38 Integrated Manufacturing Systems

Chapter Contents

The manufacturing systems discussed in this chapter consist of multiple workstations and/or machines whose operations are integrated by means of a material handling subsystem that moves parts or products between stations. In addition, most of these systems use computer control to coordinate the actions of the stations and material handling equipment and to collect data on overall system performance. Thus, the components of an integrated manufacturing system are (1) workstations and/or machines, (2) material handling equipment, and (3) computer control. In addition, human workers are required to manage the system, and workers may be used to operate the individual workstations and machines.

Integrated manufacturing systems include manual and automated production lines, manufacturing cells (from which the term "cellular manufacturing" is derived), and flexible manufacturing systems, all of which are described in this chapter. The final section defines computer integrated manufacturing (CIM), the ultimate integrated manufacturing system. It is appropriate to begin this chapter with a concise overview of material handling, the physical integrator in integrated manufacturing systems.

38.1 Material Handling

Material handling is defined as "the movement, storage, protection and control of materials throughout the manufacturing and distribution process . . ."[1] The term is usually associated with activities that occur inside a facility, as contrasted with transportation between facilities that involves rail, truck, air, or waterway delivery of goods.

[1]This definition is published each year in the Annual Report of The Material Handling Industry of America (MHIA), the trade association for material handling companies doing business in North America.

Materials must be moved during the sequence of manufacturing operations that convert them into final products. Material handling functions in manufacturing include (1) loading and positioning work units at each workstation, (2) unloading work units from the station, and (3) transporting work units between workstations. Loading involves moving the work units into the production machine from a location in close proximity to or within the workstation. Positioning means locating the work units in a fixed orientation relative to the processing or assembly operation. At the end of the operation, the work units are unloaded or removed from the station. Loading and unloading are accomplished manually or by automated devices such as industrial robots. If the manufacturing operations require multiple workstations, then the units must be transported from one station to the next in the sequence. In many cases, a temporary storage function must also be provided by the material handling system, as work units await their turn at each workstation. The purpose of storage in this instance is to make sure that work is always present at each station, so that idle time of workers and equipment is avoided.

Material handling equipment and methods used in manufacturing can be divided into the following general categories: (1) material transport, (2) storage, and (3) unitizing.

Material transport equipment is used to move parts and materials between workstations in the factory. This movement may include intermediate stops for temporary storage of work-in-process. There are five main types of material transport equipment: (1) industrial trucks, the most important of which are fork lift trucks, (2) automated guided vehicles, (3) rail-guided vehicles, (4) conveyors, and (5) hoists and cranes. This equipment is briefly described in Table 38.1.

Two general categories of material transport equipment can be distinguished, according to the type of routing between workstations: fixed and variable. In ***fixed routing***, all of the work units are moved through the same sequence of stations. This implies that the processing sequence required on all work units is either identical or very similar. Fixed routing is used on manual assembly lines and automated production lines. Typical material handling equipment used in fixed routing includes conveyors and rail-guided vehicles. In ***variable routing***, different work units are moved through different workstation sequences, meaning that the manufacturing system processes or

TABLE • 38.1 Five types of material transport equipment.

Type	Description	Typical Production Applications
Industrial trucks	Powered trucks include fork lift trucks as in Figure 38.1(a). Hand trucks include wheeled platforms and dollies.	Movement of pallet and container loads in factories and warehouses. Hand trucks used for small loads over short distances.
Automated guided vehicles	Independently operated, self-propelled vehicles guided along defined pathways, as in Figure 38.1(b). Powered by on-board batteries.	Movement of parts and products in assembly lines and flexible manufacturing systems.
Rail-guided vehicles	Motorized vehicles guided by a fixed rail system. Powered by electrified rail.	Monorails used for overhead delivery of large components and subassemblies.
Conveyors	Apparatus to move items along fixed path using chain, moving belt, rollers (Figure 38.1(c), or other mechanical drive.	Movement of large quantities of items between specific locations. Movement of product on production lines.
Hoists and cranes	Apparatus used for vertical lifting (hoists) and horizontal movement (cranes).	Lifting and transporting heavy materials and loads.

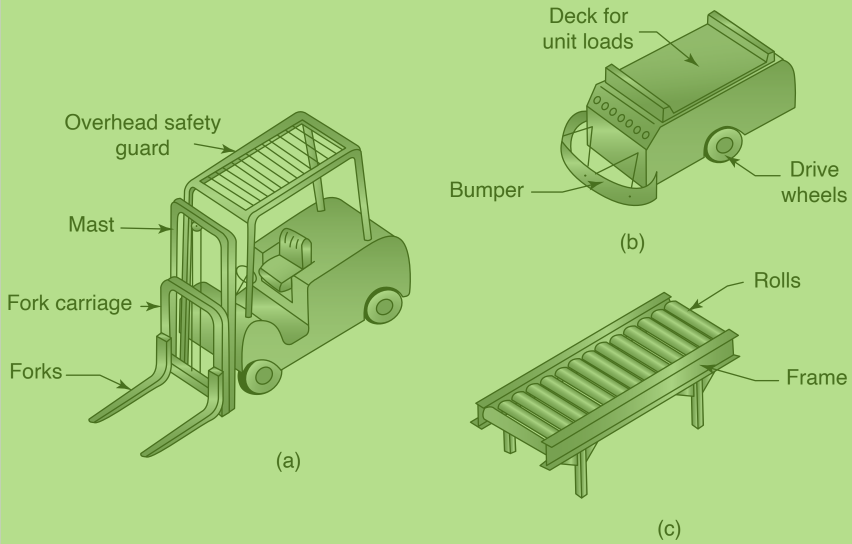

FIGURE 38.1 Several types of material handling equipment: (a) fork lift truck, (b) automated guided vehicle, and (c) roller conveyor.

assembles different types of parts or products. Manufacturing cells and flexible manufacturing systems usually operate this way. Typical handling equipment found in variable routing includes industrial trucks, automated guided vehicles, and hoists and cranes.

Storage systems in factories are used for temporary storage of raw materials, work-in-process, and finished products. Storage systems can be classified into two general categories: (1) conventional storage methods and equipment, which include bulk storage in an open area, rack systems, and shelves; and (2) automated storage systems, which include rack systems served by automatic cranes that store and retrieve pallet loads.

Finally, unitizing refers to containers used to hold individual items during transport and storage, as well as equipment used to make up such unit loads. Containers include pallets, tote pans, boxes, and baskets that hold parts during handling. Unitizing equipment includes palletizers that are used to load and stack cartons onto pallets and depalletizers that are used to accomplish the unloading operation. Palletizers and depalletizers are generally associated with cartons of finished product leaving a facility and boxes of raw materials coming into the facility, respectively.

Section 1.4.1 describes four types of plant layout: (1) fixed position layout, (2) process layout, (3) cellular layout, and (4) product layout. In general, different types of material handling methods and equipment are associated with these four types, as summarized in Table 38.2.

TABLE • 38.2 Types of material handling methods and systems generally associated with the four types of plant layout.

Layout Type	Features	Typical Methods and Equipment
Fixed-Position	Product is large and heavy, low production rates	Cranes, hoists, fork lift trucks
Process	Medium and hard product variety, low and medium production rates	Fork lift trucks, automated guided vehicles, manual loading at workstations
Cellular	Soft product variety, medium production rates	Conveyors, manual handling for loading and moving between stations
Product	No product variety or soft product variety, high production rates	Conveyors for product flow, fork lift trucks or automated guided vehicles to deliver parts to stations

38.2 Fundamentals of Production Lines

Production lines are an important class of manufacturing system when large quantities of identical or similar products are to be made. They are suited to situations where the total work to be performed on the product or part consists of many separate steps. Examples include assembled products (e.g., automobiles and appliances) and mass-produced machined parts on which multiple machining operations are required (e.g., engine blocks and transmission housings). In a production line, the total work is divided into small tasks, and workers or machines perform these tasks with great efficiency. For purposes of organization production lines are divided into two basic types: manual assembly lines and automated production lines. However, hybrid lines consisting of both manual and automated operations are not uncommon. Before examining these particular systems, some of the general issues involved in production line design and operation are considered.

A ***production line*** consists of a series of workstations arranged so that the product moves from one station to the next, and at each location a portion of the total work is performed on it, as depicted in Figure 38.2. The production rate of the line is limited by its slowest station. Workstations whose pace is faster than the slowest will ultimately be limited by that bottleneck station. Transfer of the product along the line is usually accomplished by a conveyor system or mechanical transfer device, although some manual lines simply pass the product from worker to worker by hand. Production lines are associated with mass production. If the product quantities are high and the work can be divided into separate tasks that can be assigned to individual workstations, then a production line is the most appropriate manufacturing system.

38.2.1 METHODS OF WORK TRANSPORT

There are various ways of moving work units from one workstation to the next. The two basic categories are manual and mechanized.

Manual Methods of Work Transport Manual methods involve passing the work units between stations by hand. These methods are associated with manual assembly lines. In some cases, the output of each station is collected in a box or tote pan; when the box is full it is moved to the next station. This can result in a significant amount of in-process inventory, which is undesirable. In other cases, work units are moved individually along a flat table or unpowered conveyor (e.g., a roller conveyor). When the task is finished at each station, the worker simply pushes the unit toward the downstream station. Space is usually allowed for one or more units to collect between stations, thereby relaxing the requirement for all workers to perform their respective

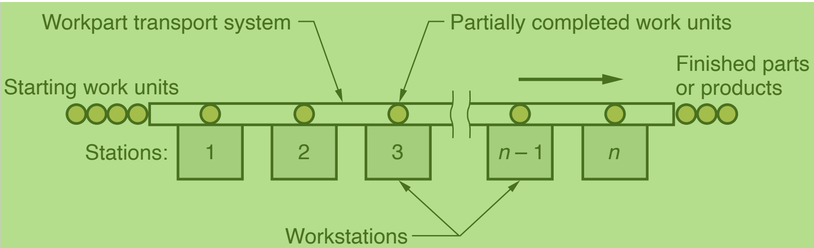

FIGURE 38.2 General configuration of a production line.

tasks in sync. One problem associated with manual methods of work transport is the difficulty in controlling the production rate on the line. Workers tend to work at a slower pace unless some mechanical means of pacing them is provided.

Mechanized Methods of Work Transport Powered mechanical systems are commonly used to move work units along a production line. These systems include lift-and-carry devices, pick-and-place mechanisms, powered conveyors (e.g., overhead chain conveyors, belt conveyors, and chain-in-floor conveyors), and other material handling equipment, sometimes combining several types on the same line. Three major types of work transfer systems are used on production lines: (1) continuous transfer, (2) synchronous transfer, and (3) asynchronous transfer.

Continuous transfer systems consist of a continuously moving conveyor that operates at a constant velocity. The continuous transfer system is most common on manual assembly lines. Two cases are distinguished: (1) parts are fixed to the conveyor and (2) parts can be removed from the conveyor. In the first case, the product is usually large and heavy (e.g., automobile, washing machine) and cannot be removed from the line. The worker must therefore walk along with the moving conveyor to complete the assigned task for that unit while it is in the station. In the second case, the product is small enough that it can be removed from the conveyor to facilitate the work at each station. Some of the pacing benefits are lost in this arrangement, since each worker is not required to finish the assigned tasks within a fixed time period. On the other hand, this case allows greater flexibility to each worker to deal with any technical problems that may be encountered on a particular work unit.

In ***synchronous transfer systems***, work units are simultaneously moved between stations with a quick, discontinuous motion. These systems are also known by the name ***intermittent transfer***, which characterizes the type of motion experienced by the work units. Synchronous transfer includes positioning of the work at the stations, which is a requirement for automated lines that use this mode of transfer. Synchronous transfer is not common for manual lines, because the task at each and every station must be finished within the cycle time or the product will leave the station as an incomplete unit. This rigid pacing discipline is stressful to human workers. By contrast, this type of pacing lends itself to automated operation.

Asynchronous transfer allows each work unit to depart its current station when processing has been completed. Each unit moves independently, rather than synchronously. Thus, at any given moment, some units on the line are moving between stations, while others are positioned at stations. Associated with the operation of an asynchronous transfer system is the tactical use of queues between stations. Small queues of work units are permitted to form in front of each station, so that variations in worker task times will be averaged and stations will always have work waiting for them. Asynchronous transfer is used for both manual and automated manufacturing systems.

38.2.2 PRODUCT VARIATIONS

Production lines can be designed to cope with variations in product models. Three types of line can be distinguished: (1) single model line, (2) batch model line, and (3) mixed model line. A ***single model line*** is one that produces only one model, and there is no variation in the model. Thus, the tasks performed at each station are the same on all product units.

Batch model and mixed model lines are designed to produce two or more different product models on the same line, but they use different approaches for dealing with the model variations. As its name suggests, a ***batch model line*** produces each model in batches. The workstations are set up to produce the desired quantity of the first model; then the stations are reconfigured to produce the desired quantity of the next model; and so on. Production time is lost between batches due to the setup changes. Assembled products are often made using this approach when the demand for each product is medium and the product variety is also medium. The economics in this case favor the use of one production line for several products rather than using many separate lines for each model.

A ***mixed model line*** also produces multiple models; however, the models are intermixed on the same line rather than being produced in batches. While a particular model is being worked on at one station, a different model is being processed at the next station. Each station is equipped with the necessary tools and is sufficiently versatile to perform the variety of tasks needed to produce any model that moves through it. Many consumer products are assembled on mixed model lines when the level of product variety is soft. Prime examples are automobiles and major appliances, which are characterized by variations in models and options.

38.3 Manual Assembly Lines

The manual assembly line was an important development in integrated manufacturing systems. It is of global importance today in the manufacture of assembled products including automobiles and trucks, consumer electronic products, appliances, power tools, and other products made in large quantities.

A ***manual assembly line*** consists of multiple workstations arranged sequentially, at which assembly operations are performed by human workers, as in Figure 38.3. The usual procedure on a manual line begins with "launching" a base part onto the

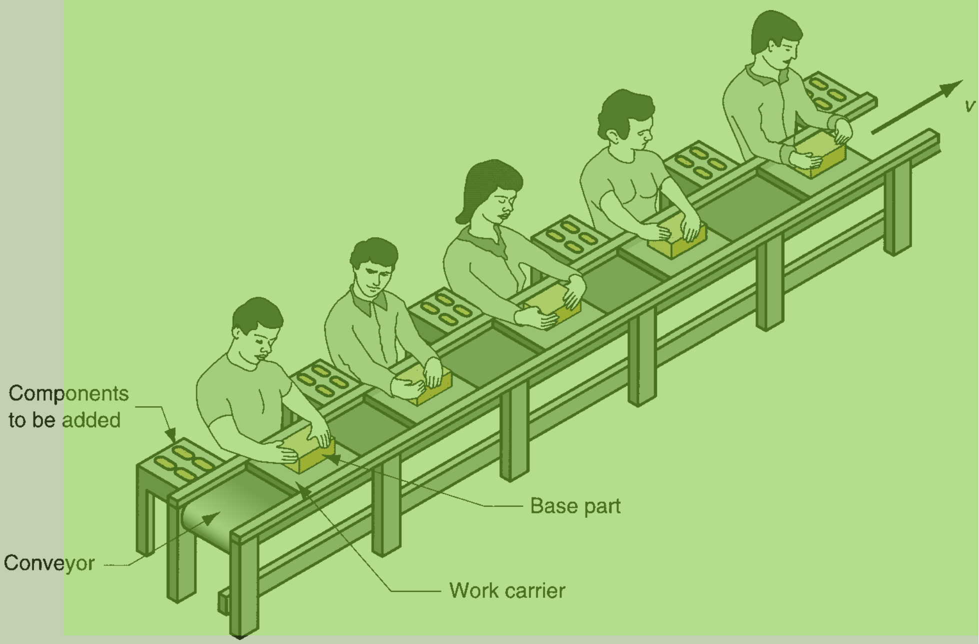

FIGURE 38.3 A portion of a manual assembly line. Each worker performs a task at his or her workstation. A conveyor moves parts on work carriers from one station to the next.

front end of the line. A work carrier is often required to hold the part during its movement along the line. The base part travels through each of the stations where workers perform tasks that progressively build the product. Components are added to the base part at each station, so that all tasks have been completed when the product exits the final station. Processes accomplished on manual assembly lines include mechanical fastening operations (Chapter 31), spot welding (Section 29.2), hand soldering (Section 30.2), and adhesive joining (Section 30.3).

38.3.1 CYCLE TIME ANALYSIS

Equations can be developed to determine the required number of workers and workstations on a manual assembly line to meet a given annual demand. Suppose the problem is to design a single model line to satisfy annual demand for a certain product. Management must decide how many shifts per week the line will operate and the number of hours per shift. If it is assumed that the plant operates 50 weeks per year, then the required hourly production rate of the line will be given by

$$R_p = \frac{D_a}{50 S_w H_{sh}} \tag{38.1}$$

where R_p = the actual average production rate, units/hr; D_a = annual demand for the product, units/year; S_w = number of shifts/wk; and H_{sh} = hours/shift. If the line operates 52 weeks rather than 50, then $R_p = D_a/52S_wH_{sh}$. The corresponding average production time per unit is the reciprocal of R_p

$$T_p = \frac{60}{R_p} \tag{38.2}$$

where T_p = actual average production time, converted to minutes.

Unfortunately, the line may not be able to operate for the entire time given by 50 S_wH_{sh}, because of lost time due to reliability problems. These reliability problems include mechanical and electrical failures, tools wearing out, power outages, and similar malfunctions. Accordingly, the line must operate at a faster time than T_p to compensate for these problems. If E = line efficiency, which is the proportion of uptime on the line, then the cycle time of the line T_c is given by

$$T_c = ET_p = \frac{60E}{R_p} \tag{38.3}$$

Any product contains a certain work content that represents all of the tasks that are to be accomplished on the line. This work content requires an amount of time called the ***work content time*** T_{wc}. This is the total time required to make the product on the line. If it is assumed that the work content time is divided evenly among the workers, so that every worker has an equal workload whose time to perform equals T_c, then the minimum possible number of workers w_{min} in the line can be determined as

$$w_{min} = \text{Minimum Integer} \geq \frac{T_{wc}}{T_c} \tag{38.4}$$

If each worker is assigned to a separate workstation, then the number of workstations is equal to the number of workers; that is $n_{min} = w_{min}$.

There are two practical reasons why this minimum number of workers cannot be achieved: (1) ***imperfect balancing***, in which some workers are assigned an amount of work that requires less time than T_c, and this inefficiency increases the total number of workers needed on the line; and (2) ***repositioning losses***, in which some time is lost at each station to reposition the work or the worker, so that the service time actually available at each station is less than T_c, and this will also increase the number of workers on the line.

38.3.2 LINE BALANCING AND REPOSITIONING LOSSES

One of the biggest technical problems in designing and operating a manual assembly line is line balancing. This is the problem of assigning tasks to individual workers so that all workers have an equal amount of work. Recall that the entirety of work to be accomplished on the line is given by the work content. This total work content can be divided into ***minimum rational work elements***, each element concerned with adding a component or joining them or performing some other small portion of the total work content. The notion of a minimum rational work element is that it is the smallest practical amount of work into which the total job can be divided. Different work elements require different times, and when they are grouped into logical tasks and assigned to workers, the task times will not be equal. Thus, simply due to the variable nature of element times, some workers will end up with more work, whereas other workers will have less. The cycle time of the assembly line is determined by the station with the longest task time.

One might think that although the work element times are different, it should be possible to find groups of elements whose sums (task times) are nearly equal, if not perfectly equal. What makes it difficult to find suitable groups is that there are several constraints on this combinatorial problem. First, the line must be designed to achieve some desired production rate, which establishes the cycle time T_c at which the line must operate, as provided by Equation (38.3). Therefore, the sum of the work element times assigned to each station must be less than or equal to T_c.

Second, there are restrictions on the order in which the work elements can be performed. Some elements must be done before others. For example, a hole must be drilled before it can be tapped. A screw that will use the tapped hole to attach a mating component cannot be fastened before the hole has been drilled and tapped. These kinds of requirements on the work sequence are called ***precedence constraints***. They complicate the line balancing problem. A certain element that might be allocated to a worker to obtain a task time $= T_c$ cannot be added because it violates a precedence constraint.

These and other limitations make it virtually impossible to achieve perfect balancing of the line, which means that some workers will require more time to complete their tasks than others. Methods of solving the line balancing problem, that is, allocating work elements to stations, are discussed in other references—excellent references indeed, such as [10]. The inability to achieve perfect balancing results in some idle time at most stations. Because of this idle time, the actual number of workers required on the line will be greater than the number of workstations given by Equation (38.4).

A measure of the total idle time on a manual assembly line is given by the ***balancing efficiency*** E_b, defined as the total work content time divided by the total available service time on the line. The total work content time is equal to the sum of the times of all work elements that are to be accomplished on the line. The total available service time on the line $= wT_s$, where w = number of workers on the line;

and T_s = the longest service time on the line; that is, $T_s = \text{Max}\{T_{si}\}$ for $i = 1, 2, \ldots n$, where T_{si} = the service time (task time) at station i, min.

The reader may wonder why a new term T_s is being used rather than the previously defined cycle time T_c. The reason is that there is another time loss in the operation of a production line in addition to idle time from imperfect balancing. Call it the ***repositioning time*** T_r. It is the time required in each cycle to reposition the worker, or the work unit, or both. On a continuous transfer line where work units are attached to the line and move at a constant speed, T_r is the time taken by the worker to walk from the unit just completed to the next unit coming into the station. In all manual assembly lines, there will be some lost time due to repositioning. Assume T_r is the same for all workers, although in fact repositioning may require different times at different stations. Then T_s, T_c, and T_r are related as follows:

$$T_c = T_s + T_r \tag{38.5}$$

The definition of balancing efficiency E_b can now be written in equation form as follows:

$$E_b = \frac{T_{wc}}{wT_s} \tag{38.6}$$

A perfect line balance yields a value of $E_b = 1.00$. Typical line balancing efficiencies in industry range between 0.90 and 0.95.

Equation (38.6) can be rearranged to obtain the actual number of workers required on a manual assembly line:

$$w = \text{Minimum Integer} \geq \frac{T_{wc}}{T_s E_b} \tag{38.7}$$

The utility of this relationship suffers from the fact that the balancing efficiency E_b depends on w in Equation (38.6). Unfortunately, this is an equation where the thing to be determined depends on a parameter that, in turn, depends on the thing itself. Notwithstanding this drawback, Equation (38.7) defines the relationship among the parameters in a manual assembly line. Using a typical value of E_b based on similar previous lines, it can be used to estimate the number of workers required to produce a given assembly.

Example 38.1 Manual assembly line

A manual assembly line is being planned for a product whose annual demand = 90,000 units. A continuously moving conveyor will be used with work units attached. Work content time = 55 min. The line will run 50 wk/yr, 5 shifts/wk, and 8 hr/day. Each worker will be assigned to a separate workstation. Based on previous experience, assume line efficiency = 0.95, balancing efficiency = 0.93, and repositioning time = 9 sec. Determine (a) hourly production rate to meet demand, (b) number of workers and workstations required, and (c) for comparison, the ideal minimum value as given by w_{min} in Equation (38.4).

Solution: (a) Hourly production rate required to meet annual demand is given by Equation (38.1):

$$R_p = \frac{90{,}000}{50(5)(8)} = \mathbf{45\ units/hr}$$

(b) With a line efficiency of 0.95, the ideal cycle time is

$$T_c = \frac{60(0.95)}{45} = \mathbf{1.2667\ min}$$

Given that repositioning time $T_r = 9$ sec $= 0.15$ min, the service time is

$$T_s = 1.2667 - 0.150 = 1.1167 \text{ min}$$

Workers required to operate the line, by Equation (38.7) equals

$$w = \text{Minimum Integer} \geq \frac{55}{1.1167(0.93)} = 52.96 \rightarrow \mathbf{53\ workers}$$

With one worker per station, n = **53 workstations**.

(c) This compares with the ideal minimum number of workers given by Equation (38.4):

$$w_{min} = \text{Minimum Integer} \geq \frac{55}{1.2667} = 43.42 \rightarrow \mathbf{44\ workers}$$

It is clear from Example 38.1 that the lost time due to repositioning and imperfect line balancing take a heavy toll on the overall efficiency of a manual assembly line.

The number of workstations on a manual assembly line does not necessarily equal the number of workers. For large products, it may be possible to assign more than one worker to a station. This practice is common in final assembly plants that build cars and trucks. For example, two workers in a station might perform assembly tasks on opposite sides of the vehicle. The number of workers in a given station is called the station ***manning level*** M_i. Averaging the manning levels over the entire line,

$$M = \frac{w}{n} \tag{38.8}$$

where M = average manning level for the assembly line; w = number of workers on the line; and n = number of stations. Naturally, w and n must be integers. Multiple manning conserves valuable floor space in the factory because it reduces the number of stations required.

Another factor that affects manning level on an assembly line is the number of ***automated stations*** on the line, including stations that employ industrial robots (Section 38.4). Automation reduces the required labor force on the line, although it increases the need for technically trained personnel to service and maintain the automated stations. The automobile industry makes extensive use of robotic workstations to perform spot welding and spray painting on sheet-metal car bodies. The robots accomplish these operations with greater repeatability than human workers can, which translates into higher product quality.

38.4 Automated Production Lines

Manual assembly lines generally use a mechanized transfer system to move parts between workstations, but the stations themselves are operated by human workers. An ***automated production line*** consists of automated workstations connected by a parts transfer system that is coordinated with the stations. In the ideal, no human workers are on the line, except to perform auxiliary functions such as tool changing, loading and unloading parts at the beginning and end of the line, and repair and maintenance activities. Modern automated lines are highly integrated systems, operating under computer control.

Operations performed by automated stations tend to be simpler than those performed by humans on manual lines. The reason is that simpler tasks are easier to automate. Operations that are difficult to automate are those requiring multiple steps, judgment, or human sensory capability. Tasks that are easy to automate consist of single work elements, quick actuating motions, and straight-line feed motions as in machining.

38.4.1 TYPES OF AUTOMATED LINES

Automated production lines can be divided into two basic categories: (1) those that perform processing operations such as machining, and (2) those that perform assembly operations. An important type in the processing category is the transfer line.

Transfer Lines and Similar Processing Systems A ***transfer line*** consists of a sequence of workstations that perform production operations, with automatic transfer of work units between stations. Machining is the most common processing operation, as depicted in Figure 38.4. Automatic transfer systems for sheet metalworking and assembly are also available. In the case of machining, the workpiece typically starts as a metal casting or forging, and a series of machining operations are performed to accomplish the high-precision details (e.g., holes, threads, and finished flat surfaces).

Transfer lines are usually expensive pieces of equipment, sometimes costing millions of dollars; they are designed for high part quantities. The amount of machining accomplished on the work part is often significant, but since the work is divided among many stations, production rates are high and unit costs are low compared to alternative production methods. Synchronous transfer of work units between stations is commonly used on automated machining lines.

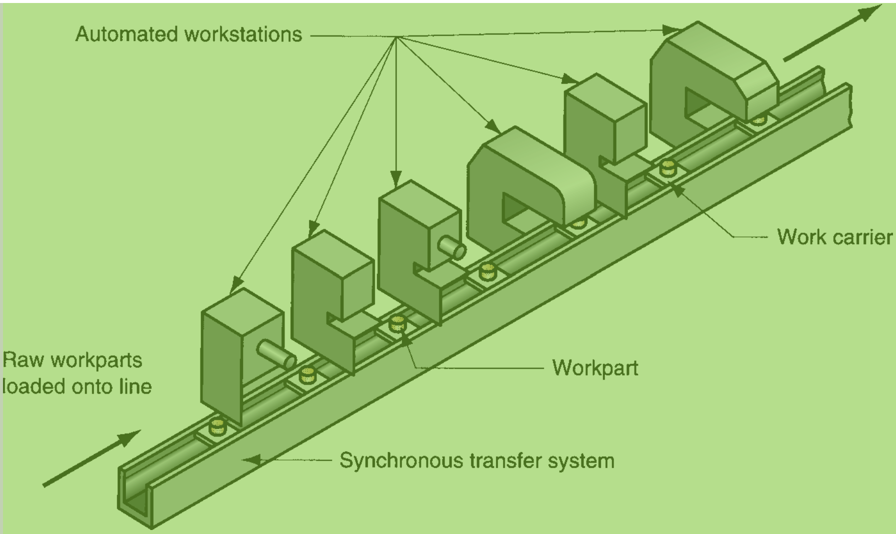

FIGURE 38.4 A machining transfer line, an important type of automated production line.

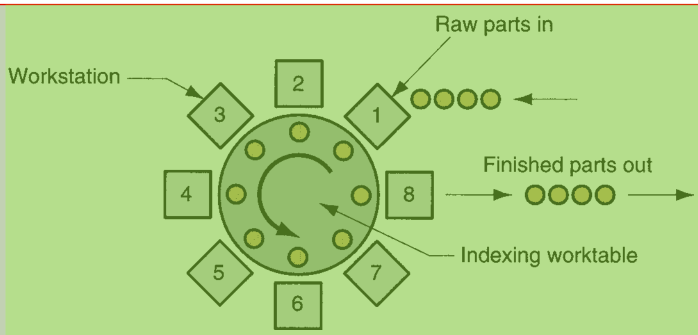

FIGURE 38.5 Configuration of a dial-indexing machine.

A variation of the automated transfer line is the ***dial indexing machine***, Figure 38.5, in which workstations are arranged around a circular worktable, called a dial. The worktable is actuated by a mechanism that provides partial rotation of the table on each work cycle. The number of rotational positions is designed to match the number of workstations around the periphery of the table. Although the configuration of a dial-indexing machine is quite different from a transfer line, its operation and application are quite similar.

Automated Assembly Systems Automated assembly systems consist of one or more workstations that perform assembly operations, such as adding components and/or affixing them to the work unit. Automated assembly systems can be divided into single station cells and multiple station systems. ***Single station assembly cells*** are often organized around an industrial robot that has been programmed to perform a sequence of assembly steps. The robot cannot work as fast as a series of specialized automatic stations, so single station cells are used for jobs in the medium production range.

Multiple station assembly systems are appropriate for high production. They are widely used for mass production of small products such as ball-point pens, cigarette lighters, flashlights, and similar items consisting of a limited number of components. The number of components and assembly steps is limited because system reliability decreases rapidly with increasing complexity.

Multiple station assembly systems are available in several configurations, pictured in Figure 38.6: (a) in-line, (b) rotary, and (c) carousel. The in-line configuration is the conventional transfer line adapted to perform assembly work. These systems are not as massive as their machining counterparts. Rotary systems are usually implemented

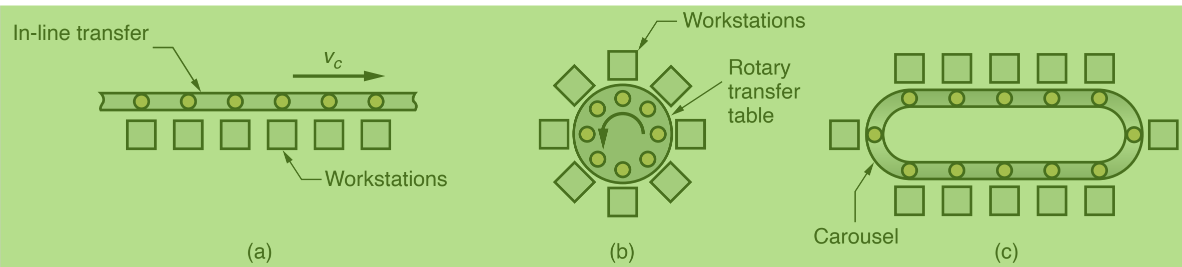

FIGURE 38.6 Three common configurations of multiple station assembly systems: (a) in-line, (b) rotary, and (c) carousel.

as dial indexing machines. Carousel assembly systems are arranged as a loop. They can be designed with a greater number of workstations than a rotary system. Owing to the loop configuration, the carousel allows the work carriers to be automatically returned to the starting point for reuse, an advantage shared with rotary systems but not with transfer lines unless provision for their return is made in the design.

38.4.2 ANALYSIS OF AUTOMATED PRODUCTION LINES

Line balancing is a problem on an automated line, just as it is on a manual assembly line. The total work content must be allocated to individual workstations. However, since the tasks assigned to automated stations are generally simpler, and the line often contains fewer stations, the problem of defining what work should be done at each station is not as difficult for an automated line as for a manual line.

A more significant problem in automated lines is reliability. The line consists of multiple stations, interconnected by a work transfer system. It operates as an integrated system, and when one station malfunctions, the entire system is adversely affected. To analyze the operation of an automated production line, assume a system that performs processing operations and uses synchronous transfer. This model includes transfer lines as well as dial indexing machines. It does not include automated assembly systems, which require an adaptation of the model [10]. The terminology will borrow symbols from the first two sections: n = number of workstations on the line; T_c = ideal cycle time on the line; T_r = repositioning time, called the transfer time in a transfer line; and T_{si} = the service time at station i. The ideal cycle time T_c is the service time (processing time) for the slowest station on the line plus the transfer time; that is,

$$T_c = T_r + \text{Max}\,\{T_{si}\} \tag{38.9}$$

In the operation of a transfer line, periodic breakdowns cause downtime on the entire line. Let F = frequency with which breakdowns occur, causing a line stoppage; and T_d = average time the line is down when a breakdown occurs. The downtime includes the time for the repair crew to swing into action, diagnose the cause of the failure, fix it, and restart the line.

Based on these definitions, the following expression can be formulated for the actual average production time T_p:

$$T_p = T_c + FT_d \tag{38.10}$$

where F = downtime frequency, line stops/cycle; and T_d = downtime in minutes per line stop. Thus, FT_d = average downtime per cycle. The actual average production rate $R_p = 60/T_p$, as previously given in Equation (38.2). It is of interest to compare this rate with the ideal production rate given by

$$R_c = \frac{60}{T_c} \tag{38.11}$$

where R_p and R_c are expressed in pc/hour, given that T_p and T_c are expressed in minutes.

Using these definitions, the line efficiency E for a transfer line can be defined. In the context of automated manufacturing systems, E refers to the proportion of uptime on the line and is really a measure of availability (Section 1.5.2) rather than efficiency:

$$E = \frac{T_c}{T_c + FT_d} \tag{38.12}$$

This is the same relationship as earlier Equation (38.3), since $T_p = T_c + FT_d$. It should be noted that the same definition of line efficiency applies to manual assembly lines, except that technological breakdowns are not as much of a problem on manual lines (human workers are more reliable than electromechanical equipment, at least in the sense discussed here).

Line downtime is usually associated with failures at individual workstations. Reasons for downtime include scheduled and unscheduled tool changes, mechanical and electrical malfunctions, hydraulic failures, and normal equipment wear. Let p_i = probability or frequency of a failure at station i, then

$$F = \sum_{i=1}^{n} p_i \tag{38.13}$$

If all p_i are assumed equal, or an average value of p_i is computed, in either case calling it p, then

$$F = np \tag{38.14}$$

Both of these equations clearly indicate that the frequency of line stops increases with the number of stations on the line. Stated another way, the reliability of the line decreases as the number of stations is increased.

Example 38.2 Automated transfer line

An automated transfer line has 20 stations and an ideal cycle time of 1.0 min. Probability of a station failure is $p = 0.01$, and the average downtime when a breakdown occurs is 10 min. Determine (a) average production rate R_p and (b) line efficiency E.

Solution: The frequency of breakdowns on the line is given by $F = pn = 0.01(20) = 0.20$. The actual average production time is therefore

$$T_p = 1.0 + 0.20(10) = 3.0 \text{ min}$$

(a) Production rate is therefore

$$R_p = \frac{60}{T_p} = \frac{60}{3.0} = \mathbf{20\ pc/hr}$$

Note that this is far lower than the ideal production rate:

$$R_c = \frac{60}{T_c} = \frac{60}{1.0} = 60 \text{ pc/hr}$$

(b) Line efficiency is computed as

$$E = \frac{T_c}{T_p} = \frac{1.0}{3.0} = \mathbf{0.333\ (or\ 33.3\%)}$$

This example clearly demonstrates how a production line with many workstations, a high average downtime per breakdown, and a seemingly low probability of station failure can spend more time down than up. Achieving high line efficiencies is a real problem in automated production lines.

The cost of operating an automated production line is the investment cost of the equipment and installation, plus the cost of maintenance, utilities, and labor assigned to the line. These costs are converted to an equivalent uniform annual cost and divided by the number of hours of operation per year to provide an hourly rate. This hourly cost rate can be used to figure the unit cost of processing a work part on the line

$$C_p = \frac{C_o T_p}{60} \tag{38.15}$$

where C_p = unit processing cost, \$/part; C_o = hourly rate of operating the line, as defined above, \$/hr; T_p = actual average production time per work part, min/part; and the constant 60 converts the hourly cost rate to \$/min for consistency of units.

38.5 Cellular Manufacturing

Cellular manufacturing refers to the use of work cells that specialize in the production of families of parts or products made in medium quantities. Parts (and products) in this quantity range are traditionally made in batches, and batch production requires downtime for setup changeovers and has high inventory carrying costs. Cellular manufacturing is based on an approach called group technology (GT), which minimizes the disadvantages of batch production by recognizing that although the parts are different, they also possess similarities. When these similarities are exploited in production, operating efficiencies are improved. The improvement is typically achieved by organizing the production around manufacturing cells. Each cell is designed to produce one part family (or a limited number of part families), thereby following the principle of specialization of operations. The cell includes special production equipment and custom-designed tools and fixtures, so that the production of the part families can be optimized. In effect, each cell becomes a factory within the factory.

38.5.1 PART FAMILIES

A central feature of cellular manufacturing and group technology is the part family. A ***part family*** is a group of parts that possess similarities in geometric shape and size, or in the processing steps used in their manufacture. It is not unusual for a factory that produces 10,000 different parts to be able to group most of those parts into 20 to 30 part families. In each part family the processing steps are similar. There are always differences among parts in a family, but the similarities are close enough that the parts can be grouped into the same family. Figures 38.7 and 38.8 show two different part families. The parts shown in Figure 38.7 have the same size and shape; however, their processing requirements are quite different because of differences in work material, production quantities, and design tolerances. Figure 38.8 shows several parts with geometries that differ, but their manufacturing requirements are quite similar.

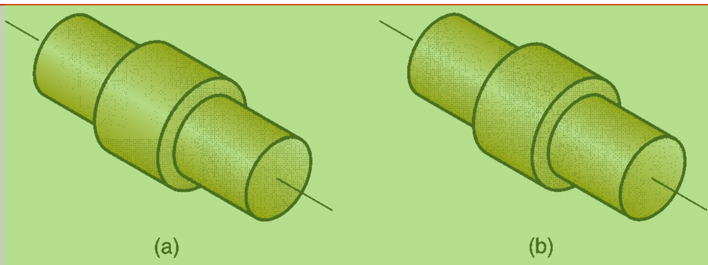

FIGURE 38.7 Two parts that are identical in shape and size but quite different in manufacturing: (a) 1,000,000 units/yr, tolerance = ±0.010 in., 1015 CR steel, nickel plate; and (b) 100/yr, tolerance = ±0.001 in, 18-8 stainless steel.

There are several ways by which part families are identified in industry. One method involves visual inspection of all the parts made in the factory (or photos of the parts) and using best judgment to group them into appropriate families. Another approach, called ***production flow analysis***, uses information contained on route sheets (Section 39.1.1) to classify parts. In effect, parts with similar manufacturing steps are grouped into the same family.

A third method, usually the most expensive but most useful, is parts classification and coding. ***Parts classification and coding*** involve the identification of similarities and differences among parts and relating these parts by means of a numerical coding scheme. Most classification and coding systems are one of the following: (1) systems based on part design attributes, (2) systems based on part manufacturing attributes, and (3) systems based on both design and manufacturing attributes. Common part design and manufacturing attributes used in GT systems are presented in Table 38.3. Because each company produces a unique set of parts and products, a classification and coding system that may be satisfactory for one company is not necessarily appropriate for another company. Each company must design its own coding

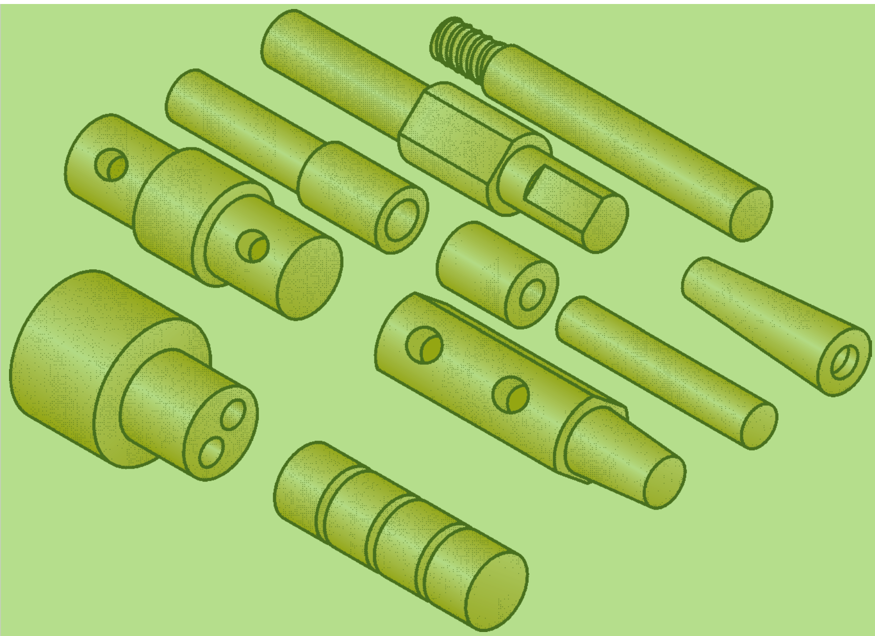

FIGURE 38.8 Ten parts that are different in size and shape, but quite similar in terms of manufacturing. All parts are machined from cylindrical stock by turning; some parts require drilling and/or milling.

TABLE • 38.3 Design and manufacturing attributes typically included in a parts classification and coding system.

Part Design Attributes		Part Manufacturing Attributes	
Major dimensions	Material type	Major process	Major dimensions
Basic external shape	Part function	Operation sequence	Basic external shape
Basic internal shape	Tolerances	Batch size	Length/diameter ratio
Length/diameter ratio	Surface finish	Annual production	Material type
		Machine tools	Tolerances
		Cutting tools	Surface finish

scheme. Parts classification and coding systems are described more thoroughly in several of the references [8], [10], [11].

Benefits often cited for a well-designed classification and coding system include that it (1) facilitates formation of part families, (2) permits quick retrieval of part design drawings, (3) reduces design duplication because similar or identical part designs can be retrieved and reused rather than designed from scratch, (4) promotes design standardization, (5) improves cost estimating and cost accounting, (6) facilitates numerical control (NC) part programming by allowing new parts to use the same basic part program as existing parts in the same family, (7) allows sharing of tools and fixtures, and (8) aids computer-aided process planning (CAPP) (Section 39.1.3) because standard process plans can be correlated to part family code numbers, so that existing process plans can be reused or edited for new parts in the same family.

38.5.2 MACHINE CELLS

To fully exploit the similarities among parts in a family, production should be organized using machine cells designed to specialize in making those particular parts. One of the principles in designing a group technology machine cell is the composite part concept.

Composite Part Concept Members of a part family possess similar design and/or manufacturing features. There is usually a correlation between part design features and the manufacturing operations that produce those features. Round holes are made by drilling; cylindrical shapes are made by turning; and so on.

The ***composite part*** for a given family (not to be confused with a part made of composite material) is a hypothetical part that includes all of the design and manufacturing attributes of the family. In general, an individual part in the family will have some of the features that characterize the family, but not all of them. A production cell designed for the part family would include those machines required to make the composite part. Such a cell would be capable of producing any member of the family, simply by omitting those operations corresponding to features not possessed by the particular part. The cell would also be designed to allow for size variations within the family as well as feature variations.

To illustrate, consider the composite part in Figure 38.9(a). It represents a family of rotational parts with features defined in part (b) of the figure. Associated

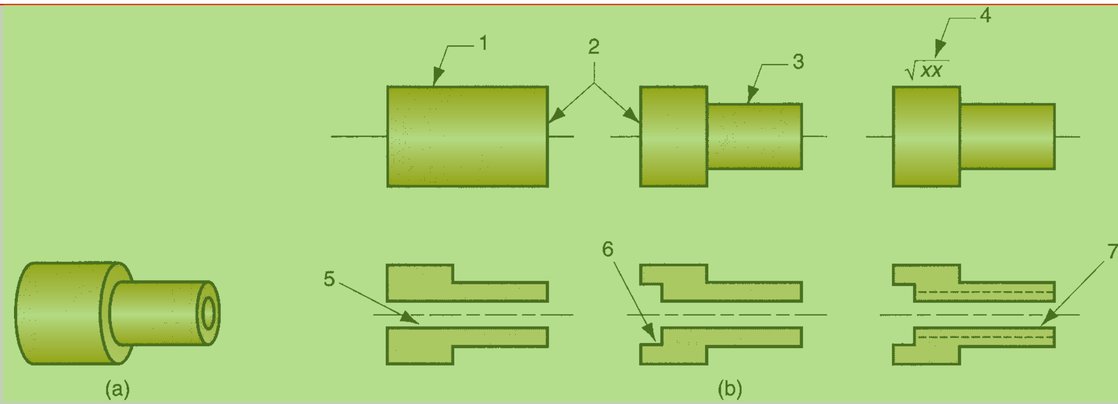

FIGURE 38.9 Composite part concept: (a) the composite part for a family of machined rotational parts, and (b) the individual features of the composite part.

with each feature is a certain machining operation, as summarized in Table 38.4. A machine cell to produce this part family would be designed with the capability to accomplish all of the operations in the last column of the table.

Machine Cell Designs Machine cells can be classified according to number of machines and level of automation. The possibilities are (a) single machine, (b) multiple machines with manual handling, (c) multiple machines with mechanized handling, (d) flexible manufacturing cell, or (e) flexible manufacturing system. These production cells are depicted in Figure 38.10.

The single machine cell has one machine that is manually operated. The cell would also include fixtures and tools to allow for feature and size variations within the part family produced by the cell. The machine cell required for the part family of Figure 38.9 would probably be of this type.

Multiple machine cells have two or more manually operated machines. These cells are distinguished by the method of work part handling in the cell, manual or mechanized. Manual handling means that parts are moved within the cell by workers, usually the machine operators. Mechanized handling refers to conveyorized

TABLE • 38.4 Design features of the composite part in Figure 38.3 and the manufacturing operations required to shape those features.

Label	Design Feature	Corresponding Manufacturing Operation
1	External cylinder	Turning
2	Face of cylinder	Facing
3	Cylindrical step	Turning
4	Smooth surface	External cylindrical grinding
5	Axial hole	Drilling
6	Counterbore	Bore, counterbore
7	Internal threads	Tapping

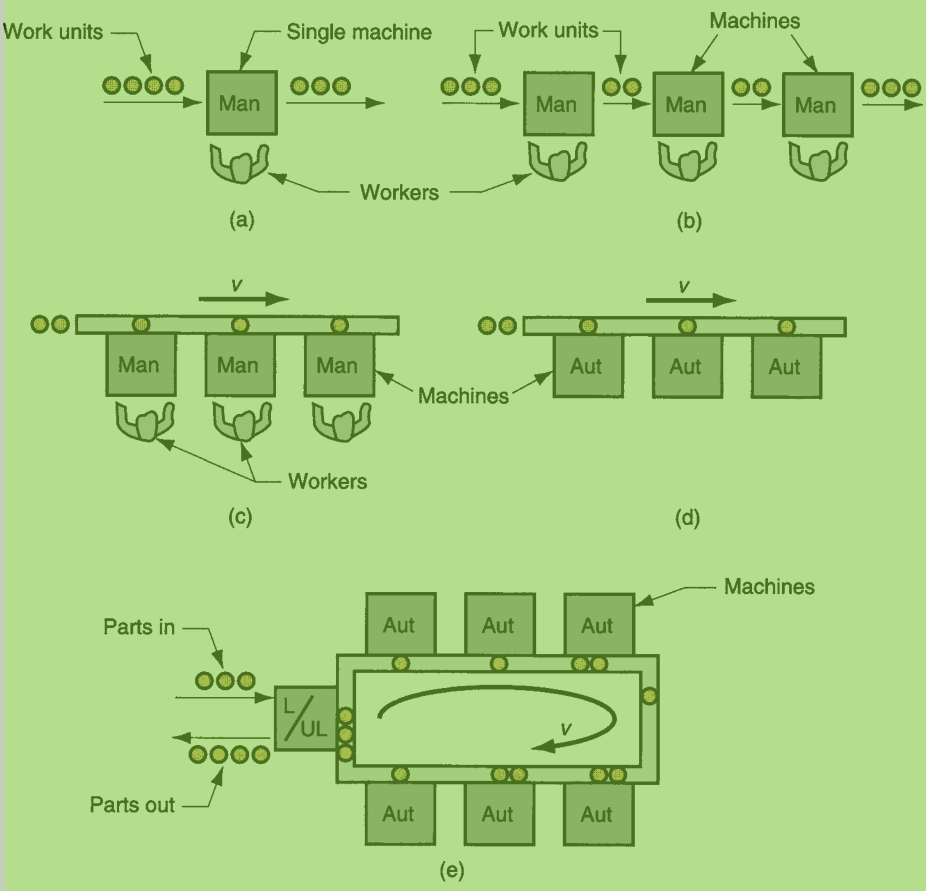

FIGURE 38.10 Types of group technology machine cells: (a) single machine, (b) multiple machines with manual handling, (c) multiple machines with mechanized handling, (d) flexible manufacturing cell, and (e) flexible manufacturing system. Key: Man = manual operation; Aut = automated station.

transfer of parts from one machine to the next. This may be required by the size and weight of the parts made in the cell, or simply to increase production rate. The sketch depicts the work flow as being a line; other layouts are also possible, such as U-shaped or loop.

Flexible manufacturing cells and flexible manufacturing systems consist of automated machines with automated handling. Given the special nature of these integrated manufacturing systems and their importance, Section 38.6 is devoted to this topic.

Benefits and Problems in Group Technology The use of machine cells and group technology provide substantial benefits to companies that have the discipline and perseverance to implement it. The potential benefits include the following: (1) GT promotes standardization of tooling, fixturing, and setups; (2) material handling is reduced because parts are moved within a machine cell rather than the entire factory; (3) production scheduling is simplified; (4) manufacturing lead time is reduced; (5) work-in-process is reduced; (6) process planning is simpler; (7) worker satisfaction usually improves working in a cell; and (8) higher quality work is accomplished.

There are several problems in implementing machine cells, however. One obvious problem is rearranging production machines in the plant into the appropriate machine cells. It takes time to plan and accomplish this rearrangement, and the machines are not producing during the changeover. The biggest problem in starting a GT program is identifying the part families. If the plant makes 10,000 different parts, reviewing all of the part drawings and grouping the parts into families are substantial tasks that consume a significant amount of time.

38.6 Flexible Manufacturing Systems and Cells

A flexible manufacturing system (FMS) is a highly automated group technology machine cell, consisting of a multiple processing stations (usually computer numerical control machine tools), interconnected by an automated material handling and storage system, and controlled by an integrated computer system. An FMS is capable of processing a variety of different part styles simultaneously under NC program control at the different workstations.

An FMS relies on the principles of group technology. No manufacturing system can be completely flexible. It cannot produce an infinite range of parts or products. There are limits to how much flexibility can be incorporated into an FMS. Accordingly, a flexible manufacturing system is designed to produce parts (or products) within a range of styles, sizes, and processes. In other words, an FMS is capable of producing a single part family or a limited range of part families.

Flexible manufacturing systems vary in terms of number of machine tools and level of flexibility. When the system has only a few machines, the term ***flexible manufacturing cell*** (FMC) is sometimes used. Both cell and system are highly automated and computer controlled. The difference between an FMS and an FMC is not always clear, but it is sometimes based on the number of machines (workstations) included. The flexible manufacturing system consists of four or more machines, whereas a flexible manufacturing cell consists of three or fewer machines [10].

To qualify as being flexible, a manufacturing system should satisfy several criteria. The tests of flexibility in an automated manufacturing system are the capability to (1) process different part styles in a nonbatch mode, (2) accept changes in production schedule, (3) respond gracefully to equipment malfunctions and breakdowns in the system, and (4) accommodate the introduction of new part designs. These capabilities are made possible by the use of a central computer that controls and coordinates the components of the system. The most important criteria are (1) and (2). Criteria (3) and (4) are less critical and can be implemented at various levels of sophistication.

38.6.1 INTEGRATING THE FMS COMPONENTS

An FMS consists of hardware and software that must be integrated into an efficient and reliable unit. It also includes human personnel. This section examines these components and how they are integrated.

Hardware Components FMS hardware includes workstations, material handling system, and central control computer. The workstations are CNC machines in a machining type system, plus inspection stations, parts cleaning and other stations, as required. A central chip conveyor system is often installed below floor level.

The material handling system is the means by which parts are moved between stations. The material handling system usually includes a limited capability to store parts. Handling systems suitable for automated manufacturing include roller conveyors, automated guided vehicles, and industrial robots. The most appropriate type depends on part size and geometry, as well as factors relating to economics and compatibility with other FMS components. Nonrotational parts are often moved in a FMS on pallet fixtures, so the pallets are designed for the particular handling system, and the fixtures are designed to accommodate the various part geometries in the family. Rotational parts are often handled by robots, if weight is not a limiting factor.

The handling system establishes the basic layout of the FMS. Five layout types can be distinguished: (1) in-line, (2) loop, (3) ladder, (4) open field, and (5) robot-centered cell. Types 1, 3, 4, and 5 are shown in Figure 38.11. Type 2 is shown in Figure 38.10(e). The ***in-line layout*** uses a linear transfer system to move parts between processing stations and load/unload station(s). The in-line transfer system is usually capable of two-directional movement; if not, then the FMS operates much like a transfer line, and the different part styles made on the system must follow the same basic processing sequence due to the one-direction flow. The ***loop layout*** consists of a conveyor loop with workstations located around its periphery. This configuration permits any processing sequence, because any station is accessible from any other station. This is also true for the ***ladder layout***, in which workstations are located on the rungs of the ladder. The ***open field layout*** is the most complex FMS configuration, and consists of several loops tied together. Finally, the robot-centered cell consists of a robot whose work volume includes the load/unload positions of the machines in the cell.

The FMS also includes a central computer that is interfaced to the other hardware components. In addition to the central computer, the individual machines and other components generally have microcomputers as their individual control units. The function of the central computer is to coordinate the activities of the components so as to achieve a smooth overall operation of the system. It accomplishes this function by means of software.

FMS Software and Control Functions FMS software consists of modules associated with the various functions performed by the manufacturing system. For example, one function involves downloading NC part programs to the individual machine tools; another function is concerned with controlling the material handling system; another is concerned with tool management; and so on. Table 38.5 lists the functions included in the operation of a typical FMS. Associated with each function are one or more software modules. The functions and modules are largely application specific.

Human Labor An additional component in the operation of a flexible manufacturing system or cell is human labor. Duties performed by human workers include (1) loading and unloading parts from the system, (2) changing and setting cutting tools, (3) maintenance and repair of equipment, (4) NC part programming, (5) programming and operating the computer system, and (6) overall management of the system.

38.6.2 APPLICATIONS OF FLEXIBLE MANUFACTURING SYSTEMS

Flexible manufacturing systems are typically used for mid-volume, mid-variety production. If the part or product is made in high quantities with no style variations, then a transfer line or similar dedicated manufacturing system is most appropriate. If the parts are low volume with high variety, then a stand-alone NC machine or even

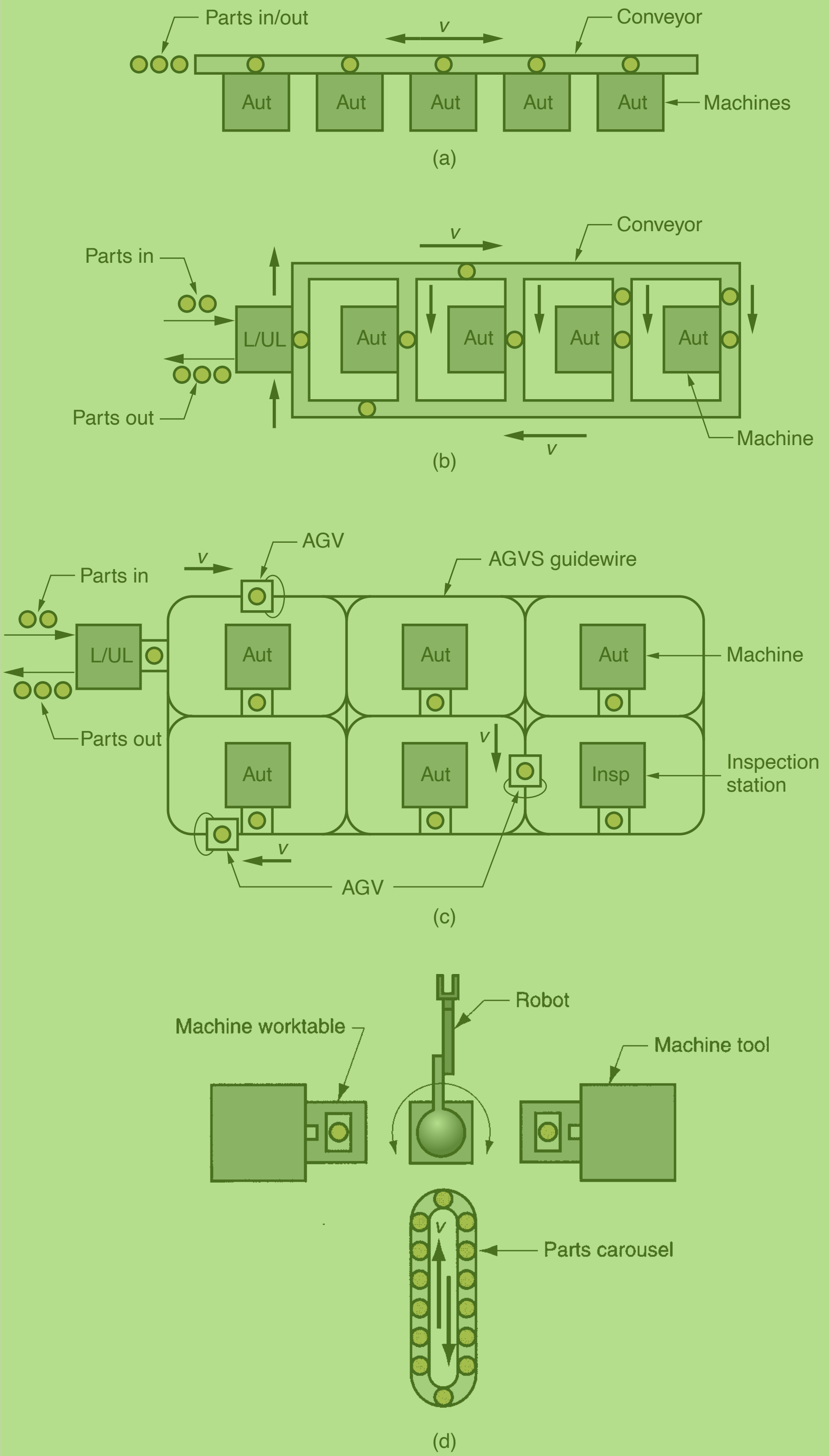

FIGURE 38.11 Four of the five FMS layout types: (a) in-line, (b) ladder, (c) open field, and (d) robot-centered cell. Key: Aut = automated station; L/UL = load/unload station; Insp = inspection station; AGV = automated guided vehicle; AGVS = automated guided vehicle system.

TABLE • 38.5 Typical computer functions implemented by application software modules in a flexible manufacturing system.

Function	Description
NC part programming	Development of NC programs for new parts introduced into the system. This includes a language package such as APT.
Production control	Product mix, machine scheduling, and other planning functions.
NC program download	Part program commands must be downloaded to individual stations from the central computer.
Machine control	Individual workstations require controls, usually computer numerical control.
Work part control	Monitor status of each work part in the system, status of pallet fixtures, orders on loading/unloading pallet fixtures.
Tool management	Functions include tool inventory control, tool status relative to expected tool life, tool changing and resharpening, and transport to and from tool grinding.
Transport control	Scheduling and control of work part handling system.
System management	Compiles management reports on performance (utilization, piece counts, production rates, etc.). FMS simulation sometimes included.

Key: NC = numericals control, APT = automatically programmed tooling, FMS = flexible manufacturing system.

manual methods would be more appropriate. These application characteristics are summarized in Figure 38.12.

Flexible machining systems comprise the most common application of FMS technology. Owing to the inherent flexibilities and capabilities of computer numerical control, it is possible to connect several CNC machine tools to a small central computer, and to devise automated material handling methods for transferring parts between machines. Figure 38.13 shows a flexible machining system consisting of five CNC machining centers and an in-line transfer system to pick up parts from a central load/unload station and move them to the appropriate machining stations.

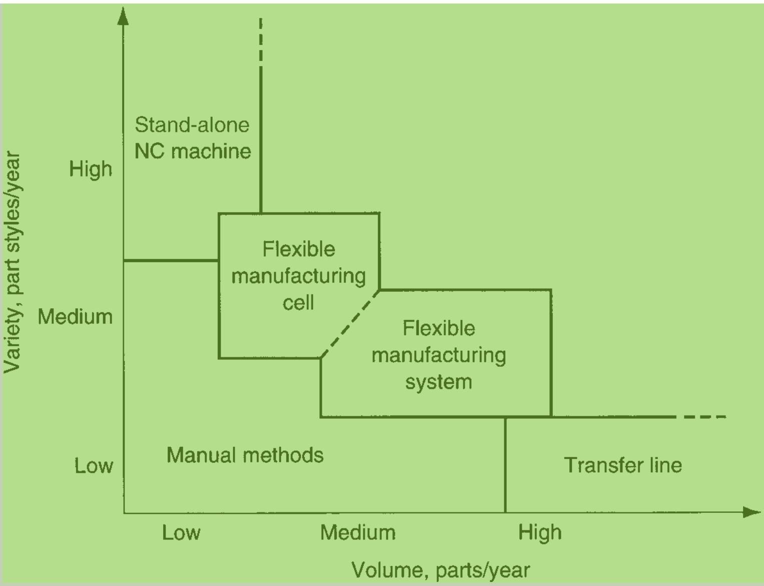

FIGURE 38.12 Application characteristics of flexible manufacturing systems and cells relative to other types of manufacturing systems.

FIGURE 38.13 A five-station flexible manufacturing system. (Photo courtesy of Cincinnati Milacron.)

In addition to machining systems, other types of flexible manufacturing systems have also been developed, although the state of technology in these other processes has not permitted the rapid implementation that has occurred in machining. The other types of systems include assembly, inspection, sheet-metal processing (punching, shearing, bending, and forming), and forging.

Most of the experience in flexible manufacturing systems has been gained in machining applications. For flexible machining systems, the benefits usually given are (1) higher machine utilization than a conventional machine shop (relative utilizations are 40% to 50% for conventional batch type operations compared with about 75% for a FMS because of better work handling, offline setups, and improved scheduling); (2) reduced work-in-process due to continuous production rather than batch production; (3) lower manufacturing lead times; and (4) greater flexibility in production scheduling.

38.6.3 MASS CUSTOMIZATION

Taken to its limit, flexible manufacturing is capable of producing a unique product for each customer. This capability is called mass customization, in which a large variety of products are made at efficiencies approaching those of mass production. Each product is individually customized according to specifications of individual customers. Referring back to the definitions of production quantity and product variety in Section 1.1.2, the distinction between mass production and mass customization is indicated in Table 38.6. In the extreme, mass production is the production of very

TABLE • 38.6 Comparison between mass production and mass customization.

	Production Quantity	Product Variety
Mass production	Large	1
Mass customization	1	Large

large quantities of one product style. Similarly, mass customization involves large product variety and only one unit is produced of each product style.

The challenge for the mass customizer is to manage its design and production operations without the waste associated with needless product proliferation, in which the company offers its customers so many choices among products and available options that it is unprofitable. The following example illustrates product proliferation at its worst.

Example 38.3 Product proliferation

A few decades ago, one of the truck manufacturers in the United States offered its customers a wide variety of model choices and options. Any of more than 100 truck models could be ordered, and each model was available in 7 different wheel bases. The customer could select among 42 basic engines, 43 different front axles, 62 transmissions, and 162 different rear axles. Thus, the company offered its customers a choice among

$$100(7)(42)(43)(62)(162) = 130(10^8) \text{ possible combinations.}$$

At its peak, the company had an annual production of 130,000 trucks. If each customer were to order a different truck, the company could produce trucks for

$$\frac{130(10^8)}{130{,}000} = 10{,}000 \text{ years without ever producing the same truck twice.}$$

The negative consequences of product proliferation include (1) large raw material, work-in-process, and finished product inventories; (2) high purchasing costs; (3) large floor space requirements, (4) too many setups and too much tooling, (5) a costly overhead to manage the variety, (6) much marketing literature and design data; and (7) customer confusion. So the question is: How can a company offer customized product variety while at the same time avoiding the negative consequences of product proliferation?

The successful mass customizer can use a number of strategies to operate efficiently in the face of a large product variety. They include: (1) soft product variety, (2) design modularity, (3) postponement, and (4) designing the product to be easily customized.

Large product variety does not mean hard product variety, recalling the terminology of Section 1.1.2. Indeed, mass customization would not be feasible unless soft product variety were practiced by the company that offered customized products to its customers. Soft product variety means that there are only small differences among available products. The differences may appear significant to the customer, but to the company, they are easily managed in production. The company's strategy is to minimize the real differences among its products while enticing the customer to appreciate the product differentiation; for example, offering a product in which all internal components are identical but the product is available in a variety of external colors.

Modularity in product design is another approach used by mass customizers, in which the product consists of standard modules that can be assembled in unique combinations to satisfy individual customers' specifications. The modules are standard building blocks that are perhaps mass produced, but they combine in different ways to achieve a singular product. Of course, the modules must be designed in such a way that facilitates their assembly. An example is the personal computer. Each PC customer specifies from a variety of features and options, all of which relate to hardware and software modules that are assembled and loaded to meet the specifications.

Postponement is closely related to design modularity. It means that the mass customizer waits until the last possible moment to complete the product which occurs after a customer order has been received. The alternative is carrying a large inventory of finished products that match all of the possible combinations of specifications that customers might want.

Finally, the mass customizer designs the product so that it can be readily customized. The customization can be accomplished at the last moment by the manufacturer, as in postponement, or it can be accomplished by the merchant who deals directly with the customer. An example of customization by the manufacturer is when the customer can select among alternative design parameters and options that are available, and the product is then made to those specifications. Automobiles are sometimes purchased this way. An example of merchant customization is when paint dealers mix colorants with a standard neutral base paint to achieve the exact color desired by the customer. The mass customizer may also design adjustability into the product, so that the customers themselves can individualize the product. Examples of product adjustability include car seat adjustments made by the driver and software settings made by users of personal computers.

38.7 Computer Integrated Manufacturing

Distributed computer networks are widely used in modern manufacturing plants to monitor and/or control the integrated systems described in this chapter. Even though some of the operations are manually accomplished (e.g., manual assembly lines and manned cells), computer systems are utilized for production scheduling, data collection, record keeping, performance tracking, and other information-related functions. In the more automated systems (e.g., transfer lines and flexible manufacturing cells), computers directly control the operations. The term ***computer integrated manufacturing*** (CIM) refers to the pervasive use of computer systems throughout the organization, not only to monitor and control the operations, but also to design the product, plan the manufacturing processes, and accomplish the business functions related to production. One might say that CIM is the ultimate integrated manufacturing system. In this final section of Part X, the scope of CIM is outlined, and a bridge is provided to Part XI on manufacturing support systems.

To begin, there are four general functions that have to be accomplished in most manufacturing enterprises: (1) product design, (2) manufacturing planning, (3) manufacturing control, and (4) business functions. Product design is usually an iterative process that includes recognition of a need for a product, problem definition, creative

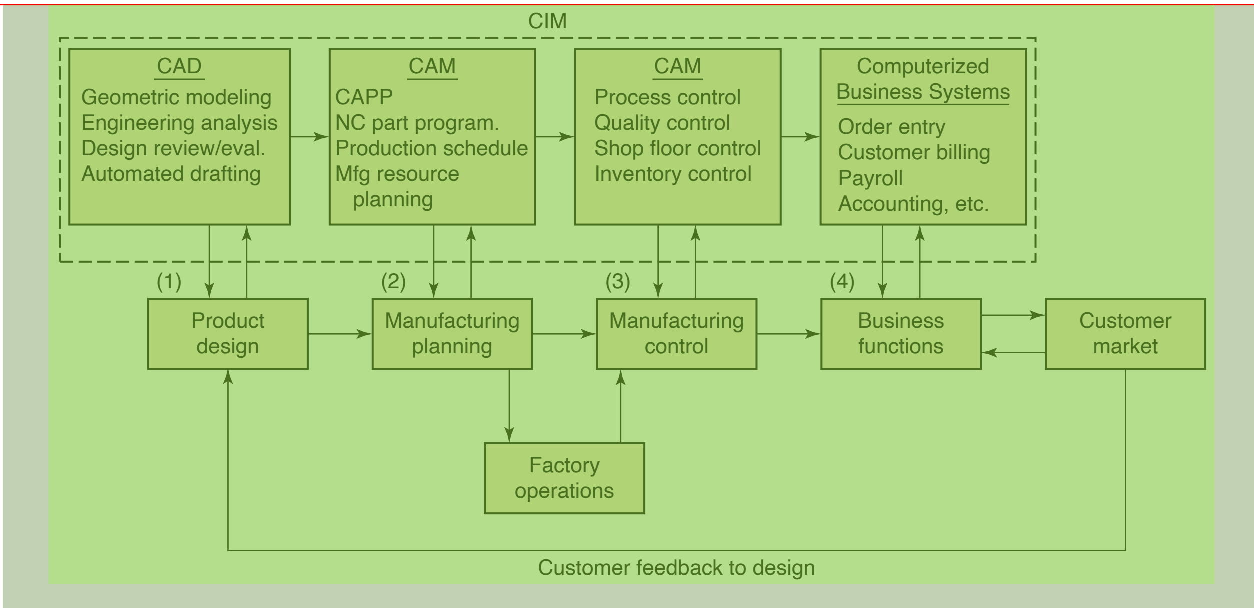

FIGURE 38.14 Four general functions in a manufacturing organization, and how computer integrated manufacturing systems support these functions.

synthesis of a solution, analysis and optimization, evaluation, and documentation. The overall quality of the resulting design is likely to be the most important factor upon which the commercial success of a product depends. In addition, a very significant portion of the final cost of the product is determined by decisions made during product design. Manufacturing planning is concerned with converting the engineering drawings and specifications that define the product design into a plan for producing the product. Manufacturing planning includes decisions on which parts will be purchased (the "make-or-buy decision"), how each "make" part will be produced, the equipment that will be used, how the work will be scheduled, and so on. Most of these decisions are discussed in Chapter 39 on process planning and production control. Manufacturing control includes not only control of the individual processes and equipment in the plant, but also the supporting functions such as shop floor control (Section 39.3.4) and quality control (Chapter 40). Finally, the business functions include order entry, cost accounting, payroll, customer billing, and other business-oriented information activities related to manufacturing.

Computer systems play an important role in these four general functions, and their integration within the organization is a distinguishing feature of computer integrated manufacturing, as depicted in Figure 38.14. Computer systems associated with product design are called CAD systems (for computer-aided design). Design systems and software include geometric modeling, engineering analysis packages such as finite element modeling, design review and evaluation, and automated drafting. Computer systems that support manufacturing planning are called CAM systems (for computer-aided manufacturing) and include computer-aided process planning (CAPP, Section 39.1.3), NC part programming (Section 38.3.3), production scheduling (Section 39.3.1), and planning packages such as material requirements planning (Section 39.3.2). Manufacturing control systems include those used in process control, shop floor control, inventory control, and computer-aided inspection for quality control. And computerized business systems are used for order entry, customer billing, and other business functions. Customer orders are entered by the company's sales force or by the customers themselves into the computerized order entry system. The orders include product specifications that provide the inputs to the design department. Based on these inputs, new products are designed on the company's CAD system. The design details serve as inputs to the manufacturing engineering group, where computer-aided process planning, computer-aided tool design, and related activities are performed in advance of actual production. The output from manufacturing engineering provides much of the input data required for manufacturing resource planning and production scheduling. Thus, computer integrated manufacturing provides the information flows required to accomplish the actual production of the product.

Today, computer integrated manufacturing is implemented in many companies using ***enterprise resource planning*** (ERP), a computer software system that organizes and integrates the information flows in an organization through a single, central database. ERP is described in Section 39.3.5.

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