+0.3)^0} = -\$15,000$	$\frac{-\$15,000}{(1+0.5)^0} = -\$15,000$
1	\$9,400	$\frac{\$9,400}{(1+0.2)^1} = \$7,833$	$\frac{\$9,400}{(1+0.3)^1} = \$7,231$	$\frac{\$9,400}{(1+0.5)^1} = \$6,267$
2	\$9,400	$\frac{\$9,400}{(1+0.2)^2} = \$6,528$	$\frac{\$9,400}{(1+0.3)^2} = \$5,562$	$\frac{\$9,400}{(1+0.5)^2} = \$4,178$
3	\$9,400	$\frac{\$9,400}{(1+0.2)^3} = \$5,440$	$\frac{\$9,400}{(1+0.3)^3} = \$4,279$	$\frac{\$9,400}{(1+0.5)^3} = \$2,785$
4	\$,9400	$\frac{\$9,400}{(1+0.2)^4} = \$4,533$	$\frac{\$9,400}{(1+0.3)^4} = \$3,291$	$\frac{\$9,400}{(1+0.5)^4} = \$1,857$
NPV		\$9,334	\$5,363	$\$86 \approx 0$

The principle advantage of the internal rate of return analysis is that there is no assumption regarding the discount rate as required in the net present value analysis. As such, the internal rate of return can be directly compared to the company's cost of capital to determine if the project is viable. For example, a well established company may be able to borrow from a bank or issue a bond at an annual interest rate of 8%. In addition to this burden, the company might charge an interest premium related to risk, overhead, and profit. If each of these items requires a premium of just 5% interest, then the total "hurdle rate" might be 23%, which is fairly typical in industry. Projects with an internal rate of return above the hurdle rate have a significant chance of being pursued since they should increase the company's profitability in the long term.

1.4 Summary

Manufacturing employment has declined even while manufacturing output has risen substantially in absolute terms. The reason is that technological progress has increased manufacturing productivity in response to a competitive global marketplace. Plastics manufacturers should strive to increase productivity by 1.5% per year to remain competitive. Increases in plastics manufacturing productivity can come from a variety of sources, including better direct material utilization, reductions in indirect materials consumption, higher labor productivity, greater energy efficiency, higher yields, lower overhead, and others.

A fundamental premise is that highly productive plastics manufacturers can be regionally competitive relative to foreign manufacturers who may have access to lower material and labor costs. The reason is that there are certain "transaction costs" related to shipping, tariffs, and logistics that must be incurred to outsource the manufacturing to a potentially lower cost supplier overseas. As such, a highly productive plastics manufacturer operating within a regional market can compete effectively with an equally productive plastics manufacturer operating overseas. Highly productive plastics manufacturers share some common traits:

- highly systematized with excellent layout, flow of materials, and uniform internal planning and quality control processes;
- very high plant utilization with machines 24 hours per day, seven days a week;
- high yields, typically above 95%, but with automatic quality assurance;
- extremely focused capability typically serving a single industry sector and application.

While this book is not focused on operations management, manufacturing systems engineering should occur in a manner compatible with the operations of the plastics manufacturing facility. The production schedule is determined from the sales estimates, inventory levels, and batch sizing rules related to the economic order quantity (EOQ). Plastics manufacturing engineers should strive to match their manufacturing processes to the product requirements and sales volumes. There is generally a trade-off between the level of process specialization and marginal production costs. More specialized processes tend to require more investment and take longer to setup, but provide increased production rates and lower manufacturing costs. Lower inventory levels are also desirable so that the plastics manufacturer has better cash flow, can more quickly diagnose quality issues, and respond more quickly to changes in demand.

Strategic planning is often conducted with a “top down” approach by which the long-term vision and plans are implemented through the annual budget process. Corporate leaders update their strategic mission based on industry data and competitive information to thereby task managers with significant objectives. There are many potential approaches by which the objectives may be fulfilled. Managers and functional contributors develop and evaluate potential projects using three common economic analyses: 1) payback period, 2) net present value, and 3) internal rate of return. While each type of analysis has certain advantages, the revenue generated from projects should be significantly greater than the implementation and on-going support costs. The required financial return will vary between companies due to their cost of borrowing capital, profitability targets, and other cost structures. However, a payback period of around three years is not atypical, which corresponds to an internal rate of return around 30%. Both managers and functional contributors are often measured on their project performance relative to the project proposal, so projects with less risk, shorter payback periods, and higher rates of return are preferred.

Despite advances in sensors, actuators, and control technologies, plastics manufacturing remains a challenging domain. Process designs and conditions are frequently not optimized, so lead to inefficiencies in plastics manufacturing. The next chapter provides an overview of plastics manufacturing systems and their common requirements. Afterwards, the book proceeds with detailed discussion and analysis of plastics processing machinery, controls, and operation.

2 Plastics Manufacturing Systems

Advances in the plastics industry have been fueled by sustained improvements in polymeric materials, product design, and process technology. Yet, requirements for plastics manufacturing processes continue to advance in tandem. This chapter provides an overview of common plastics manufacturing processes. The goal of Section 2.1 is only to briefly describe these processes so that their common characteristics can be recognized. Section 2.2 characterizes these processes with respect to machine and control system design and operation. Section 2.3 then introduces the concept of performance measurement with respect to process control, and provides some important considerations relative to plastics processing.

2.1 Overview of Plastics Processing

While there are many types of plastics manufacturing systems, four of the most common are extrusion, injection molding, blow molding, and thermoforming. With rotomolding, these five plastics conversion processes accounted for sales in the United States of over ninety four billion dollars in 2007 [32]; global sales of plastics products is several multiples higher [33]. A breakout of the 2007 sales by type of process is provided in Figure 2-1. Sales by extrusion represents 36% of the dollar sales and a majority of the resin consumption since this process provides high volumes of pipe, profile, film, tubing, and sheet products. Injection and blow molding both provide roughly one fourth of the industry sales, though with lesser volumes of resin consumption. Thermoforming and rotomolding combined provide roughly 10% of the plastics product sales.

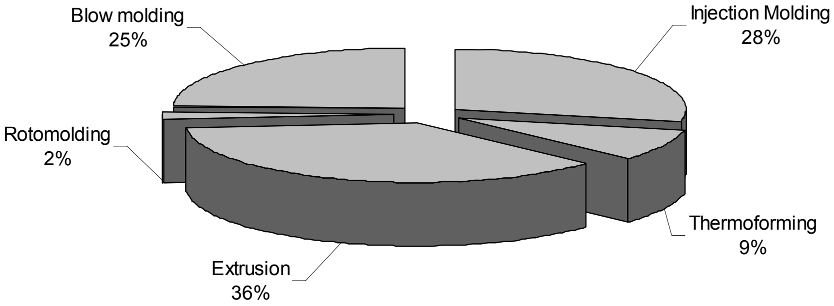

Figure 2-1: Sales of plastics by type of process

2.1.1 Extrusion

Plastics extrusion [34] is a continuous process used to form a linear product having a constant cross section. A single screw extruder is depicted in Figure 2-2, and is comprised of a heated barrel surrounding one or more rotating screws driven by a motor. During operation, the solid plastic pellets are fed to the screw. The screw is carefully designed to auger the material forward towards the die with continued rotation. As the material is conveyed forward, the plastic is compressed and converted to a molten state by a combination of heat conduction from the warmer barrel and internal shear heating caused by the flow of the plastic within the screw. By the time the plastic reaches the extruder outlet, a homogenous polymer melt should be formed with a desired melt temperature.

A breaker plate, screen pack, and die are located at the extruder outlet. These components serve to seal the interface between die and the extruder, filter any contaminants, increase the flow resistance and plastication pressure, and ultimately form the polymer melt into a desired shape. As the plastic leaves the die, it may swell due to the change in pressure at the die lip and subsequent polymer relaxation. Afterwards, the extrudate may pass through calibrator dies or calendar rolls to control the solidification and dimensions [35]. If dimensional control is not critical, the extrudate may simply be pulled through a water bath or just air cooled prior to spooling, cutoff, or other post-processing.

In terms of sheer volumes, the most common applications of extrusion are pipe, tubing, film, sheet, and custom profiles. Altogether, extruded products represent approximately 35% of the plastics industry output. While this is a significant amount unto itself, extrusion is even more significant given that

1. the extrusion process is used in the production and compounding of polymer resins and,
2. extruders are an integral subsystem of other plastics processes such as extrusion blow molding and plastics injection molding.

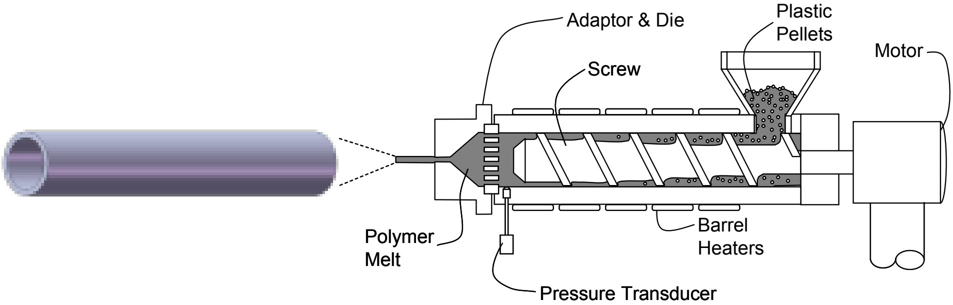

Figure 2-2: Plastics extrusion

2.1.2 Blow Molding

Blow molding [36] is a common process for production of hollow containers, ranging from commodity products such as soda or water bottles to highly engineered products such as gas tanks and electrical enclosures. The two most common types of blow molding are extrusion blow molding and injection blow molding with many variants related to handling of the parison and molds. Figure 2-3 depicts an extrusion blow molding process, in which a cylinder of semi-molten plastic, called a parison, is extruded downwards between two open mold halves. Once a parison of sufficient length is extruded, the mold is closed and a blow pin pressurizes the inside of the parison. The air pressure forces the parison to inflate until it contacts the entire surface of the mold cavity. The heat from the formed plastic is then transferred through the mold to the cooling lines. Once the plastic is sufficiently rigid, the mold is opened, the product is removed, and any flashing is trimmed.

Because of the mold's irregular interior geometry, blow molded products will tend to have a non-uniform thickness. To optimize the wall thickness, the die head in many blow molding machines can be programmed to adjust the parison's thickness down the length and across the diameter of the parison. While this level of control is often sufficient for commodity products, better distribution of the material may be provided with injection blow molding, in which a pre-form is injection molded and later inflated in a blow mold, or injection stretch blow molding, in which the pre-form is stretched prior to inflation. Furthermore, many blow molding processes use multiple extruders and complex die heads to provide a multi-layer parison or pre-form. These multi-layer systems can provide improved structural and barrier properties while minimizing the processing and materials costs [37].

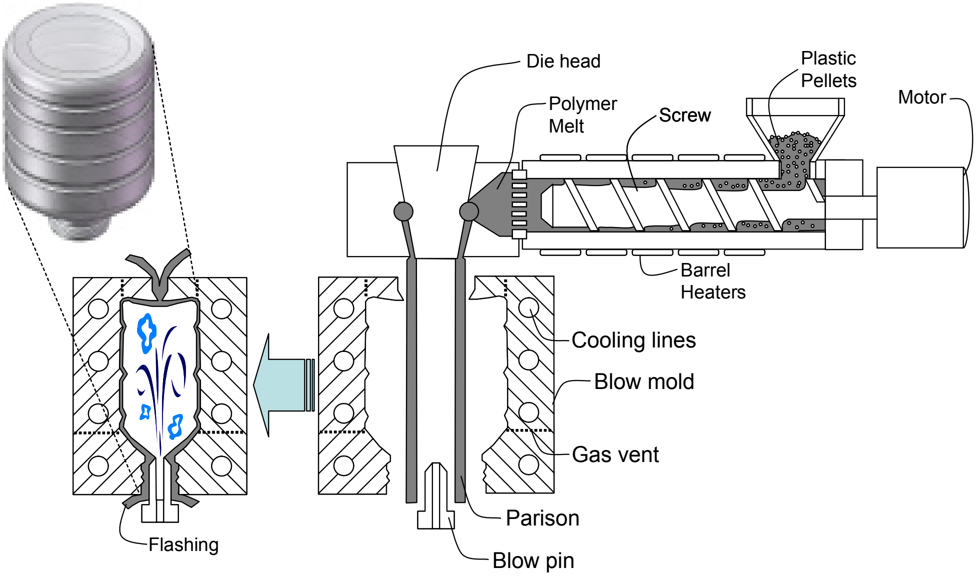

Figure 2-3: Plastics blow molding

2.1.3 Injection Molding

Injection molding [38] is a cyclic process used to make extremely complex parts to tight tolerances. An injection molding machine is depicted in Figure 2-4. While there are many different variants of the injection molding process, most injection molding processes generally include plastication, injection, packing, cooling, and mold resetting stages. During the plastication stage, the polymer melt is plasticized from solid granules or pellets through the combination of heat conduction from the heated barrel and the internal viscous heating caused by molecular deformation with the rotation of the screw. During the filling stage, the polymer melt is forced from the barrel of the molding machine and into the mold. The molten resin travels down a feed system, through the gate(s), and throughout one or more mold cavities where it will form the desired product(s). Since the polymer melt flows inside a thin walled cavity, the melt pressures in injection molding are typically much higher than those in extrusion or blow molding.

After the mold cavity is filled with the polymer melt, the packing stage provides additional material into the mold cavity as the molten plastic melt cools and contracts. The plastic's volumetric shrinkage varies with the material properties and application requirements, but the molding machine typically forces 1 to 10% additional melt into the mold cavity during the packing stage. After the polymer melt ceases to flow, the cooling stage provides additional time for the resin in the cavity to solidify and become sufficiently rigid for ejection. Then, the molding machine actuates the necessary cores, slides, and pins to open the mold and remove the molded part(s) during the mold resetting stage. Compared to the other processes described here, injection molding tends to provide not only the fastest cycle times because the mold cools the plastic from two sides but also the best dimensional consistency since the mold also acts as a fixture during cooling.

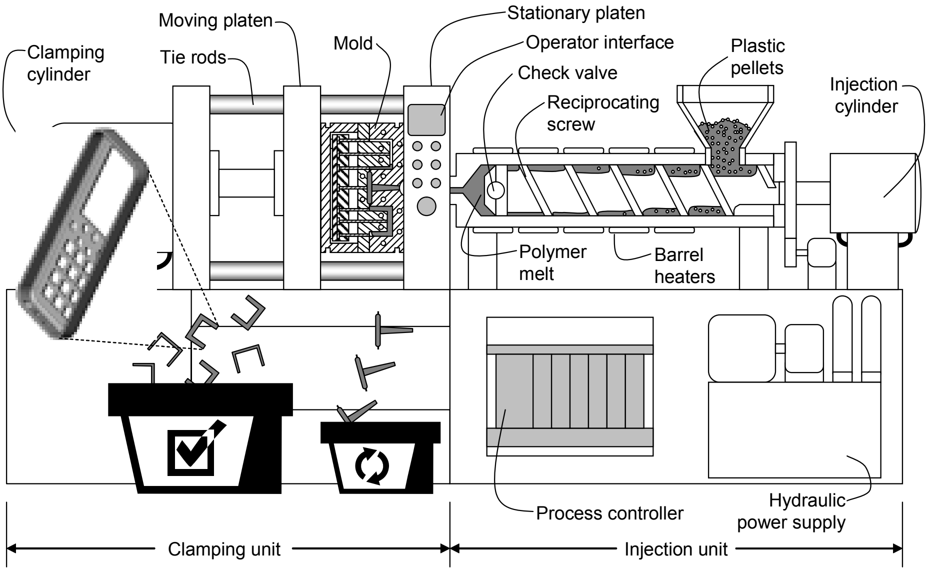

Figure 2-4: Plastics injection molding

2.1.4 Thermoforming

Thermoforming [39] is a cyclic process for making large or small plastic products that typically have one large open face, such as refrigerator liners, bath tubs, or drinking cups. There are many different types of thermoforming processes including vacuum forming, pressure forming, plug assist forming, and others. Figure 2-5 depicts a vacuum forming process, which is the simplest of these processes. In this setup, the thermoplastic sheet or film is heated in an oven by radiant heaters. Once the sheet is sufficiently compliant, the sheet is shuttled to the mold where a vacuum is applied to remove the air between the sheet and the mold cavity surfaces. The sheet is held against the mold surface until sufficiently cooled and rigid. The sheet with the formed part is then removed from the mold and trimmed. As with blow molding, the inflation of the sheet into a deep, non-uniform mold cavity can result in broad variations in the wall thickness of the thermoformed part.

Compared to the previous processes, thermoforming may be the simplest process with the lowest investment in tooling but also the lowest production rates. Additional investment can improve the economics and capability of thermoforming processes. For example, the two-station setup of Figure 2-5 may have almost twice the production output of a single-station thermoformer since one sheet may be heated while a previously heated sheet may be loaded, formed, cooled, and unloaded. As another example, pressure forming uses larger positive pressures than vacuum forming to more rapidly deform the sheet with larger forces, thereby forming more complex and thinner sheets to higher levels of detail. As yet another example, moving plugs may be used to deform the heated sheet during the former process and thereby assist the distribution of the plastic throughout the thermoformed part.

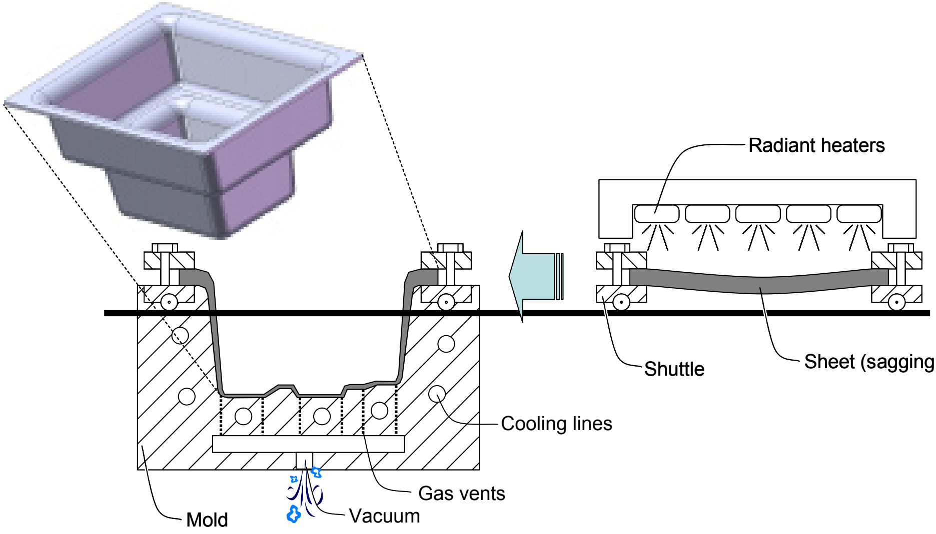

Figure 2-5: Plastics thermoforming

2.2 Characteristics

While these processes seem quite different with respect to the type of finished product, they all share a few generic traits. First, all of these processes rely on heating of the plastic so that the material is pliable and deformable. It should then be expected that all the corresponding plastics processing machines would have some means for heating, sensing, and controlling the temperature of the plastic. Second, all of these processes rely on the deformation of the heated plastic to a desired shape. As such, it should be expected that the machinery would include some way to control the pressure or forces applied to the plastic. Third, all of these processes rely on heat transfer from the formed plastic to solidify and maintain the desired shape. As such, it should be expected that all these machines would have some way to reliably cool the molded plastic. Finally, all of these processes require some sort of material handling systems to provide the raw materials and to remove the finished products. The ramifications of these process similarities are next considered with respect to the machine and control system design.

2.2.1 Closed Loop Control

All these plastics manufacturing processes rely on the controlled transfer of heat and pressure to melt, form, and solidify the plastic. The critical term here is "control", which means the purposeful manipulation of the process states (for example, temperature or pressure) for a specific reason. To provide the desired level of control, there are usually several different machine elements required. Consider the block diagram shown in Figure 2-6 for control of barrel temperature. Many practitioners are not aware of the number or function of machine elements that are typically used.

In Figure 2-6, each block represents a machine element, process step, or manufacturing function. While there are many ways to draw block diagrams, this book will use the IDEF

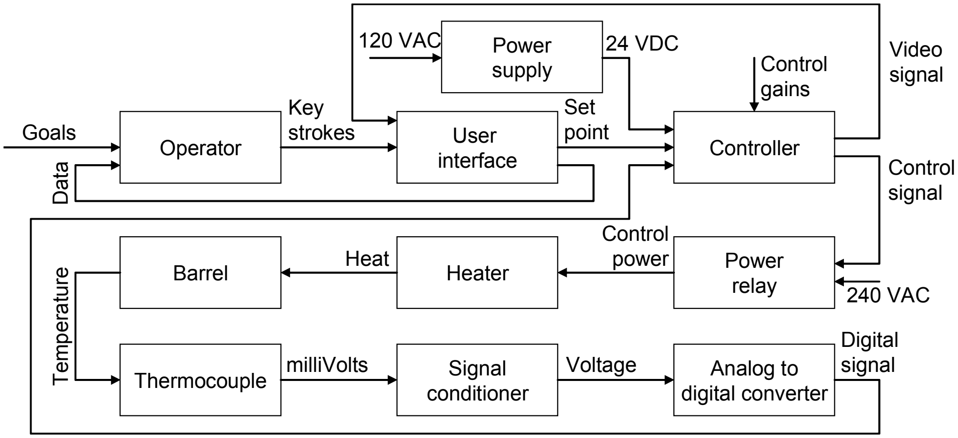

Figure 2-6: Barrel temperature control block diagram

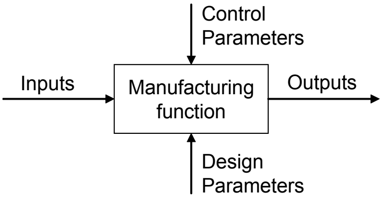

Figure 2-7: Block diagram representation

modeling technique, based on the **I**ntegrated computer aided manufacturing **DEF**inition developed by the United States Air Force [40]. As shown in Figure 2-7, the inputs to the process enter at the left of the block while the outputs from the process exit at the right. Some blocks have other inputs such as control parameters entering at the top as well as machine design parameters entering at the bottom. While this is the standard representation, block diagrams may reverse the input and output arrows to have the inputs entering from the right, so as to provide a simpler and more compact depiction as shown in the example of Figure 2-6.

Consider again the block diagram of Figure 2-6 for control of barrel temperature. The operator initiates the control process by specifying the temperature set-point based upon their goals for the manufacturing application. In most modern machines, the operator indicates the desired set-point by entering key strokes via the machine's user interface. The software logic in the machine accepts the data from these key strokes and then validates that the entered value is within acceptable range. This digital representation of the set-point is then sent to the temperature controller. The controller compares the desired set-point and determines if a control action is necessary. Since the controller can't directly power the barrel heater using the small amount of energy available from the machine's internal 24 V direct current (DC) power supply, the controller sends a control signal to a power relay or similar device which is also provided 120 or 240 voltage with alternating current (AC) power from the machine's primary electrical circuit. The heater will then provide heat to the barrel.

The resulting barrel temperature will depend on the heater characteristics, the amount of power supplied to the heater, the barrel and heater geometry, and other properties and conditions. A thermocouple or other device is necessary to sense the barrel temperature and provide a millivolt signal in proportion to the barrel temperature. This voltage signal may be inappropriate for direct integration with the machine controller, so a signal conditioner may amplify, filter, or otherwise convert the signal into a more useable form. Even so, the conditioned voltage cannot be read directly by the controller so an analog to digital converter (ADC) is used to deliver a digital representation of the temperature back to the controller.

The control block diagram of Figure 2-6 may seem excessively detailed, yet indeed is representative of typical machine controls. Even so, it is common to combine some of the blocks so as to create a simpler diagram as shown in Figure 2-8. In this representation, the controller includes the operator, user interface, DC power supply, and previous controller. The actuator includes the power relay and heater while the process represents the barrel, plastics, and surrounding environment. The sensor represents the thermocouple, signal conditioner, and analog to digital converter. In control terminology [41], the plant represents everything between the controller and the sensor.

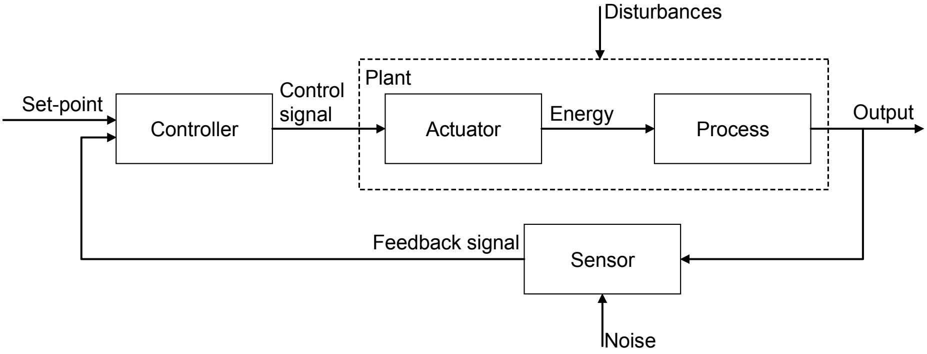

Figure 2-8: Closed loop control block diagram

Note that the controller in Figure 2-8 emits a control signal to the plant, and receives a feedback signal from the sensor. The feedback signal closes the loop between the process output and the controller, so this type of control system design is widely known as closed loop control.[1] The use of the feedback signal allows the controller to compare the desired set-point to the current output of the process and so update the control signal to drive the process output to the set-point. The difference between the desired set-point and the process output is known as the error. To minimize the error, controllers contain control laws that hopefully output an appropriate control signal based on the error and the error history.

2.2.2 Open Loop Control

Not all systems use closed loop control. Consider the block diagram depicted in Figure 2-9. Here, a variable voltage transformer (sometimes referred to as a variac) can be used to provide constant power to a heater. The heater then provides a constant amount of heat to the barrel, which in turn changes temperature. In this control system design, the temperature of the barrel is not directly used to adjust the power to the heater, so no feedback loop is formed. Accordingly, this control system design is known as open loop control.

There are, in fact, many reasons that open loop control systems are used in the plastics industry. First, open loop designs are often used when the size and cost of a closed loop implementation exceeds the available space or investment allowed for the application. For example, the nozzle tips in molding machines are often quite small and/or changed frequently so it may not be practical to install a thermocouple and link it to the machine controller. Second, open loop controls are often used as a fallback when a more sophisticated closed loop controller fails. For example, an installed thermocouple on the barrel may fail at an inopportune time. In such cases, it is possible to continue the plastics molding process by specifying a constant power

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[1] Closed loop controls are not only found in engineered systems. For instance, body temperature is regulated by changes in the body's metabolism together with perspiration or shivering in extreme conditions. As another example, the depth of a lake may be regulated by the seepage of water as dependent on the water pressure resulting from the inflows and water height. As yet another example, product prices may vary as a function of supply and demand.

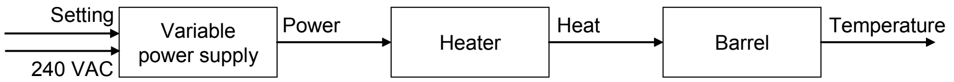

Figure 2-9: Open loop heater control block diagram

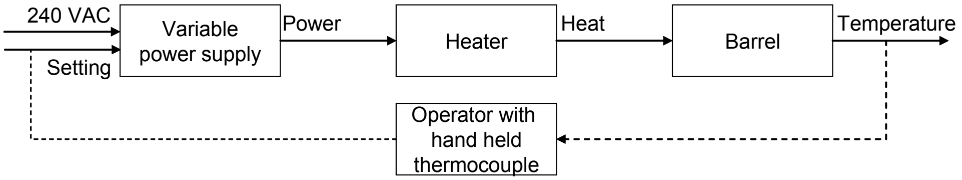

Figure 2-10: Operator providing intermittent closed loop control

output to the heater, and subsequently verifying that the process is behaving in an acceptable manner. Some other examples of open loop systems in the plastics industry include the use of fans for ventilation, flow rates of circulating coolant for mold temperature control, and gravity for part handling. Since there is no sensing of the state being controlled, however, open loop control provides limited precision. For example, the flow rate from the fan, mold wall temperature, and part location are all often unknown.

Such open loop controls can be perilous since the appropriate amount of control power can change with the dynamics of the process and potential disturbances. For example, at start-up a nozzle tip or barrel heater may be provided a suitable voltage of 200 V, which may correspond to 750 W. Once the process is up and running, however, this amount of power might be unsuitable and cause the area being heated to rise to an undesirably high temperature. As such, the operator relying on an open loop heater control should intermittently verify the temperature with a hand held thermocouple and then adjust the heater power to correct any temperature error. As shown by the design in Figure 2-10, the operator is now providing the sensing and control functions of a closed loop system design. Such a design will generally under-perform the original closed loop design of Figure 2-6, since the operator can not constantly verify the process state, may not have good access to sense the process temperature with a hand-held thermocouple, and may not know how best to adjust the control power to minimize the temperature error.

Compared to an open loop control system, closed loop control systems usually provide a more rapid response and lower steady state error even when there are disturbances to the plant. In plastics processing, there are many disturbances that could adversely affect the product quality if not otherwise compensated. Some of the most common disturbances relate to the material properties, environmental conditions, or tooling and machine changes. For example, in an injection molding process:

- the material properties may change due to varying molecular weight distributions across batches, the type and loading of fillers such as colorants, impact modifiers, or glass fibers and the varying use of regrind, among other causes [42];
- environmental conditions can affect the process including environment temperature, environment humidity, plant water temperature, and other factors [43, 44], and

- long term changes in the mold and processing machinery may include changes in the mold surface finish, gating, wear in the barrel and/or check ring, and wear in the hydraulic valves or electric motors, among others [45].

Plant disturbances are not the only issue since closed loop control systems rely on sensors to provide feedback about the process outputs. Sadly, electrical noise reduces the quality of the feedback signal from the sensor. Noise can come from a variety of sources [46]. The most frequent source is 60 Hz noise from nearby electrical circuits, but noise can also derive from other sources including electrical motors, heaters, and solar radiation. Even without noise, sensors are not perfect, and their physical design and manufacturing can induce errors between the true process output and the feedback signal provided to the machine controller. Accordingly, the capability of the sensor to provide an accurate representation of the process is central to the control system performance.

2.2.3 Dynamic Control

Reflecting again on the various attributes of common plastics manufacturing processes, extrusion might be considered a relatively steady state process while blow molding, injection molding, and thermoforming are clearly cyclic processes. The cyclic nature of these latter processes will tend to dictate more complex control systems for two reasons. First, a comparison of Figure 2-2 through Figure 2-5 indicates that the cyclic processes have more subsystems; the additional subsystems require additional control systems to coordinate the timing and actuation of the process. The second reason for more complex control systems in cyclic processes is that the pressure, flow rate, and other states must vary as a function of time. In fact, many if not most cyclic molding processes allow for the profiling of the process output as a function of time. While extrusion operates continuously, the process should actually be considered dynamic rather than steady from a controls perspective. The reason is that even though a constant temperature, pressure, screw rotation speed, and flow rate are all desired, each of these process states are fluctuating slightly as a function of time due to process disturbances and limitations in the machine and control system designs.

Plastics manufacturing processes almost always use dynamic control systems. Figure 2-11 plots the desired and observed temperature in one barrel zone, along with the control signal to the corresponding barrel heater. It is observed that the barrel temperature is initially at 20 °C. The desired temperature is then set to 225 °C at a time of 50 s. The controller immediately turns the heater on and the barrel begins to heat up. After 800 s, the barrel reaches the desired temperature and so controller turns off the heater. However, there is a slight overshoot as the residual heat in the heater is transferred to the barrel and thermocouple. The barrel temperature drops below the desired set-point so the controller again turns on the heater. The barrel temperature and heater continue to cycle in a dynamic fashion, even though a steady state temperature is desired.

This type of oscillating behavior is very common in closed loop control systems. It can be due to a wide variety of phenomena. In this case, the oscillations are due to two primary reasons. First, there is a lag between the time when the controller turns the heater on and when the thermocouple senses an increased temperature. This lag largely prevents the controller from providing a uniform process output, especially when process disturbances are present. Second,