Part XI Manufacturing Support Systems

39 Process Planning and Production Control

CHAPTER CONTENTS

This final part of the book is concerned with ***manufacturing support systems***, which are the procedures and systems used by a company to solve the technical and logistics problems encountered in planning the processes, ordering materials, controlling production, and ensuring that the company's products meet required quality specifications. The position of the manufacturing support systems in the overall operations of the company is portrayed in Figure 39.1. Like the manufacturing systems in the factory, the manufacturing support systems include people. People make the systems work. Unlike the manufacturing systems in the factory, most of the support systems do not directly contact the product during its processing and assembly. Instead, they plan and control the activities in the factory to ensure that the products are completed and delivered to the customer on time, in the right quantities, and to the highest quality standards.

The quality control system is one of the manufacturing support systems, but it also consists of facilities located in the factory—inspection equipment used to measure and gage the materials being processed and products being assembled. The quality control system is covered in Chapter 40. Many of the traditional measurement and gaging techniques used in inspection are described in Chapter 5. Other manufacturing support

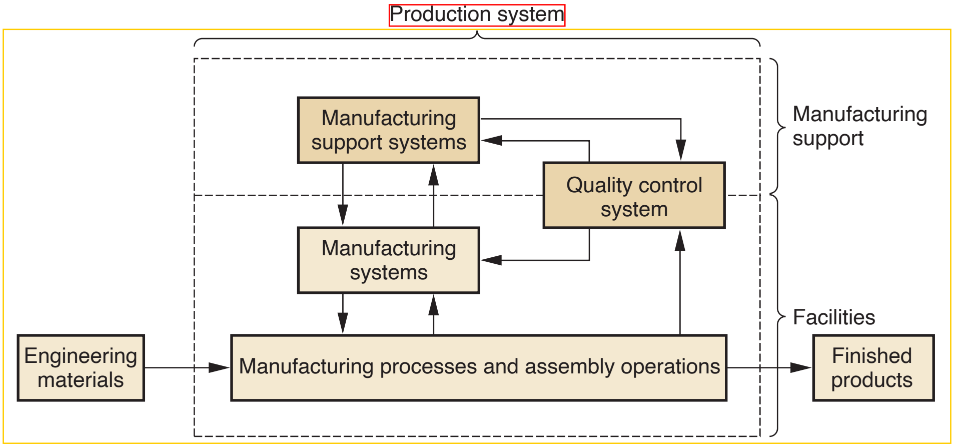


FIGURE 39.1 The position of the manufacturing support systems in the production system.

systems include process planning, production planning and control, just-in-time, and lean production, covered in the present chapter.

Process planning is a technical staff function that plans the sequence of manufacturing processes for the economic production of high-quality products. Its purpose is to engineer the transition from design specification to physical product. Process planning includes (a) deciding what processes and methods should be used and in what sequence, (b) determining tooling requirements, (c) selecting production equipment and systems, and (d) estimating costs of production for the selected processes, tooling, and equipment.

Process planning is usually the principal function within the manufacturing engineering department, whose overall goal is to optimize the production operations in a given organization. In addition to process planning, the scope of manufacturing engineering usually includes other functions such as the following:

- ***Problem solving and continuous improvement***. Manufacturing engineering provides staff support to the operating departments (parts fabrication and product assembly) to solve technical production problems. It should also be engaged in continuous efforts to reduce production costs, increase productivity, and improve product quality.
- ***Design for manufacturability***. In this function, which chronologically precedes the other two, manufacturing engineers serve as manufacturability advisors to product designers. The objective is to develop product designs that not only meet functional and performance requirements, but that also can be produced at reasonable cost with minimum technical problems at highest possible quality in the shortest possible time.

Manufacturing engineering must be performed in any industrial organization that is engaged in production. The manufacturing engineering department usually reports to the manager of manufacturing in a company. In some companies the department is known by other names, such as process engineering or production engineering. Often included under manufacturing engineering are tool design, tool fabrication, and various technical support groups.

39.1 Process Planning

Process planning involves determining the most appropriate manufacturing processes and the sequence in which they should be performed to produce a given part or product specified by design engineering. If it is an assembled product, process planning includes deciding the appropriate sequence of assembly steps. The process plan must be developed within the limitations imposed by available processing equipment and productive capacity of the factory. Parts or subassemblies that cannot be made internally must be purchased from external suppliers. In some cases, items that can be produced internally may be purchased from outside vendors for economic or other reasons.

39.1.1 TRADITIONAL PROCESS PLANNING

Traditionally, process planning has been accomplished by manufacturing engineers who are knowledgeable in the particular processes used in the factory and are able to read engineering drawings. Based on their knowledge, skill, and experience, they develop the processing steps in the most logical sequence required to make each part. Table 39.1 lists the many details and decisions usually included within the scope of process planning. Some of these details are often delegated to specialists, such as tool designers; but manufacturing engineering is responsible for them.

Process Planning for Parts The processes needed to manufacture a given part are determined largely by the material out of which it is to be made. The material is selected by the product designer based on functional requirements. Once the material has been selected, the choice of possible processes is narrowed considerably.

A typical processing sequence to fabricate a discrete part consists of (1) a basic process, (2) one or more secondary processes, (3) operations to enhance physical properties, and (4) finishing operations, as illustrated in Figure 39.2. Basic and secondary processes are shaping processes that alter the geometry of a work part (Section 1.3.1). A ***basic process*** establishes the initial geometry of the part. Examples

TABLE • 39.1 Decisions and details required in process planning.

Processes and sequence. The process plan should briefly describe all processing steps used on the work unit (e.g., part, assembly) in the order in which they are performed.

Equipment selection. In general, manufacturing engineers try to develop process plans that utilize existing equipment. When this is not possible, the component in question must be purchased (Section 39.1.2), or new equipment must be installed in the plant.

Tools, ***dies***, ***molds***, ***fixtures***, and ***gages***. The process planner must decide what tooling is needed for each process. Actual design is usually delegated to the tool design department, and fabrication is accomplished by the tool room.

Cutting tools and ***cutting conditions*** for machining operations. These are specified by the process planner, industrial engineer, shop foreman, or machine operator, often with reference to standard handbook recommendations.

Methods. Methods include hand and body motions, workplace layout, small tools, hoists for lifting heavy parts, and so forth. Methods must be specified for manual operations (e.g., assembly) and manual portions of machine cycles (e.g., loading and unloading a production machine). Methods planning is traditionally done by industrial engineers.

Work standards. Work measurement techniques are used to establish time standards for each operation.

Estimating production costs. This is often accomplished by cost estimators with help from the process planner.

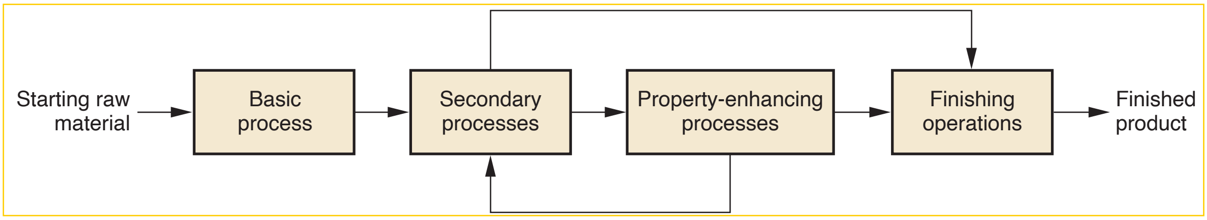


FIGURE 39.2 Typical sequence of processes required in part fabrication.

include metal casting, forging, and sheet-metal rolling. In most cases, the starting geometry must be refined by a series of ***secondary processes***. These operations transform the basic shape into the final geometry. There is a correlation between the secondary processes that might be used and the basic process that provides the initial form. For example, when a rolling mill produces strips or coils of sheet metal, the secondary processes are stamping operations such as blanking, punching, and bending. When casting or forging are the basic processes, machining operations are generally the secondary processes. Figure 39.3 shows a plumbing fixture, the production of which consists of casting as the basic process followed by machining as the secondary process. Selection of certain basic processes minimizes the need for secondary processes. For example, if plastic injection molding is the basic process, secondary operations are usually not required because molding is capable of providing the detailed geometric features with good dimensional accuracy.

Shaping operations are generally followed by operations to enhance physical properties and/or finish the product. ***Operations to enhance properties*** include heat treating operations on metal components and glassware. In many cases, parts do not

FIGURE 39.3 This plumbing fixture illustrates the basic and secondary processes. Casting (basic process) provides the starting geometry on the left, followed by a series of machining operations (secondary process) that accurately shape the holes and threads for the finished part on the right. (Courtesy of George E. Kane Manufacturing Technology Laboratory, Lehigh University.)

TABLE • 39.2 Some typical process sequences.

Basic Process	Secondary Process(es)	Property-Enhancing Processes	Finishing Operations
Sand casting	Machining	(none)	Painting
Die casting	(none, net shape)	(none)	Painting
Casting of glass	Pressing, blow molding	(none)	(none)
Injection molding	(none, net shape)	(none)	(none)
Rolling of bar stock	Machining	Heat treatment (optional)	Electroplating
Rolling of sheet metal	Blanking, bending, drawing	(none)	Electroplating
Forging	Machining (near net shape)	(none)	Painting
Extrusion of aluminum	Cut to length	(none)	Anodize
Atomize metal powders	Pressing of powder metal part	Sintering	Painting

Compiled from [6].

require these property-enhancing steps in their processing sequence. This is indicated by the alternate arrow path in our figure. ***Finishing operations*** are the final operations in the sequence; they usually provide a coating on the work part (or assembly) surface. Examples of these processes are electroplating and painting.

In some cases, property-enhancing processes are followed by additional secondary operations before proceeding to finishing, as suggested by the return loop in Figure 39.2. An example is a machined part that is hardened by heat treatment. Prior to heat treatment, the part is left slightly oversized to allow for distortion. After hardening, it is reduced to final size and tolerance by finish grinding. Another example, again in metal parts fabrication, is when annealing is used to restore ductility to the metal after cold working to permit further deformation of the workpiece.

Table 39.2 presents some of the typical processing sequences for various materials and basic processes. The task of the process planner usually begins after the basic process has provided the initial shape of the part. Machined parts begin as bar stock or castings or forgings, and the basic processes for these starting shapes are often external to the fabricating plant. Stampings begin as sheet metal coils or strips purchased from the mill. These are the raw materials supplied from external suppliers for the secondary processes and subsequent operations to be performed in the factory. Determining the most appropriate processes and the order in which they must be accomplished relies on the skill, experience, and judgment of the process planner. Some of the basic guidelines and considerations used by process planners to make these decisions are outlined in Table 39.3.

The Route Sheet The process plan is prepared on a form called a ***route sheet***, a typical example of which is shown in Figure 39.4 (some companies use other names for this form). It is called a route sheet because it specifies the sequence of operations and equipment that will be visited by the part during its production. The route sheet is to the process planner what the engineering drawing is to the product designer. It is the official document that specifies the details of the process plan. The route sheet should include all manufacturing operations to be performed on the work part, listed in the proper order in which they are to be accomplished. For each operation, the following should be listed: (1) a brief description of the

TABLE • 39.3 Guidelines and considerations in deciding processes and their sequence in process planning.

Design requirements. The sequence of processes must satisfy the dimensions, tolerances, surface finish, and other specifications established by product design.

Quality requirements. Processes must be selected that satisfy quality requirements in terms of tolerances, surface integrity, consistency and repeatability, and other quality measures.

Production volume and ***rate***. Is the product in the category of low, medium, or high production? The selection of processes and systems is strongly influenced by volume and production rate.

Available processes. If the product and its components are to be made in-house, the process planner must select processes and equipment already available in the factory.

Material utilization. It is desirable for the process sequence to make efficient use of materials and minimize waste. When possible, net shape or near net shape processes should be selected.

Precedence constraints. These are technological sequencing requirements that determine or restrict the order in which the processing steps can be performed. A hole must be drilled before it can be tapped; a powder-metal part must be pressed before sintering; a surface must be cleaned before painting; and so on.

Reference surfaces. Certain surfaces of the part must be formed (usually by machining) near the beginning of the sequence so they can serve as locating surfaces for other dimensions that are formed subsequently. For example, if a hole is to be drilled a certain distance from the edge of a given part, that edge must first be machined.

Minimize setups. The number of separate machine setups should be minimized. Wherever possible, operations should be combined at the same workstation. This saves time and reduces material handling.

Eliminate unnecessary steps. The process sequence should be planned with the minimum number of processing steps. Unnecessary operations should be avoided. Design changes should be requested to eliminate features not absolutely needed, thereby eliminating the processing steps associated with those features.

Flexibility. Where feasible, the process should be sufficiently flexible to accommodate engineering design changes. This is often a problem when special tooling must be designed to produce the part; if the part design is changed, the special tooling may be rendered obsolete.

Safety. Worker safety must be considered in process selection. This makes good economic sense, and it is the law (Occupational Safety and Health Act).

Minimum cost. The process sequence should be the production method that satisfies all of the above requirements and also achieves the lowest possible product cost

operation indicating the work to be done, surfaces to be processed with references to the part drawing, and dimensions (and tolerances, if not specified on part drawing) to be achieved; (2) the equipment on which the work is to be performed; and (3) any special tooling required, such as dies, molds, cutting tools, jigs or fixtures, and gages. In addition, some companies include cycle time standards, setup times, and other data on the route sheet.

Sometimes a more detailed ***operation sheet*** is also prepared for each operation listed in the routing. This is retained in the particular department where the operation is performed. It indicates the specific details of the operation, such as cutting speeds, feeds, and tools, and other instructions useful to the machine operator. Setup sketches are sometimes also included.

Process Planning for Assemblies For low production, assembly is generally done at individual workstations and a worker or team of workers performs the assembly work elements to complete the product. In medium and high production, assembly is usually performed on production lines (Section 37.2). In either case, there is a precedence order in which the work must be accomplished.

Process planning for assembly involves preparation of the assembly instructions that must be performed. For single stations, the documentation is similar to the

Part No: 031393	Part Name: Housing, valve		Rev. 2	Page 1 of 2		
Matl: 416 Stainless	Size: 2.0 dia × 5. long		Planner: MPG		Date: 3/13/XX	
No.	**Operation**	**Dept.**	**Machine**	**Tooling, gages**	**Setup time**	**Cycle time**
10	Face; rough & finish turn to 1.473 ± 0.003 dia. × 1.250 ± 0.003 length; face shoulder to 0.313 ± 0.002; finish turn to 1.875 ± 0.002 dia.; form 3 grooves at 0.125 width × 0.063 deep.	L	325	G857	1.0 h	8.22 m
20	Reverse; face to 4.750 ± 0.005 length; finish turn to 1.875 ± 0.002 dia.; drill 1.000 + 0.006, −0.002 dia. axial hole.	L	325		0.5 h	3.10 m
30	Drill & ream 3 radial holes at 0.375 ± 0.002 dia.	D	114	F511	0.3 h	2.50 m
40	Mill 0.500 ± 0.004 wide × 0.375 ± 0.003 deep slot.	M	240	F332	0.3 h	1.75 m
50	Mill 0.750 ± 0.004 wide × 0.375 ± 0.003 deep flat.	M	240	F333	0.3 h	1.60 m

FIGURE 39.4 Typical route sheet for specifying the process plan.

processing route sheet in Figure 39.4. It contains a list of the assembly steps in the order in which they must be done. For assembly line production, process planning consists of allocating work elements to particular stations along the line, a procedure called ***line balancing*** (Section 37.3). In effect, the assembly line routes the work units to individual stations, and the line balancing solution determines what assembly steps must be performed at each station. As with process planning for parts, any tools and fixtures needed to accomplish a given assembly work element must be decided, and the workplace layout must be designed.

39.1.2 MAKE OR BUY DECISION

Inevitably, the question arises as to whether a given part should be purchased from an outside vendor or made internally. First of all, it should be recognized that virtually all manufacturers purchase their starting materials from suppliers. A machine shop buys bar stock from a metals distributor and castings from a foundry. A plastic molder obtains molding compound from a chemical company. A pressworking company purchases sheet metal from a rolling mill. Very few companies are vertically integrated all the way from raw materials to finished product.

Given that a company purchases at least some of its starting materials, it is reasonable to ask whether the company should purchase at least some of the parts that would otherwise be made in its own factory. The answer to the question is the ***make or buy decision***. The make versus buy question is probably appropriate to ask for every component used by the company.

Cost is the most important factor in deciding whether a part should be made in-house or purchased. If the vendor is significantly more proficient in the processes required to make the component, it is likely that the internal production cost will be greater than the purchase price even when a profit is included for the vendor. On the other hand, if purchasing the part results in idle equipment in the factory, then an apparent cost advantage for the vendor may be a disadvantage for the home factory. Consider the following example.

Example 39.1 Make or buy cost comparison

Suppose that the quoted price for a certain component from a vendor is $8.00 per unit for 1000 units. The same part made in the home factory would cost $9.00. The cost breakdown on the make alternative is as follows:

$$\begin{aligned} \text{Unit material cost} &= \$2.25 \text{ per unit} \\ \text{Direct labor} &= \$2.00 \text{ per unit} \\ \text{Labor overhead at } 150\% &= \$3.00 \text{ per unit} \\ \text{Equipment fixed cost} &= \$1.75 \text{ per unit} \\ \hline \text{Total} &= \$9.00 \text{ per unit} \end{aligned}$$

Should the component by bought or made in-house?

Solution: Although the vendor's quote seems to favor the buy decision, consider the possible effect on the factory if the quote is accepted. The equipment fixed cost is an allocated cost based on an investment that has already been made (Section 1.5.2). If it turns out that the equipment is rendered idle by the decision to buy the part, then one might argue that the fixed cost of $1.75 continues even if the equipment is not in use. Similarly, the overhead cost of $3.00 consists of factory floor space, indirect labor, and other costs that will also continue even if the part is bought. By this reasoning, the decision to purchase might cost the company as much as $\$8.00 + \$1.75 + \$3.00 = \$12.75$ per unit if it results in idle time in the factory on the machine that would have been used to make the part.

On the other hand, if the equipment can be used to produce other components for which the internal prices are less than the corresponding external quotes, then a buy decision makes good economic sense.

Make or buy decisions are rarely as clear as in Example 39.1. Some of the other factors that enter the decision are listed in Table 39.4. Although these factors appear to be subjective, they all have cost implications, either directly or indirectly. In recent years, major companies have placed strong emphasis on building close relationships with parts suppliers. This trend has been especially prevalent in the automobile industry, where long-term agreements have been reached between each carmaker and a limited number of vendors who are able to deliver high-quality components reliably on schedule.

39.1.3 COMPUTER-AIDED PROCESS PLANNING

During the last several decades, there has been considerable interest automating the process planning function by means of computer systems. Shop people knowledgeable in manufacturing processes are gradually retiring. An alternative approach to process planning is needed, and computer-aided process planning (CAPP) systems

TABLE • 39.4 Key factors in the make or buy decision.

Factor	Explanation and Effect on Make/Buy Decision
Process available in-house	If a given process is not available internally, then the obvious decision is to purchase. Vendors often develop proficiency in a limited set of processes that makes them cost competitive in external-internal comparisons. There are exceptions to this guideline, in which a company decides that, in its long-term strategy, it must develop a proficiency in a manufacturing process technology that it does not currently possess.
Production quantity	Number of units required. High volume tends to favor make decisions. Low quantities tend to favor buy decisions.
Product life	Long product life favors internal production.
Standard items	Standard catalog items, such as bolts, screws, nuts, and many other types of components are produced economically by suppliers specializing in those products. It is almost always better to purchase these standard items.
Supplier reliability	The reliable supplier gets the business.
Alternative source	In some cases, factories buy parts from vendors as an alternative source to their own production plants. This is an attempt to ensure uninterrupted supply of parts, or to smooth production in peak demand periods.

provide this alternative. CAPP systems are designed around either of two approaches: retrieval systems and generative systems.

Retrieval CAPP Systems Retrieval CAPP systems, also known as ***variant CAPP systems***, are based on group technology and parts classification and coding (Section 38.5). In these systems, a standard process plan is stored in computer files for each part code number. The standard plans are based on current part routings in use in the factory, or on an ideal plan that is prepared for each family. Retrieval CAPP systems operate as indicated in Figure 39.5. The user begins by identifying the GT code of the part for which the process plan is to be determined. A search is made of the part family file to determine if a standard route sheet exists for the given part code. If the file contains a process plan for the part, it is retrieved and displayed for the user. The standard process plan is examined to determine whether modifications are necessary. Although the new part has the same code number, minor differences in the processes might be required to make the part. The standard plan is edited accordingly. The capacity to alter an existing process plan is why retrieval CAPP systems are also called variant systems.

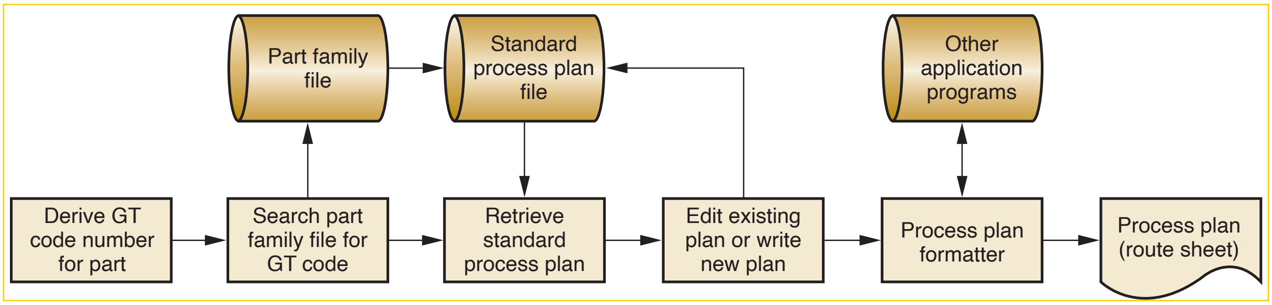


FIGURE 39.5 Operation of a retrieval computer-aided process planning system. (Source: [6].)

If the file does not contain a standard process plan for the given code number, the user may search the file for a similar code number for which a standard routing exists. By editing the existing process plan, or by starting from scratch, the user develops the process plan for the new part. This becomes the standard process plan for the new part code number.

The final step is the process plan formatter, which prints the route sheet in the proper format. The formatter may access other application programs; for example, to determine cutting conditions for machine tool operations, to calculate standard times for machining operations, or to compute cost estimates.

Generative CAPP Systems Generative CAPP systems are an alternative to retrieval systems. Rather than retrieving and editing existing plans from a database, a generative system creates the process plan using systematic procedures that might be applied by a human planner. In a fully generative CAPP system, the process sequence is planned without human assistance and without predefined standard plans.

Designing a generative CAPP system is a problem in the field of expert systems, a branch of artificial intelligence. ***Expert systems*** are computer programs capable of solving complex problems that normally require a human who has years of education and experience. Process planning fits that definition. Several ingredients are required in a fully generative CAPP system:

1. ***Knowledge base***. The technical knowledge of manufacturing and the logic used by successful process planners must be captured and coded into a computer program. An expert system applied to process planning requires the knowledge and logic of human process planners to be incorporated into a knowledge base. Generative CAPP systems then use the knowledge base to solve process planning problems; that is, to create route sheets.
2. ***Computer-compatible part description***. Generative process planning requires a computer-compatible description of the part. The description contains all the pertinent data needed to plan the process sequence. Two possible descriptions are (1) the geometric model of the part developed on a CAD system during product design or (2) a group technology code number of the part defining its features in significant detail.
3. ***Inference engine***. A generative CAPP system requires the capability to apply the planning logic and process knowledge contained in the knowledge base to a given part description. The CAPP system applies its knowledge base to solve a specific problem of planning the process for a new part. This problem-solving procedure is referred to as the inference engine in the terminology of expert systems. By using its knowledge base and inference engine, the CAPP system synthesizes a new process plan for each new part presented to it.

Benefits of CAPP Benefits of computer-automated process planning include the following: (1) process rationalization and standardization—automated process planning leads to more logical and consistent process plans than when traditional process planning is used; (2) increased productivity of process planners—the systematic approach and availability of standard process plans in the data files permit a greater number of process plans to be developed by the user; (3) reduced lead time to prepare process plans; (4) improved legibility compared to manually prepared route sheets; and (5) ability to interface CAPP programs with other application programs, such as cost estimating, work standards, and others.

39.2 Other Manufacturing Engineering Functions

Although process planning is the principal function of manufacturing engineering, two additional functions are (1) problem solving and continuous improvement, and (2) design for manufacturing and assembly. A related topic is concurrent engineering.

39.2.1 PROBLEM SOLVING AND CONTINUOUS IMPROVEMENT

Problems arise in manufacturing that require technical staff support beyond what is normally available in the line organization of the production departments. Providing this technical support is one of the responsibilities of manufacturing engineering. The problems are usually specific to the particular technologies of the processes performed in the operating department. In machining, the problems may relate to selection of cutting tools, fixtures that do not work properly, parts with out-of-tolerance conditions, or nonoptimal cutting conditions. In plastic molding, the problems may be excessive flash, parts sticking in the mold, or any of several defects that can occur in a molded part. These problems are technical, and engineering expertise is often required to solve them.

In some cases, the solution may require a design change; for example, changing the tolerance on a part dimension to eliminate a finish grinding operation while still achieving the functionality of the part. The manufacturing engineer is responsible for developing the proper solution to the problem and proposing the engineering change to the design department.

One of the areas that is ripe for improvement is setup time. The procedures involved in changing over from one production setup to the next (i.e., in batch production) are time consuming and costly. Manufacturing engineers are responsible for analyzing changeover procedures and finding ways to reduce the time required to perform them. Some of the approaches used in setup reduction are described in Section 39.4.

In addition to solving current technical problems ("fire fighting," as it might be called), the manufacturing engineering department is often responsible for continuous improvement projects. Continuous improvement means constantly searching for and implementing ways to reduce cost, improve quality, and increase productivity in manufacturing. It is accomplished one project at a time. Depending on the type of problem area, it may involve a project team whose membership includes not only manufacturing engineers, but also other personnel such as product designers, quality engineers, and production workers.

39.2.2 DESIGN FOR MANUFACTURING AND ASSEMBLY

Much of the process planning function discussed in Section 39.1 is preempted by decisions made in product design. Decisions on material, part geometry, tolerances, surface finish, grouping of parts into subassemblies, and assembly techniques limit the available manufacturing processes that can be used to make a given part. If the product engineer designs an aluminum sand casting with features that can be achieved only by machining (e.g., flat surfaces with good finishes, close tolerances, and threaded holes), then the process planner has no choice but to plan for sand casting followed by the required machining operations. If the product designer specifies a collection of sheet-metal stampings to be assembled by threaded fasteners, then the process planner must lay out the series of blanking, punching, and forming steps to fabricate the stampings and then assemble them. In both of these examples, a plastic molded part might be a superior design, both functionally and economically. It is important for the manufacturing engineer to act as an advisor to the design engineer in matters of manufacturability because manufacturability matters, not only to the production departments but to the design engineer. A product design that is functionally superior and at the same time can be produced at minimum cost holds the greatest promise of success in the marketplace. Successful careers in design engineering are built on successful products.

Terms often associated with this attempt to favorably influence the manufacturability of a product are ***design for manufacturing*** (DFM) and ***design for assembly*** (DFA). Of course, DFM and DFA are inextricably coupled, so refer to the pair as DFM/A. Design for manufacturing and assembly is an approach to product design that systematically includes considerations of manufacturability and assemblability in the design. DFM/A includes organizational changes and design principles and guidelines.

To implement DFM/A, a company must change its organizational structure, either formally or informally, to provide closer interaction and better communication between design and manufacturing personnel. This is often accomplished by forming project teams consisting of product designers, manufacturing engineers, and other specialties (e.g., quality engineers, material scientists) to design the product. In some companies, design engineers are required to spend some career time in manufacturing to learn about the problems encountered in making things. Another possibility is to assign manufacturing engineers to the product design department as full-time consultants.

DFM/A also includes principles and guidelines that indicate how to design a given product for maximum manufacturability. Many of these are universal design guidelines, such as those presented in Table 39.5. They are rules of thumb that can be applied to nearly any product design situation. In addition, several of our chapters on manufacturing processes include design guidelines that are specific to those processes.

The guidelines are sometimes in conflict. For example, one guideline for part design is to make the geometry as simple as possible. Yet, in design for assembly, it is often desirable to combine features of several assembled parts into a single component to reduce part count and assembly time. In these instances, design for manufacture conflicts with design for assembly, and a compromise must be found that achieves the best balance between opposing sides of the conflict.

Benefits typically cited for DFM/A include (1) shorter time to bring the product to market, (2) smoother transition into production, (3) fewer components in the final product, (4) easier assembly, (5) lower costs of production, (6) higher product quality, and (7) greater customer satisfaction [1], [4].

39.2.3 CONCURRENT ENGINEERING

Concurrent engineering refers to an approach to product design in which companies attempt to reduce the elapsed time required to bring a new product to market by integrating design engineering, manufacturing engineering, and other functions

TABLE • 39.5 General principles and guidelines in design for manufacturing and assembly.

Minimize number of components. Assembly costs are reduced. The final product is more reliable because there are fewer connections. Disassembly for maintenance and field service is easier. Reduced part count usually means automation is easier to implement. Work-in-process is reduced, and there are fewer inventory control problems. Fewer parts need to be purchased, which reduces ordering costs.

Use standard commercially available components. Design time and effort are reduced. Design of custom-engineered components is avoided. There are fewer part numbers. Inventory control is facilitated. Quantity discounts may be possible.

Use common parts across product lines. There is an opportunity to apply group technology (Section 38.5). Implementation of manufacturing cells may be possible. Quantity discounts may be possible.

Design for ease of part fabrication. Net shape and near net shape processes may be feasible. Part geometry is simplified, and unnecessary features are avoided. Unnecessary surface finish requirements should be avoided; otherwise, additional processing may be needed.

Design parts with tolerances that are within process capability. Tolerances tighter than the process capability (Section 40.2) should be avoided; otherwise, additional processing or sortation will be required. Bilateral tolerances should be specified.

Design the product to be foolproof during assembly. Assembly should be unambiguous. Components should be designed so they can be assembled only one way. Special geometric features must sometimes be added to components to achieve foolproof assembly.

Minimize use of flexible components. Flexible components include parts made of rubber, belts, gaskets, cables, etc. Flexible components are generally more difficult to handle and assemble.

Design for ease of assembly. Part features such as chamfers and tapers should be designed on mating parts. Design the assembly using base parts to which other components are added. The assembly should be designed so that components are added from one direction, usually vertically. Threaded fasteners (screws, bolts, nuts) should be avoided where possible, especially when automated assembly is used; instead, fast assembly techniques such as snap fits and adhesive bonding should be employed. The number of distinct fasteners should be minimized.

Use modular design. Each subassembly should consist of five to fifteen parts. Maintenance and repair are facilitated. Automated and manual assembly are implemented more readily. Inventory requirements are reduced. Final assembly time is minimized.

Shape parts and products for ease of packaging. The product should be designed so that standard packaging cartons can be used, which are compatible with automated packaging equipment. Shipment to customer is facilitated.

Eliminate or reduce adjustment required. Adjustments are time-consuming in assembly. Designing adjustments into the product means more opportunities for out-of-adjustment conditions to arise.

Compiled from [1], [4], [9].

in the company. One might argue that concurrent engineering is a logical extension of DFM/A because it includes collaboration of more than just design and manufacturing, and it attempts to reduce the product launch cycle. The traditional approach to launch a new product tends to separate the two functions, as illustrated in Figure 39.6(a). The product design engineer develops the new design, sometimes with little regard for the manufacturing capabilities possessed by the company. There is no interaction between design engineers and manufacturing engineers who might provide advice on these capabilities and how the product design might be altered to accommodate them. It is as if a wall exists between the two functions; when design engineering completes the design, the drawings and specifications are tossed over the wall so that process planning can commence.

In a company that practices concurrent engineering (also known as ***simultaneous engineering***), manufacturing planning begins while the product design is being developed, as pictured in Figure 39.6(b). Manufacturing engineering becomes

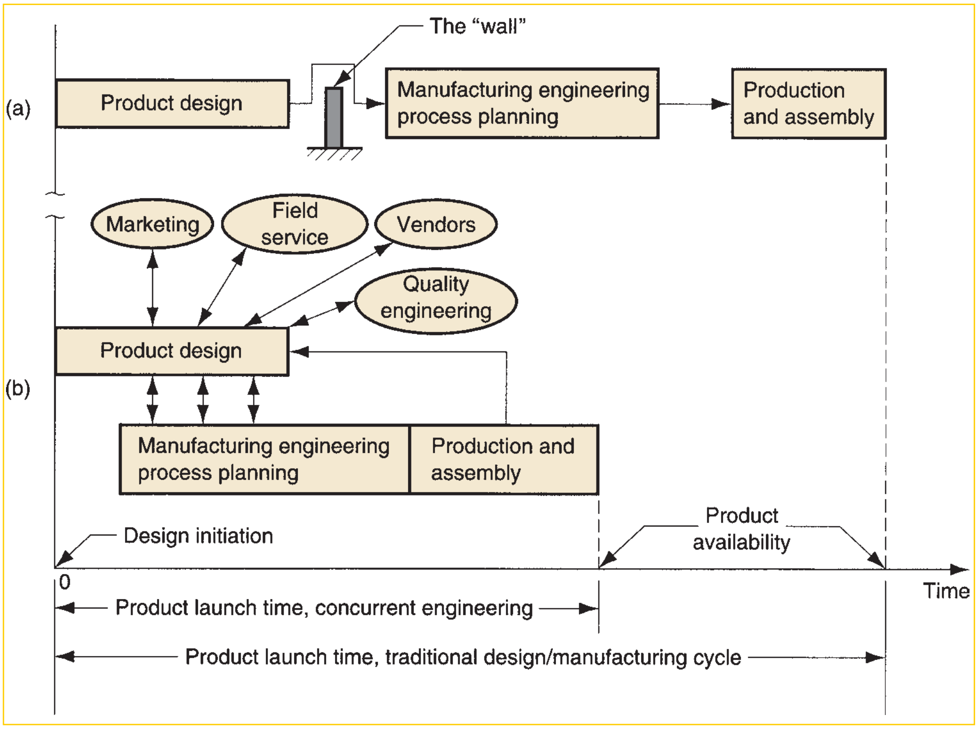


FIGURE 39.6 Comparison of: (a) traditional product development cycle, and (b) product development using concurrent engineering.

involved early in the product development cycle. In addition, other functions are also involved, such as field service, quality engineering, the manufacturing departments, vendors supplying critical components, and in some cases customers who will use the product. All of these functions can contribute to a product design that not only performs well functionally, but is also manufacturable, assemblable, inspectable, testable, serviceable, maintainable, free of defects, and safe. All viewpoints have been combined to design a product of high quality that will deliver customer satisfaction. And through early involvement, rather than a procedure of reviewing the final design and suggesting changes after it is too late to conveniently make them, the total product development cycle is substantially reduced.

Concurrent engineering embraces other objectives beyond DFM/A such as design for quality, design for life cycle, and design for cost. With the importance of quality in international competition, and the demonstrated success of those companies that have been able to produce products of high quality, one must conclude that ***design for quality*** is very important. Chapter 40 deals with quality control and includes a discussion of several quality approaches related to product design.

Design for life cycle refers to the product after it has been manufactured. In many cases, a product can involve a significant cost to the customer beyond the purchase price. These costs include installation, maintenance and repair, spare parts, future upgrading of the product, safety during operation, and disposition of the product at the end of its useful life. The price paid for the product may be a small portion of its total cost when life cycle costs are included. Some customers (e.g., federal government) consider life cycle costs in their purchasing decisions. The manufacturer must often include service contracts that limit customer vulnerability to excessive maintenance and service costs. In these cases, accurate estimates of these life cycle costs must be included in the total product cost.

A product's cost is a major factor in determining its commercial success. Cost affects the price charged for the product and the profit made on it. ***Design for product cost*** refers to the efforts of a company to identify the impact of design decisions on overall product costs and to control those costs through optimal design. Many of the DFM/A guidelines are directed at reducing product cost.

39.3 Production Planning and Control

Production planning and control are the manufacturing support systems concerned with logistics problems in the production function. ***Production planning*** is concerned with planning what products are to be produced, what quantities, and when. It also considers the resources required to accomplish the plan. ***Production control*** determines whether the resources to execute the plan have been provided and, if not, takes the necessary action to correct the deficiencies.

The problems in production planning and control are different for different types of manufacturing. One of the important factors is the relationship between product variety and production quantity (Section 1.1.2). At one extreme is ***job shop production***, in which different product types are each produced in low quantities. The products are often complex, consisting of many components, each of which must be processed through multiple operations. Solving the logistics problems in such a plant requires detailed planning—scheduling and coordinating the large numbers of different components and processing steps for the different products.

At the other extreme is ***mass production***, in which a single product (with perhaps some model variations) is produced in very large quantities (up to millions of units). The logistics problems in mass production are simple if the product and process are simple. In more complex situations, such as the production of automobiles and major appliances, the product is an assembly consisting of many components, and the facility is organized as a production line (Section 38.2). The logistics problem in operating such a plant is to get each component to the right workstation at the right time so that it can be assembled to the product as it passes through that station. Failure to solve this problem can result in stoppage of the entire production line for lack of a critical part.

To distinguish between these two extremes in terms of the issues in production planning and control, the planning function is emphasized in a job shop, whereas the control function is emphasized in mass production of assembled products. There are many variations between these extremes, with accompanying differences in the way production planning and control are implemented.

Figure 39.7 presents a block diagram depicting the activities of a modern production planning and control system and their interrelationships. The activities can be divided into three phases: (1) aggregate production planning, (2) detailed planning of material and capacity requirements, and (3) purchasing and shop floor control. Our discussion of production planning and control in this section is organized around this framework.

39.3.1 AGGREGATE PLANNING AND THE MASTER PRODUCTION SCHEDULE

Any manufacturing firm must have a business plan, and the plan must include what products will be produced, how many, and when. The manufacturing plan should take into account current orders and sales forecasts, inventory levels, and plant capacity.

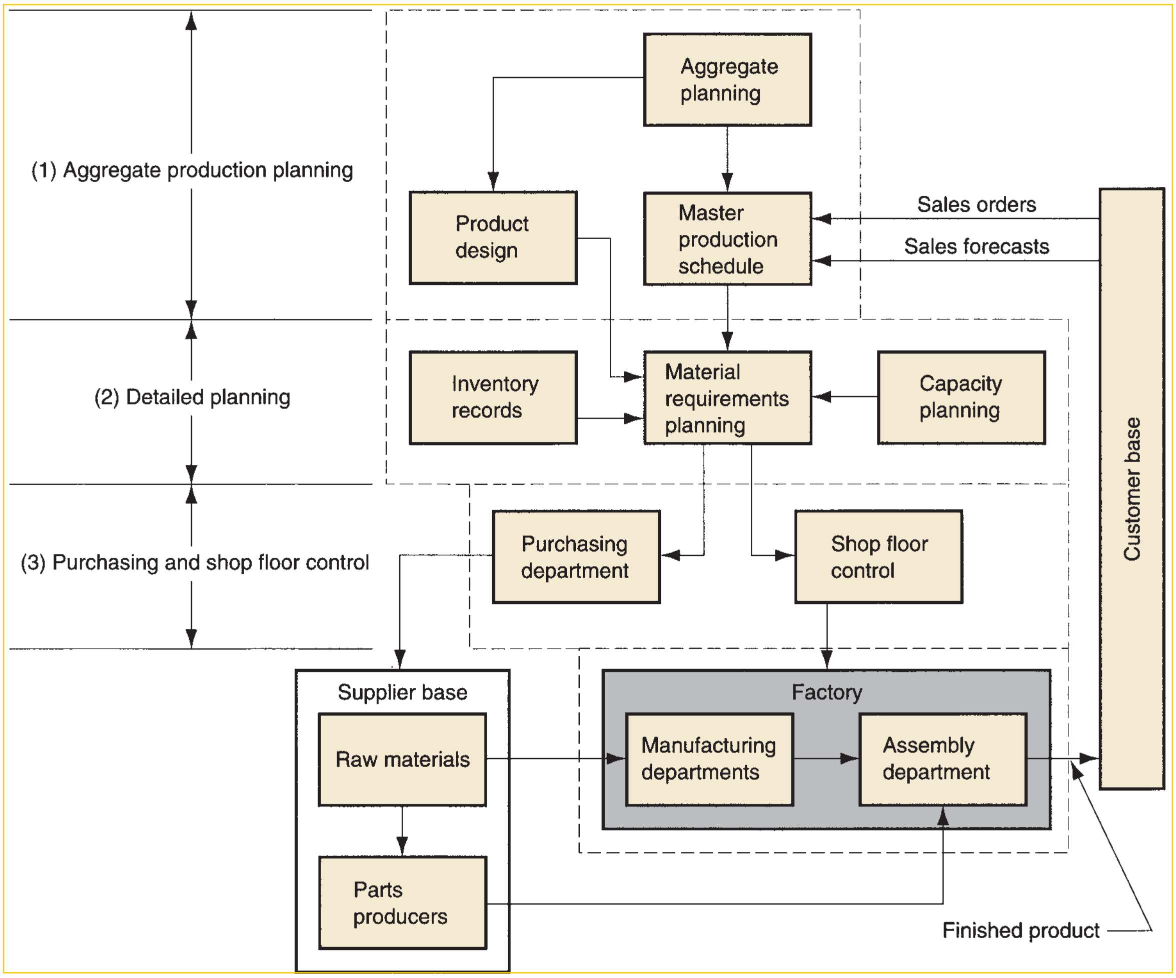


FIGURE 39.7 Activities in a production planning and control system.

The ***aggregate production plan*** indicates production output levels for major product lines rather than specific products. It must be coordinated with the sales and marketing plan of the company. Aggregate planning is therefore a high-level corporate planning activity, although details of the planning process are delegated to staff. The aggregate plan must reconcile the marketing plans for current products and new products under development against the capacity resources available to make those products.

The planned output levels of the major product lines in the aggregate schedule must be converted into a specific schedule of individual products. This is called the ***master production schedule*** (or ***master schedule***, for short), and it lists the products to be manufactured, when they should be completed, and in what quantities.

Three categories of items are listed in the master schedule: (1) firm customer orders, (2) forecasted demand, and (3) spare parts. Customer orders for specific products usually obligate the company to a delivery date that has been promised to a customer by the sales department. The second category consists of production output levels based on forecasted demand, in which statistical forecasting techniques are applied to previous demand patterns, estimates by the sales staff, and other sources. The third category is demand for individual component parts—repair parts to be stocked in the firm's service department. Some companies exclude this third category from the master schedule because it does not represent end products.

The master production schedule must consider the lead times required to order raw materials and components, fabricate parts in the factory, and then assemble and test the final products. Depending on type of product, these lead times can run from several months to more than a year. It is usually considered to be fixed in the near term, meaning that changes are not allowed within about a six-week horizon. However, adjustments in the schedule beyond six weeks are possible to cope with shifts in demand or new product opportunities. It should therefore be noted that the aggregate production plan is not the only input to the master schedule. Other drivers that may cause it to deviate from the aggregate plan include new customer orders and changes in sales over the near term.

39.3.2 MATERIAL REQUIREMENTS PLANNING

Two techniques for planning and controlling production are used in industry, depending on product variety and production quantities. This section covers procedures for job shop and midrange production of assembled products. Section 39.4 examines procedures appropriate for high production.

Material requirements planning (MRP) is a computational procedure used to convert the master production schedule for end products into a detailed schedule for raw materials and components used in the end products. The detailed schedule indicates the quantities of each item, when it must be ordered, and when it must be delivered to implement the master schedule. ***Capacity requirements planning*** (Section 39.3.3) coordinates labor and equipment resources with material requirements.

MRP is most appropriate for job shop and batch production of products that have multiple components, each of which must be purchased and/or fabricated. It is a technique that determines the quantities of items used in end products. Once the number of end products has been decided and included in the master production schedule, then the numbers of each component can be directly computed. For example, each car listed in the master schedule needs four tires (five, if the spare is included). Thus, if the production schedule calls for 1000 cars to be produced in a certain week, the plant needs to order 4000 tires for those cars. Demand for the end products may be forecasted, but materials and parts used in the end products are not.

MRP is relatively straightforward in concept. Its application is complicated by the sheer magnitude of the data that must be processed. The master schedule specifies the production of final products in terms of month-by-month deliveries. Each product may contain hundreds of components. These components are produced from raw materials, some of which are common among the components (e.g., sheet steel for stampings). Some of the components themselves may be common to several different products (called ***common use items*** in MRP). For each product, the components are assembled into simple subassemblies, which are added to form other subassemblies, and so on, until the final products are completed. Each step in the sequence consumes time. All of these factors must be accounted for in material requirements planning. Although each calculation is simple, the large number of calculations and massive amounts of data require that MRP be implemented by computer.

The lead time for a job is the time that must be allowed to complete the job from start to finish. There are two kinds of lead times in MRP: ordering lead times and manufacturing lead times. ***Ordering lead time*** is the time required from initiation of the purchase requisition to receipt of the item from the vendor. If the item is a raw material stocked by the vendor, the ordering lead time should be relatively short, perhaps a few days. If the item is fabricated, the lead time may be substantial, perhaps several months. ***Manufacturing lead time*** is the time required to produce the item in the company's own plant, from order release to completion. It includes lead times for both making the parts and assembling the end products.

Inputs to the MRP System For the MRP processor to function properly, it must receive inputs from several files: (1) master production schedule, (2) bill of materials file, (3) inventory records, and (4) capacity requirements planning. Figure 39.7 shows the data flow into the MRP processor and the recipients of its output reports.

The master production schedule was discussed in Section 39.3.1, and capacity requirements planning is covered in Section 39.3.3. The ***bill-of-materials file*** lists the component parts and subassemblies that make up each product. It is used to compute the requirements for raw materials and components used in the end products listed in the master schedule. The ***inventory record file*** identifies each item (by part number) and provides a time-phased record of its inventory status. This means that not only is the current quantity of the item listed, but also any future changes in inventory status that will occur and when they will occur.

How MRP Works Based on the inputs from the master schedule, bill-of-materials file, and inventory record file, the MRP processor computes how many of each component and raw material will be needed in future time periods by "exploding" the end product schedule to include these items. How many tires and other components must be ordered to produce the numbers of cars listed in each time period (e.g., each week) of the master production schedule?

The MRP computations must deal with several complicating factors. First, component and subassembly quantities must be adjusted for any inventories on hand or on order. Second, quantities of common use items must be combined during parts explosion to obtain a total requirement for each component and raw material in the schedule. Third, the time-phased delivery of end products must be converted into time-phased requirements for components and materials by factoring in the appropriate lead times. For every unit of final product listed in the master schedule, the required number of components of each type must be ordered or fabricated, taking into account its ordering and/or manufacturing lead times. For each component, the raw material must be ordered, accounting for its ordering lead time. And assembly lead times must be considered in the scheduling of subassemblies and final products.

Output Reports MRP generates various output reports that can be used in planning and managing plant operations. The reports include (1) order releases, which authorize the orders planned by the MRP system; (2) planned order releases in future periods; (3) rescheduling notices, indicating changes in due dates for open orders; (4) cancellation notices, which indicate that certain open orders have been canceled due to changes in the master schedule; (5) inventory status reports; (6) performance reports; (7) exception reports, showing deviations from schedule, overdue orders, scrap, and so forth; and (8) inventory forecasts, which project inventory levels in future periods.

39.3.3 CAPACITY REQUIREMENTS PLANNING

Capacity requirements planning is concerned with determining the labor and equipment requirements needed to achieve the master production schedule. It is also concerned with identifying the firm's long-term future capacity needs. Finally and importantly, capacity planning serves to identify production resource limitations so that a realistic master production schedule can be planned.

A realistic master schedule must take into account the manufacturing capabilities of the plant that is to make the products. The firm must be aware of its production capacity and must plan for changes in capacity to meet changing production requirements specified in the master schedule. The relationship between capacity planning and other functions in production planning and control is shown in Figure 39.7. The master schedule is reduced to material and component requirements using MRP. These requirements provide estimates of the required labor hours and other resources needed to produce the components. The required resources are then compared to plant capacity over the planning horizon. If the master schedule is not compatible with plant capacity, adjustments must be made either in the schedule or in plant capacity.

Plant capacity can be adjusted in the short term and in the long term. Short-term capacity adjustments include (1) ***employment levels***—increasing or decreasing the number of workers in the plant; (2) ***shift hours***—increasing or decreasing the number of labor hours per shift through the use of overtime or reduced hours; (3) ***number of work shifts***—increasing or decreasing the number of shifts worked per production period by authorizing evening and night shifts and/or weekend shifts; (4) ***inventory stockpiling***—this tactic is used to maintain steady employment levels during slow demand periods; (5) ***order backlogs***—delaying deliveries to the customer during busy periods when production resources are insufficient to keep up with demand; and (6) ***subcontracting***—contracting work to outside shops during busy periods or taking in extra work during slack periods.

Long-term capacity adjustments include possible changes in production capacity that generally require long lead times, including the following types of decisions: (1) ***new equipment***—investments in additional machines, more productive machines, or new types of machines to match future changes in product design; (2) ***new plants***—construction of new plants or purchase of existing plants from other companies; and (3) ***plant closings***—closing plants not needed in the future.

39.3.4 SHOP FLOOR CONTROL

The third phase in production planning and control in Figure 39.7 is concerned with releasing production orders, monitoring and controlling progress of the orders, and acquiring up-to-date information on order status. The purchasing department is responsible for these functions among suppliers. The term ***shop floor control*** is used to describe these functions when accomplished in the company's own factories. In basic terms, shop floor control is concerned with managing work-in-progress in the factory. It is most relevant in job shop and batch production, where there are a variety of different orders in the shop that must be scheduled and tracked according to their relative priorities.

A typical shop floor control system consists of three modules: (1) order release, (2) order scheduling, and (3) order progress. The three modules and how they relate to other functions in the factory are depicted in Figure 39.8. The computer software

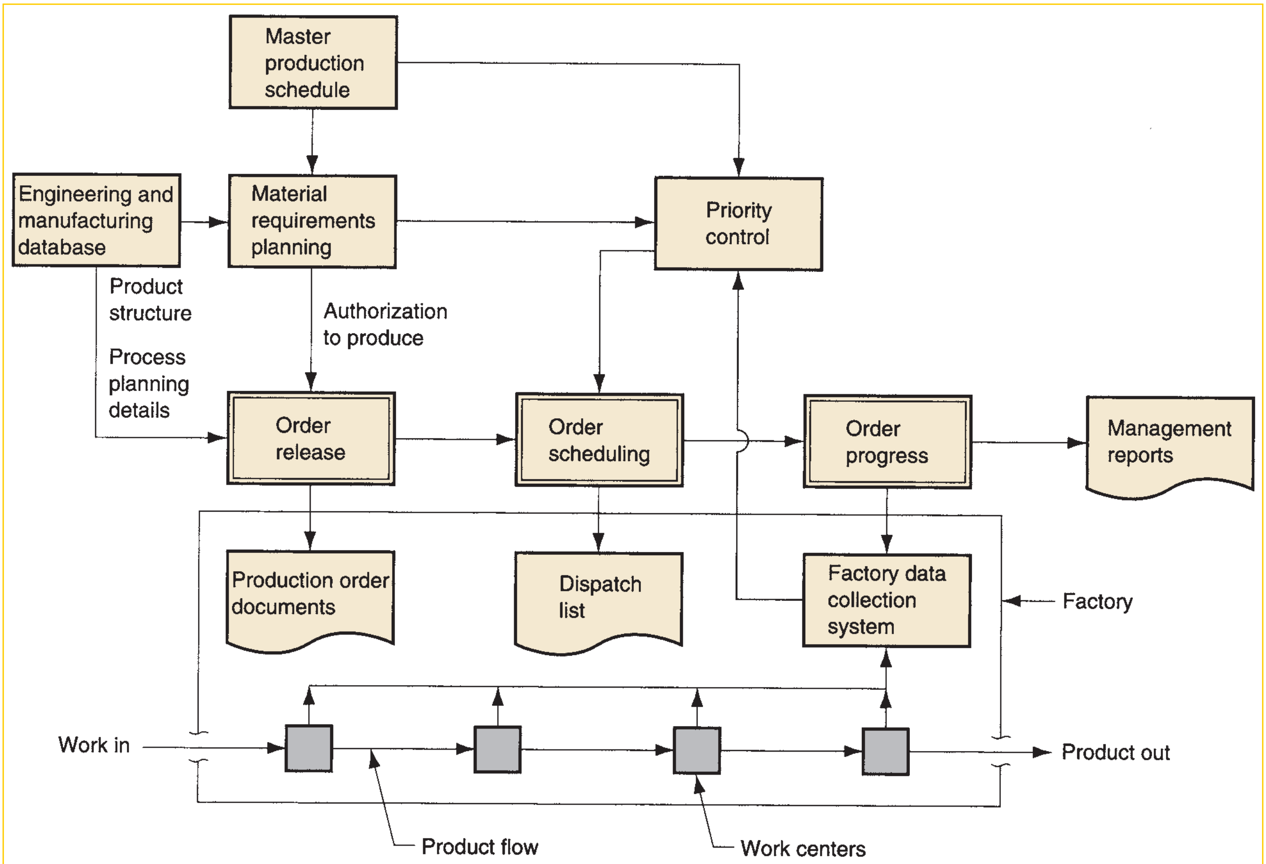


FIGURE 39.8 Three modules in a shop floor control system, and interconnections with other production planning and control functions.

that supports shop floor control is referred to as a ***manufacturing execution system***, which includes the capability to interact in real time with users seeking status information in any of the three phases.

Order Release Order release in shop floor control generates the documents needed to process a production order through the factory. The documents are sometimes called the shop packet; it typically consists of (1) route sheet, (2) material requisitions to draw the starting materials from stores, (3) job cards to report direct labor time used on the order, (4) move tickets to authorize transport of parts to subsequent work centers in the routing, and (5) parts list—required for assembly jobs. In a traditional factory, these are paper documents that move with the production order and are used to track its progress through the shop. In modern factories, automated methods such as bar code technology and shop floor computers are used to monitor order status, making some or all of the paper documents unnecessary.

Order release is driven by two principal inputs, as indicated in Figure 39.8: (1) material requirements planning, which provides the authorization to produce; and (2) engineering and manufacturing database that indicates product structure and process planning details required to generate the documents that accompany the order through the shop.

Order Scheduling Order scheduling assigns the production orders to work centers in the factory. It serves as the dispatching function in production control. In order scheduling, a dispatch list is prepared indicating which orders should be accomplished at each work center. It also provides relative priorities for the different jobs (e.g., by showing due dates for each job). The dispatch list helps the department foreman assign work and allocate resources to achieve the master schedule.

Order scheduling addresses two problems in production planning and control: machine loading and job sequencing. To schedule production orders through the factory, they must first be assigned to work centers. Assigning orders to work centers is called ***machine loading***. Loading all of the work centers in the plant is called ***shop loading***. Since the number of production orders is likely to exceed the number of work centers, each work center will have a queue of orders waiting to be processed.

Job sequencing deals with the problem of deciding the sequence in which to process jobs through a given machine. The processing sequence is decided by means of priorities among the jobs in the queue. The relative priorities are determined by a function called ***priority control***. Some of the rules used to establish priorities for production orders in a plant include (1) ***first-come-first-serve***—orders are processed in the sequence in which they arrive at the work center; (2) ***earliest due date***—orders with earlier due dates are given higher priorities; (3) ***shortest processing time***—orders with shorter processing times are given higher priorities; and (4) ***least slack time***—orders with the least slack in their schedule are given higher priorities (slack time is defined as the difference between the time remaining until due date and the process time remaining). When a job is completed at one work center, it is moved to the next machine in its routing. It becomes part of the machine loading for that work center, and priority control is again used to determine the sequence among jobs to be processed at that machine.

Order Progress Order progress in shop floor control monitors the status of the orders, work-in-process, and other parameters in the plant that indicate progress and performance. The objective is to provide information to manage production based on data collected from the factory.

Various techniques are available to collect data from factory operations. The techniques range from clerical procedures requiring workers to submit paper forms that are later compiled, to highly automated systems requiring minimal human participation. The term ***factory data collection system*** is sometimes used for these techniques. More complete coverage of this topic is presented in [6].

Information presented to management is often summarized in the form of reports. These include (1) ***work order status reports***, which indicate status of production orders, including the work center where each order is located, processing hours remaining before each order will be completed, whether the job is on time, and priority level; (2) ***progress reports*** that report shop performance during a certain time period such as a week or month—how many orders were completed during the period, how many orders should have been completed during the period but were not completed, and so forth; and (3) ***exception reports*** that indicate deviations from the production schedule, such as overdue jobs. These reports are helpful to management in deciding resource allocation issues, authorizing overtime, and identifying problem areas that adversely affect achievement of the master production schedule.

39.3.5 ENTERPRISE RESOURCE PLANNING

The first MRP systems released in the 1970s were limited to the planning of purchase orders and production work orders derived from the master production schedule. They did not include capacity planning and feedback of data from the factory. These deficiencies became apparent by the 1980s, and additional capabilities were added to the basic MRP packages, including capacity requirements planning and shop floor control. The term manufacturing resource planning was used to distinguish the enhanced systems from the initial material requirements planning, and the abbreviation MRP II was adopted. ***Manufacturing resource planning*** can be defined "as a computer-based system for planning, scheduling, and controlling the materials, resources, and supporting activities needed to meet the master production schedule."[1] MRP II integrates material requirements planning, capacity requirements planning, and shop floor control into one system.

Further improvements were made to MRP II during the 1990s by adding features that went beyond just the manufacturing activities of a firm by including all of the operations and functions of the entire enterprise. Also, the new packages, called enterprise resource planning, were applicable to service organizations as well as firms in the production industries. ***Enterprise resource planning*** (ERP) is a computer-based "system that organizes and integrates all of the data and business functions of an organization through a single, central database."[2] For a manufacturing firm, ERP accomplishes the functions of MRP II. Additional functions in most ERP systems include sales and service, marketing, logistics, distribution, inventory control, accounting and finance, human resources, and customer relationship management. ERP systems consist of multiple software modules, each devoted to its particular function. A user company may elect to include only certain modules of particular interest in its ERP system. For example, a service organization may have no need for modules related to manufacturing.

Today's ERP systems are based on open architecture standards, which means that a user company can purchase certain modules from one company and other modules from a different company and integrate them into their own ERP system. This open architecture feature gave rise to the term ERP II during the early 2000s. Also, enterprise resource planning can be implemented as a cloud-based system, in which the user company's data reside in large data centers external to the company and accessed through the Internet [19]. This permits them to avoid the expenses of investing in and maintaining their own central database.

ERP II is installed as a client-server system that serves the entire company rather than individual plants as MRP and MRP II often do. Employees access and work with the system using their personal computers. Because ERP has only one database, it avoids problems of data redundancy and conflicting information that arise when an organization maintains multiple databases. It also minimizes time delays and compatibility issues associated with different databases and software modules. With ERP, all employees have access to the same data depending on their individual responsibilities and "need-to-know" authorizations.

39.4 Just-In-Time Delivery Systems

Just-in-ime (JIT) is an approach to production control that was developed by Toyota Motors in Japan to minimize inventories. Work-in-process and other inventories are

[1]M. P. Groover. ***Automation, Production Systems, and Computer-Integrated Manufacturing*** [6], p. 762.
[2]M. P. Groover. ***Automation, Production Systems, and Computer-Integrated Manufacturing*** [6], p. 763.

viewed as waste that should be eliminated. Inventory ties up investment funds and takes up space. To reduce this form of waste, the JIT approach includes a number of principles and procedures aimed at reducing inventories, either directly or indirectly. JIT is an important component of lean production, a principal goal of which is to reduce all forms of waste in production operations. Lean production is described in Section 39.6.

Just-in-time procedures have proven most effective in high-volume repetitive manufacturing, such as the automobile industry [10]. The potential for in-process inventory accumulation in this type of manufacturing is significant because both the quantities of products and the number of components per product are large. A just-in-time system produces exactly the right number of each component required to satisfy the next operation in the manufacturing sequence just when that component is needed; that is, "just in time." The ideal batch size is one part. As a practical matter, more than one part are produced at a time, but the batch size is kept small. Under JIT, producing too many units is to be avoided as much as producing too few units. JIT has been adopted by many U.S. companies in both the automotive and other manufacturing industries.

Although the principal theme in JIT is inventory reduction, this cannot simply be mandated. Several requisites must be pursued to make it possible: (1) stable production schedules; (2) small batch sizes and short setup times; (3) on-time delivery; (4) defect-free components and materials; (5) reliable production equipment; (6) pull system of production control; (7) a work force that is capable, committed, and cooperative; and (8) a dependable supplier base.

Stable Schedule For JIT to be successful, work must flow smoothly with minimal perturbations from normal operations. Perturbations require changes in operating procedures—increases and decreases in production rate, unscheduled setups, variations from the regular work routine, and other exceptions. When perturbations occur in downstream operations (i.e., final assembly), they tend to be amplified in upstream operations (i.e., parts feeding). A master production schedule that remains relatively constant over time is one way of achieving smooth work flow and minimizing disturbances and changes in production. The term ***production leveling*** is sometimes used for this practice of maintaining a constant production output.

Small Batch Sizes and Setup Reduction Two requirements for minimizing inventories are small batch sizes and short setup times. Large batch sizes mean longer production runs and higher inventory levels, both in-process and final inventories. Long setup times are costly in both labor and lost production time, but they necessitate long production runs to economically justify the setups. Thus, large batch sizes and long setup times are closely correlated, and they result in higher operating costs in the factory. Instead of tolerating them, efforts are focused on reducing setup time, thereby permitting smaller batch sizes and lower work-in-process levels.

Some of the approaches used to reduce setup time include (1) performing as much of the setup as possible while the previous job is still running; (2) using quick-acting clamping devices instead of bolts and nuts; (3) eliminating or minimizing adjustments in the setup; and (4) using group technology and cellular manufacturing so that similar part styles are produced on the same equipment. These approaches have sometimes resulted in dramatic decreases in setup times. Reductions of 95% and greater have been reported in the literature.[3]

[3]Suzaki, K. ***The New Manufacturing Challenge: Techniques for Continuous Improvement***, Free Press, New York, 1987.

On-Time Delivery, Zero Defects, and Reliable Equipment Success of just-in-time production requires near perfection in on-time delivery, parts quality, and equipment reliability. The small lot sizes and parts buffers used in JIT require parts to be delivered before stock-outs occur at downstream stations. Otherwise, production must be suspended at these stations for lack of parts. If the delivered parts are defective, they cannot be used in assembly. This tends to encourage zero defects in parts fabrication. Workers inspect their own output to make sure it is right before it proceeds to the next operation.

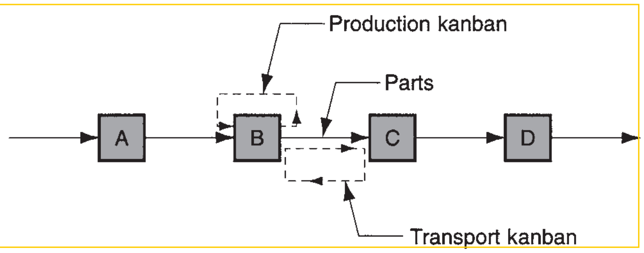
Low work-in-process also requires reliable production equipment. Machines that break down cannot be tolerated in a JIT production system. This emphasizes the need for reliable equipment designs and preventive maintenance. Toyota's Total Productive Maintenance program is discussed in Section 39.6.1.

Pull System of Production Control JIT requires a ***pull system*** of production control, in which the order to produce parts at a given workstation comes from the downstream station that uses those parts. As the supply of parts becomes exhausted at a given station, it "places an order" at the upstream workstation to replenish the supply. This order provides the authorization for the upstream station to produce the needed parts. This procedure, repeated at each workstation throughout the plant, has the effect of pulling parts through the production system. By contrast, a ***push system*** of production operates by supplying parts to each station in the plant, in effect driving the work from upstream stations to downstream stations. MRP is a push system. The risk in a push system is to overload the factory by scheduling more work than it can handle. This results in large queues of parts in front of machines that cannot keep up with arriving work. A poorly implemented MRP system, one that does not include capacity planning, manifests this risk.

One famous pull system is the ***kanban*** system used by Toyota Motors. Kanban (pronounced kahn-bahn) is a Japanese word meaning ***card***. The kanban system of production control is based on the use of cards to authorize production and work flow in the plant. There are two types of kanbans: (1) production kanbans, and (2) transport kanbans. A ***production kanban*** authorizes production of a batch of parts. The parts are placed in containers, so the batch must consist of just enough parts to fill the container. Production of additional parts is not permitted. The ***transport kanban*** authorizes movement of the container of parts to the next station in the sequence.

Refer to Figure 39.9 as the operation of a kanban system is explained. The figure shows four stations, but B and C are the stations to focus on here. Station B is the supplier in this pair, and station C is the consumer. Station C supplies downstream station D. B is supplied by upstream station A. When station C starts work on a full

FIGURE 39.9 Operation of a kanban system between workstations.



container, a worker removes the transport kanban from that container and takes it back to B. The worker finds a full container of parts at B that have just been produced, removes the production kanban from that container, and places it on a rack at B. The worker then places the transport kanban in the full container, which authorizes its movement to station C. The production kanban on the rack at station B authorizes production of a new batch of parts. Station B produces more than one part style, perhaps for several other downstream stations in addition to C. The scheduling of work is determined by the order in which the production kanbans are placed on the rack.

The kanban pull system between stations A and B and between stations C and D operates the same as it does between stations B and C, described here. This system of production control avoids unnecessary paperwork. The cards are used over and over rather than generating new production and transport orders every cycle. An apparent disadvantage is the considerable labor involvement in material handling (moving the cards and containers between stations); however, it is claimed that this promotes teamwork and cooperation among workers.

Workforce and Supplier Base Another requirement of a JIT production system is workers who are cooperative, committed, and capable of performing multiple tasks. The workers must be flexible to produce a variety of part styles at their respective stations, to inspect the quality of their work, and to deal with minor technical problems with the production equipment so that major breakdowns do not occur.

Just-in-time extends to the suppliers of the company, who are held to the same standards of on-time delivery, zero defects, and other JIT requisites as the company itself. Some of the vendor policies used by companies to implement JIT include (1) reducing the total number of suppliers, (2) selecting suppliers with proven records for meeting quality and delivery standards, (3) establishing long-term partnerships with suppliers, and (4) selecting suppliers that are located near the company's manufacturing plant.

39.5 Lean Production

Just-in-time delivery systems are an important aspect of lean production, which is focused on reducing waste in production operations, and just-in-time reduces the waste of too much inventory. ***Lean production*** can be defined as "an adaptation of mass production in which workers and work cells are made more flexible and efficient by adopting methods that reduce waste in all forms."[4] Its origins are traced to the Toyota Production System at Toyota Motors in Japan starting in the 1950s (Historical Note 39.1). Although its initial applications were in the automotive industry, the objective of minimizing waste is important in all industries.

Historical Note 39.1 *Toyota Production System and lean production (7)*

Taiichi Ohno (1912–1990) is the man credited with developing the Toyota Production System in Japan following World War II. He was an engineer and vice president at Toyota Motors when the company was struggling to overcome the war's devastating impact on the Japanese automobile industry. The auto

[4] M. P. Groover. ***Automation, Production Systems, and Computer Integrated Manufacturing*** [6], p. 834.

market in Japan in the 1950s was much smaller than in the United States, so American mass production techniques could not be used. Ohno recognized that Toyota's plants had to operate on a much smaller scale and be more flexible. The situation, as well as his own aversion to waste, motivated him to develop some of the procedures of the Toyota Production System to reduce waste and increase efficiency and product quality. He and his colleagues experimented with and perfected the procedures over several decades, including just-in-time delivery, the kanban system, setup time reduction, and control of product quality.

Ohno did not use the term "lean production" to refer to his system. In fact, he died before the term came into prominence, so he may never have heard of it. In his book, he called it the "Toyota Production System" [12]. The term ***lean production*** was coined by researchers at the Massachusetts Institute of Technology to refer to the techniques and procedures used at Toyota that explained its success in producing so efficiently cars with such high quality. The research was known as the International Motor Vehicle Program and documented in the book *The Machine that Changed the World* (published in 1991). The term lean production appeared in the book's subtitle.

In effect, lean production means accomplishing more work with fewer resources by eliminating waste in manufacturing operations. Activities in manufacturing can be classified into three categories: (1) actual work activities that add value such as processing steps that alter the product in a positive way, (2) auxiliary work activities that support the actual work such as loading and unloading a production machine, and (3) wasteful activities that do not add value and do not support the value-adding activities. If these wasteful activities were omitted, the product would not be adversely affected.

Seven forms of waste in manufacturing were identified in the Toyota Production System: (1) production of defective parts, (2) production of more parts than needed, (3) excessive inventories, (4) unnecessary processing steps, (5) unnecessary movement of workers, (6) unnecessary handling and transport of materials, and (7) workers waiting [12]. The various systems and procedures developed at Toyota were designed to reduce or eliminate these seven forms of waste.

The principal components of the Toyota Production System were just-in-time delivery, autonomation (which has been defined as "automation with a human touch"),[5] and worker involvement. Just-in-time delivery is described in Section 39.4. The other two components are discussed in the following sections. More complete treatments of lean production and/or the Toyota Production System are given in several of our references [3], [6], [7], [10], and [12].

39.5.1 AUTONOMATION

Autonomation refers to the design of production machines that operate autonomously so long as they function the way they are supposed to. If and when they do not operate the way they should, they are designed to stop. Circumstances that would trigger a machine to stop include producing defective parts and producing more than the number of parts needed. Other aspects of autonomation include error prevention and high reliability.

Stop the Process The underlying principle is that when something goes wrong, the process should be stopped so that corrective action can be taken. This applies to both automatic machines and manually operated processes. Production machines in

[5]This is the way Taiichi Ohno described autonomation.

the Toyota Production System are designed with sensors and automatic stop devices that are activated when a defective unit is produced or when the required number of units have been made. Accordingly, when a machine stops, it draws attention, either to make adjustments to the process to avoid future defects, or to change over the process for the next batch of parts. The alternative to autonomation is that the machine would continue to make bad parts or it would make too many parts.

The notion of "stop the process" can also be applied to manual production, such as the final assembly line in an automobile plant. Workers on the line are empowered to stop the line when they discover a problem such as a quality defect. They do this by means of pull cords that are located along the line. Downtime on an assembly line draws attention and is costly to the plant. Significant efforts are made to fix the problem that caused the line to be stopped. Defective components must be avoided by pursuing the goal of zero defects.

Error Prevention A second objective of autonomation is preventing mistakes. Mistakes in manufacturing include using the wrong tool, starting a process with the wrong raw material, omitting a processing step on a part, neglecting to add a component in an assembly operation, incorrectly locating a part in a fixture, and incorrectly locating the fixture on the machine. To avoid these and other kinds of mistakes, devices are designed to detect abnormal conditions in a given operation. Examples include instruments to detect overweight parts, counting devices to determine whether the correct number of spot welds has been made, and sensors to determine whether a part has been properly located in a fixture. When the device encounters a mistake, it is designed to respond by stopping the process or providing an audible or visible alert that an error has occurred.

Total Productive Maintenance Just-in-time delivery requires production equipment that is highly reliable. When a production machine breaks down, it disrupts the delivery of parts to the downstream workstation, forcing that machine to be idle. JIT does not provide for inventory buffers to keep production going when breakdowns occur. ***Total Productive Maintenance*** (TPM) is a program that aims to minimize production losses due to machine failures, malfunctions, and poor utilization. One of the elements of the program is to hold workers who operate equipment responsible for routine tasks such as inspecting, cleaning, and lubricating their machines. In some cases, they also make minor repairs on their equipment.

Three categories of maintenance are performed on a plant's equipment by trained specialists: (1) emergency maintenance, which involves the immediate repair of a machine that has broken down; (2) preventive maintenance, which consists of routine repairs designed to avoid or minimize breakdowns; and (3) predictive maintenance, which attempts to anticipate machine malfunctions by monitoring the equipment for signs of problems and abnormal behavior. Emergency maintenance is undesirable because it means the machine is out of action and production has ceased. Preventive maintenance can be scheduled during hours when the machine is not running, for example, during the third shift in a plant that runs two shifts. Predictive maintenance is performed while the machine is running. A TPM program integrates preventive maintenance and predictive maintenance in order to avoid emergency maintenance.

One of the metrics used in TPM is overall equipment effectiveness, which combines several individual measures of a production machine's operation, as follows:

$$OEE = AUYr_{os} \tag{39.1}$$

where $OEE =$ overall equipment effectiveness; $A =$ availability, a reliability measure defined as the proportion uptime on the equipment; $U =$ utilization, the proportion of the available time that the machine is actually running; $Y =$ yield of acceptable product, a quality measure defined as the proportion of good product to total output; and $r_{os} =$ ratio of the actual operating speed of the machine relative to its designed operating speed. The objective of TPM is to make OEE as close to 100% as possible.

39.5.2 WORKER INVOLVEMENT

This is the third component of lean production, as practiced in the Toyota Production System. Three aspects of worker involvement are discussed in the following paragraphs: (1) continuous improvement, (2) visual management, and (3) standard work procedures.

Continuous Improvement This topic was briefly discussed in the context of manufacturing engineering in Section 39.2.1. In lean production, continuous improvement projects are carried out by worker teams. The projects are focused on problems related to productivity, quality, safety, maintenance, and any other area that is of interest to the organization. Members of each team are selected on the basis of their knowledge of the particular problem area. Teams may consist of workers from more than one department. They perform their regular duties in their respective departments and serve on the team part-time, holding several meetings per month, with each meeting lasting about an hour. The company benefits when the problems are solved, and the workers benefit by being recognized for their contributions and improving their technical skills.

Visual Management This refers to the notion that the status of a work situation is usually obvious just be looking at it. If something is amiss, it should be self-evident to the observer. This applies to individual workstations. If a machine has stopped, this can be seen. It also applies to the entire plant. It should be possible to view the entire interior of the plant, and so objects that unnecessarily obstruct the view are removed. For example, build-up of work-in-process is limited to a certain maximum height in the plant (of course, JIT should limit the build-up of inventory anyway).

Workers are involved in visual management in several ways. For example, the kanbans used in just-in-time delivery systems are a visual mechanism for controlling production and movement of materials in the plant. Also, workers and supervisors can observe the status of plant operations through the use of ***andon boards***, which are overhead light panels located above sections of the plant. Using different colored lights, they indicate the status of operations. For instance, green indicates normal operation, red indicates a line stoppage. Other color codes may be used to indicate impending material shortages, need for a setup changeover, and so forth. Other elements of visual management include the extensive use of drawings, pictures, and diagrams in worker training programs, and promoting good housekeeping practices at employees' workstations (so that workers work in a clean and visible work space).

Standard Work Procedures Standardized work procedures and standard times are used in the Toyota Production System with the objectives of increasing productivity, balancing workloads, and minimizing work-in-process. The procedures document

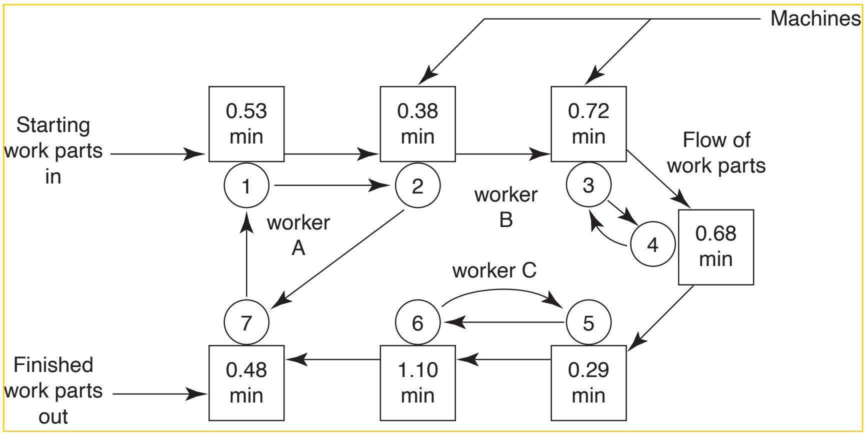


FIGURE 39.10 U-shaped work cell with three workers performing seven operations at seven machines. The arrows indicate the paths followed by each worker during each work cycle, and the numbers in circles indicate the operations each worker performs. Task times at each machine are labeled inside each machine block.

the work elements and their element times in each repetitive task performed by workers. For workers responsible for multiple machines operating under semi-automatic cycle, the procedures indicate the sequence of machines and the task required at each machine. The sequence is designed to minimize idle times of the worker and machines. One of the objectives in designing these tasks and work sequences is to make the rate of parts production in these operations equal to the respective demand rates for the parts. When this is achieved, overproduction is avoided and work-in-process inventory is minimized, consistent with just-in-time delivery.

Production is often organized within work cells, which are teams of workers and machines arranged in sequential order to produce parts in small batch sizes. The cells are often U-shaped as shown in Figure 39.10 rather than straight line. This configuration is said to promote teamwork and camaraderie amongst the workers. Each worker may operate more than one machine in the cell, as suggested in the figure, and the tasks are assigned to workers so that their workloads are balanced and the production cycle time is consistent with the demand rate for the part.

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