NEHRU COLLEGE OF ENGINEERING AND RESEARCH CENTRE

(Accredited by NAAC, Approved by AICTE New Delhi, Affiliated to APJKTU)

Pampady, Thiruvilwamala (PO), Thrissur (DT), Kerala 680 588

DEPARTMENT OF MECHATRONICS

COURSE MATERIALS

MR 401 ADVANCED AUTOMATION SYSTEMS

VISION OF THE INSTITUTION
To mould true citizens who are millennium leaders and catalysts of change through excellence in education.

MISSION OF THE INSTITUTION
NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values. We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- Established in: 2013
- Course offered: B.Tech Mechatronics Engineering
- Approved by AICTE New Delhi and Accredited by NAAC
- Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

To develop professionally ethical and socially responsible Mechatronics engineers to serve the humanity through quality professional education.

DEPARTMENT MISSION

1) The department is committed to impart the right blend of knowledge and quality education to create professionally ethical and socially responsible graduates.
2) The department is committed to impart the awareness to meet the current challenges in technology.
3) Establish state-of-the-art laboratories to promote practical knowledge of mechatronics to meet the needs of the society

PROGRAMME EDUCATIONAL OBJECTIVES

I. Graduates shall have the ability to work in multidisciplinary environment with good professional and commitment.
II. Graduates shall have the ability to solve the complex engineering problems by applying electrical, mechanical, electronics and computer knowledge and engage in life long learning in their profession.
III. Graduates shall have the ability to lead and contribute in a team entrusted with professional social and ethical responsibilities.
IV. Graduates shall have ability to acquire scientific and engineering fundamentals necessary for higher studies and research.

COURSE OUTCOME

Course Outcomes: After the completion of the course the student will be able to

C401.1	Describe the functions of the elements of modern manufacturing systems
C401.2	Interpret the modern philosophies of automated manufacturing and the advanced automation systems
C401.3	Acquire knowledge about the functions of the elements of a manufacturing system
C401.4	Understand the functions of a cellular manufacturing system
C401.5	Explain the working of a common measurement systems
C401.6	Understand the functions of the elements of a flexible manufacturing system

CO VS PO'S AND PSO'S MAPPING

CO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PS01	PSO1
CO 1	3	-	2	-	-	-	-	-	-	-	-	3	3	3
CO 2	3	-	2	-	-	-	-	-	-	-	-	3	3	3
CO 3	3	-	2	-	-	-	-	-	-	-	-	3	3	3
CO 4	3	-	2	-	-	-	-	-	-	-	-	3	3	3
CO 5	3	-	2	-	-	-	-	-	-	-	-	3	3	3
CO 6	3	-	2	-	-	-	-	-	-	-	-	3	3	3

Note: H-Highly correlated=3, M-Medium correlated=2, L-Less correlated=1

SYLLABUS

Module 1

Production system facilities-low medium and high quantity production-Manufacturing support systems-Automation in production systems-manual labor in production systems automaton principles and strategies-USA principle-ten strategies of Automation and Production Systems-Automation Migration strategy-manufacturing industries and products manufacturing operations-processing and assembly operations product /production relationships-production quantity and product variety-product and part complexity-limitations and capabilities of a manufacturing plant

Module 2

Elements of an automated system- power to accomplish the Automated process-program of Instructions-control systems advanced automation functions-safety monitoring-maintenance and repair diagnostics-Error detection and Recovery-levels of automation, variables and parameters in process industries and discrete manufacturing industries-continuous and discrete control systems-computer process control-control requirements-capabilities of computer control and levels of industrial process control-computer process monitoring-direct digital control-numerical control and robotics-PLC supervisory control-distributed control systems

Module 3

Components of a manufacturing system-production machines material handling system- computer control system-human resources-classification of manufacturing systems-types of operations performed-number of work stations-automation levels-part or product variety-Type I type II and type III manufacturing systems-manufacturing progress functions learning curves

Module 4

Part families-parts classification and coding-features and examples of part classification and coding systems-production flow analysis-cellular manufacturing-composite part conceptmachine cell design-application of group technology-survey of industry practice-quantitative analysis in cellular manufacturing-grouping parts and machinery by rank order clustering-arranging machines in GT Cells.

Module 5

Inspection metrology-contact and non contact inspection techniques-conventional measuring and gauging techniques coordinate measuring machines-CMM construction-CMM operation and planning-CMM softwares-CMM applications and benefits-flexible inspection systems-inspection probes on machine tools-surface measurements-stylus instruments machine vision-image acquisition and digitizing-image processing, digitizing analysis and interpretation- machine vision applications –non contact non optical inspection techniques.

Module 6

Flexible manufacturing systems-types of FMS-FMS components-workstations-material handling and storage systems-computer control systems-human resources-FMS applications and benefits-FMS planning and implementation issues-FMS planning and design issues-FMS operational issues-lean production-agile manufacturing-market forces and agility-reorganizing the production for agility-manning relationships for agility-agility versus mass production comparison of lean and agile manufacturing

QUESTION BANK

MODULE I				
Q:NO:	**QUESTIONS**	**CO**	**KL**	**PAGE NO:**
1	What is a production system?	CO1	K1	9
2	Production system can be divided into two categories or levels. name and define the two level	CO1	K3	9
3	What are manufacturing system and how they distinguished from production system?	CO1	K1	36
4	What are the four functions included within the scope of manufacturing support system?	CO1	K2	17
5	What is a programmable automation and what are some of its features?	CO1	K2	20
6	Identify three situation in which manual labour is preferred over automation	CO1	K3	27
7	What are some of the reason why companies automate their operations?	CO1	K2	26
8	What is a USA principle? what does each of the letters stand for?	CO1	K2	32
9	List out ten strategies for automation and process improvement.	CO1	K2	32
10	What is an automation migration strategy?	CO1	K2	35
MODULE II				
1	**What is automation?**	CO2	K2	55
2	An automated system consists of what three basic elements	CO2	K1	55
3	What are the difference between a process parameter and a process variable?	CO2	K2	57
4	What is the difference between a closed loop control system and open loop control system?	CO2	K2	63

5	What is safety monitoring in an automated system?	CO2	K1	68
6	What is error detection and recovery in an automated system?	CO2	K1	70
7	Name three of the four possible strategies in error recovery.	CO2	K1	70
8	Identify the five levels of automation in a production plant.	CO2	K2	74
MODULE III				
1	What is a manufacturing system?	CO3	K2	93
2	Name the four components of a manufacturing system	CO3	K3	93
3	What are the three classification of production machine, in terms of worker participation?	CO3	K2	101
4	What are the five material handling functions that provided in a manufacturing system?	CO3	K3	96
5	What is the difference between fixed routing and variable routing in manufacturing system consisting of multiple workstations?	CO3	K1	110
6	What is a pallet fixture in work transport in a manufacturing system?	CO3	K2	111
MODULE IV				
1	What is group technology?	CO4	K3	119
2	What is a cellular manufacturing?	CO4	K2	136
3	What are the two major task that accompany under take when it implements group technology	CO4	K2	119
4	What is part family?	CO4	K2	119
5	What are three methods for solving the problem of grouping parts part families?	CO4	K2	119
6	What is production flow analysis?	CO4	K2	132
7	What are the objective s when implementing cellular	CO4		136

	manufacturing?		K2	
8	What is composite part concept, as the term applied in group technology?	CO4	K2	137
9	What are the four common GT cell configurations?	CO4	K2	142
10	What is the applications of rank order clustering?	CO4	K2	149
MODULE V				
1	Define the term measurement.	CO5	K1	162
2	What is metrology?	CO5	K2	163
3	What are the seven basic quantities used in metrology from which all other variables are derived?	CO5	K2	168
4	Explain contact inspection methods.	CO5	K3	170
5	Explain the term coordinate metrology.	CO5	K3	170
6	What are the two basic components of a coordinate measuring machine?	CO5	K2	172
7	What is machine vision?	CO5	K2	187
	MODULE 6			
1	What is a flexible manufacturing system?	CO6	K2	205
2	What are the four basic components a FMS?	CO6	K2	205
3	What is the difference between primary and secondary handling system in FMS?	CO6	K2	217
4	Name the five categories of layout configurations that are found in a FMS?	CO6	K1	220

5	What is the difference between a dedicated FMS and random order FMS?	CO6	K2	211
6	Name the seven functions performed by human resources in an FMS	CO6	K1	225

APPENDIX 1

CONTENT BEYOND THE SYLLABUS

S:NO;	**TOPIC**	**PAGE NO:**
1	OTHER FACTORY OPERATIONS	44
2	INDUSTRIAL CONTROL SYSTEM	76
3	COPUTER CONTROLLED CMM	182

MODULE 1

PRODUCTION SYSTEM FACILITIES

The 111*facilities* in the production system are the factory, production machines and tooling, material handling equipment, inspection equipment, and the computer systems that control the manufacturing operations. Facilities also include the *plant layout*, which is the way the equipment is physically arranged in the factory. The equipment is usually arranged into logical groupings, and we refer to these equipment arrangements and the workers who operate them as the *manufacturing systems* in the factory. Manufacturing systems can be individual work cells, consisting of a single production machine and worker assigned to that machine. We more commonly think of manufacturing systems as groups of machines and workers, for example, a production line. The manufacturing systems come in directphysical contact with the parts and/or assemblies being made. They ―touch‖ the product.

A manufacturing company attempts to organize its facilities in the most efficient way to serve the particular mission of that plant. Over the years, certain types of production facilities have come to be recognized as the most appropriate way to organize for a given type of manufacturing. Of course, one of the most important factors that determine the type of manufacturing is the type of products that are made. Our book is concerned primarily with

the production of discrete parts and products, compared with products that are in liquid or bulk form, such as chemicals.

If we limit our discussion to discrete products, the quantity produced by a factory has a very significant influence on its facilities and the way manufacturing is organized. *Production quantity* refers to the number of units of a given part or product produced annually by the plant. The annual part or product quantities produced in a given factory can be classified into three ranges:

1. *Low production*: Quantities in the range of 1 to 100 units per year.

2. *Medium production*: Quantities in the range of 100 to 10,000 units annually.

3. *High production*: Production quantities are 10,000 to millions of units.

The boundaries between the three ranges are somewhat arbitrary (author's judgment). Depending on the types of products we are dealing with, these boundaries may shift by an order of magnitude or so.

Some plants produce a variety of different product types, each type being made in low or medium quantities. Other plants specialize in high production of only one product type. It is instructive to identify product variety as a parameter distinct from production quantity. *Product variety* refers to the different product designs or types that are produced in a plant. Different products have different shapes and sizes and styles; they perform different functions; they are sometimes intended for different markets; some have more components than others; and so forth. The number of different product types made each year can be counted. Whenthe number of product types made in a factory is high, this indicates high product variety.

There is an inverse correlation between product variety and production quantity in terms of factory operations. When product variety is high, production quantity tends to be low; and vice versa. This relationship is depicted in Figure 1.2. Manufacturing plants tend to specialize in a combination of production quantity and product variety that lies somewhere inside the diagonal band in Figure 1.2. In general, a given factory tends to be limited to the product variety value that is correlated with that production quantity.

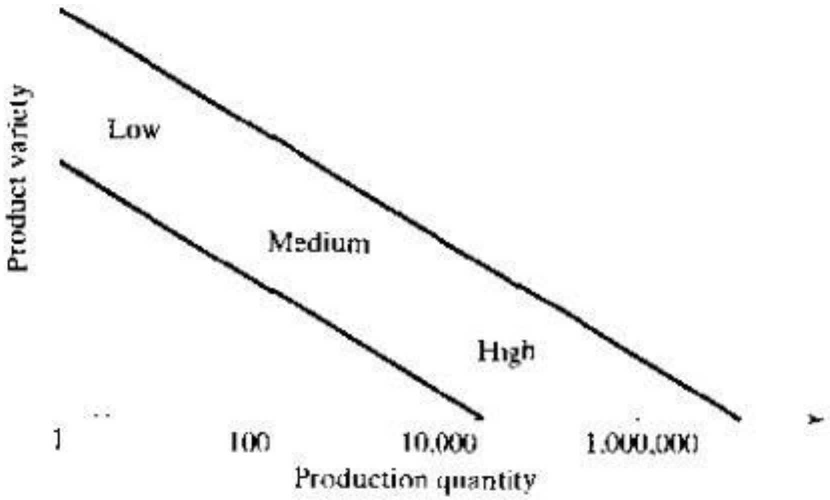


Figure 1.2 Relationship between product variety and production quantity in discrete product manufacturing.

Figure 1.2 Relationship between product variety and production quantity in discrete product manufacturing.

Although we have identified product variety as a quantitative parameter (the number of different product types made by the plant or company), this parameter is much less exact than production quantity is because details on how much the designs differ is not captured simply by the number of different designs. The differences between an automobile and an air conditioner are far greater than between an air conditioner and a heat pump. Products can be different, but the extent of the differences may be small or great. The automotive industry provides some examples to illustrate this point. Each of the U.S. automotive companies produces cars with two or three different nameplates in the same assembly plant, although the body styles and other design features are nearly the same. In different plants, the same auto company builds heavy trucks. Let us use the terms –hard‖ and –soft‖ to describe these differences in product variety. *Hard product variety* is when the products differ substantially. In an assembled product, hard variety is characterized by a low proportion of common parts among the products; in many cases, there are no common parts. The difference between a car and a truck is hard. *Soft product variety* is when there are only small differences between products, such as the differences between car models made on the same productionline. There is a high proportion of common parts among assembled products whosevariety is soft. The variety between different product categories tends to be hard;

the variety between different models within the same product category tends to be soft.

We can use the three production quantity ranges to identify three basic categories of production plants. Although there are variations in the work organization within each category, usually depending on the amount of product variety, this is nevertheless a reasonable way to classify factories for the purpose of our discussion.

1 Low Quantity Production

The type of production facility usually associated with the quantity range of 1 to 100 units/year is the *job shop*, which makes low quantities of specialized and customized products. The products are typically complex, such as space capsules, aircraft, and special machinery. Job shop production can also include fabricating the component parts for the products. Customer orders for these kinds of items are often special, and repeat orders may never occur. Equipment in a job shop is general purpose and the labor force is highly skilled.

A job shop must be designed for maximum flexibility to deal with the wide part and product variations encountered (hard product variety). If the product is large and heavy, and therefore difficult to move in the factory, it typically remains in a single location, at least during its final assembly. Workers and processing equipment are brought to the product, rather than moving the product to theequipment. This type of layout is referred to as a *fixed–position layout*, shown in Figure 1.3(a). In the pure situation, the product remains in a single location during its entire fabrication. Examples of such products include ships, aircraft, railway locomotives, and heavy machinery. In actual practice, these items are usually built in large modules at single locations, and then the completed modules are brought together for final assembly using largecapacity cranes.

The individual parts that comprise these large products are often made in factories that have a *process layout*, in which the equipment is arranged according to function or type. The lathes are in one department, the milling machines are in another department, and so on, as in Figure 1.3(b). Different parts, each requiring a different operation sequence,

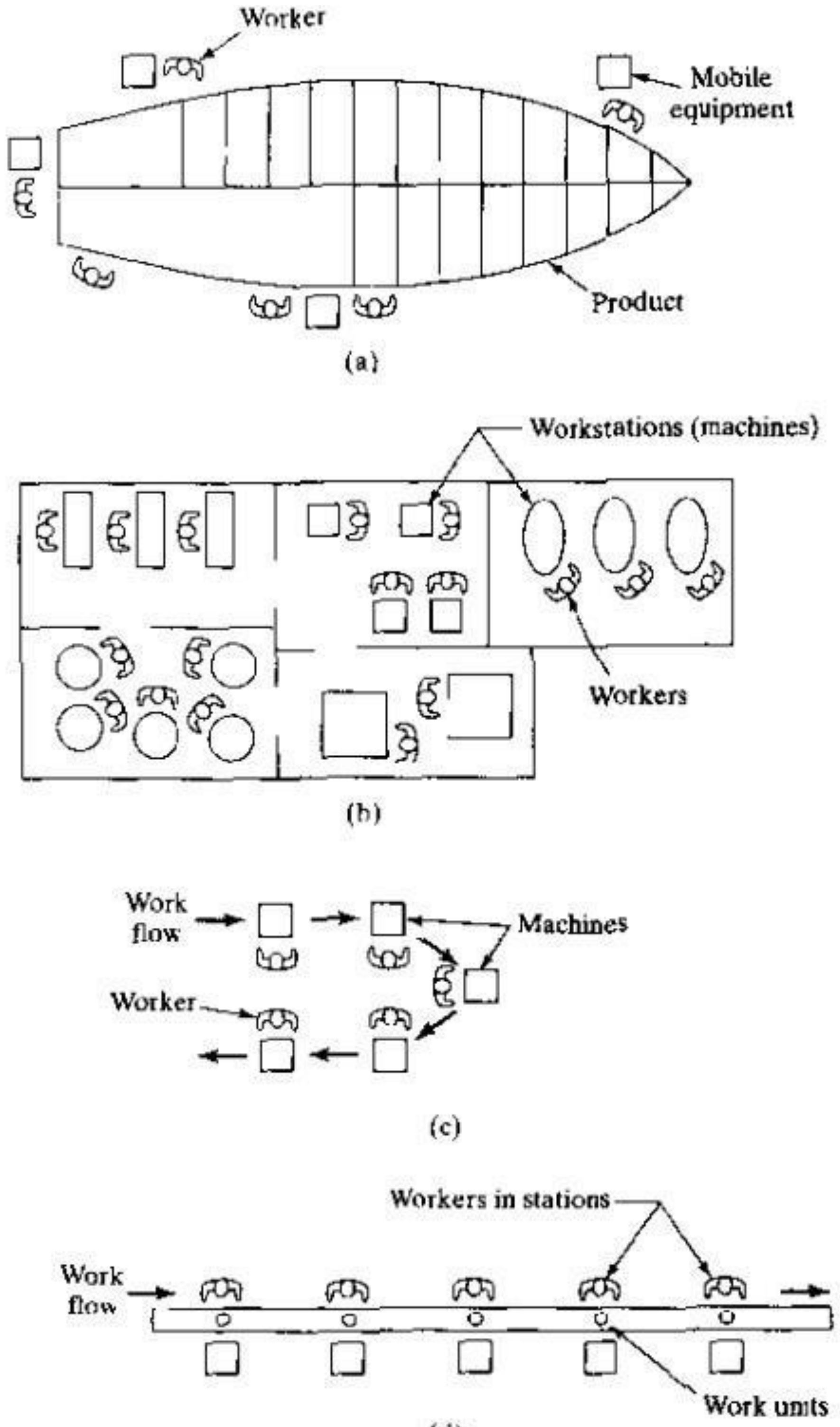


Figure 1.3 Various types of plant layout: (a) fixed-position layout, (b) process layout, (c) cellular layout, and (d) product layout.

are routed through the departments in the particular order needed for their processing, usually in batches. The process layout is noted for its flexibility; it can accommodate a great variety of alternative operation sequences for different part configurations. Its disadvantage is that the machinery and methods to produce a part are not designed for high efficiency. Much material handling is required to move parts between departments, so inprocess inventory can be high.

2 Medium Quantity Production

In the medium quantity range (100–10,000 units annually), we distinguish between two different types of facility, depending on product variety. When product variety is hard, the traditional approach is *batch production*, in which a batch of one product is made, after which the facility is changed over to produce a batch of the next product, and so on. Orders for each product are frequently repeated. The production rate of the equipment is greater than the demand rate for any single product type, and so the same equipment can be shared among multiple products. The changeover between production runs takes time. Called the *setup time* or *changeover time*, it is the time to change tooling and to set up and reprogram the machinery. This is lost production time, which is a disadvantage of batch manufacturing. Batch production is commonly used in maketostock situations, in which items are manufactured to replenish inventory that has been gradually depleted by demand. The equipment is usually arranged in a process layout, Figure 1.3(b).

An alternative approach to medium range production is possible if product variety is soft. In this case, extensive changeovers between one product style and the next may not be required. It is often possible to configure the equipment so that groups of similar parts or products can be made on the same equipment without significant lost time for changeovers. The processing or assembly of different parts or products is accomplished in cells consisting of several workstations or machines. The term *cellular manufacturing* is often associated with this type of production. Each cell is designed to produce a limited variety of part configurations; that is, the cell specializes in the production of a given set of similar parts or products, according to the principles of *group technology* (Chapter 15). The layout is called a *cellular layout*, depicted in Figure 1.3(c).

3 High Production

The high quantity range (10,000 to millions of units per year) is often referred to as *mass production*. The situation is characterized by a high demand rate for the product, and the production facility is dedicated to the manufacture of that product.Two categories of mass production can be distinguished: (1) quantity production and (2) flow line production. *Quantity production* involves the mass production of single parts on single pieces of equipment. The method of production typically involves standard machines (such as stamping presses) equipped with special tooling (e.g., dies and material handling devices), in effect dedicating the equipment to the production of one part type. The typical layout used in quantity production is the process layout, Figure 1.3(b).

Flow line production involves multiple workstations arranged in sequence, and the parts or assemblies are physically moved through the sequence to complete the product. The workstations consist of production machines and/or workers equipped with specialized tools. The collection of stations is designed specifically for the product to maximize efficiency. The layout is called a *product layout*, and the workstations are arranged into one long line, as in Figure 1.3(d), or into a series of connected line segments. The work is usually moved between stations by powered conveyor. At each station, a small amount of the total work is completed on each unit of product.

The most familiar example of flow line production is the assembly line, associated with products such as cars and household appliances. The pure case of flow line production is where there is no variation in the products made on the line. Every product is identical, and the line is referred to as a *single model production line*. However, to successfully market a

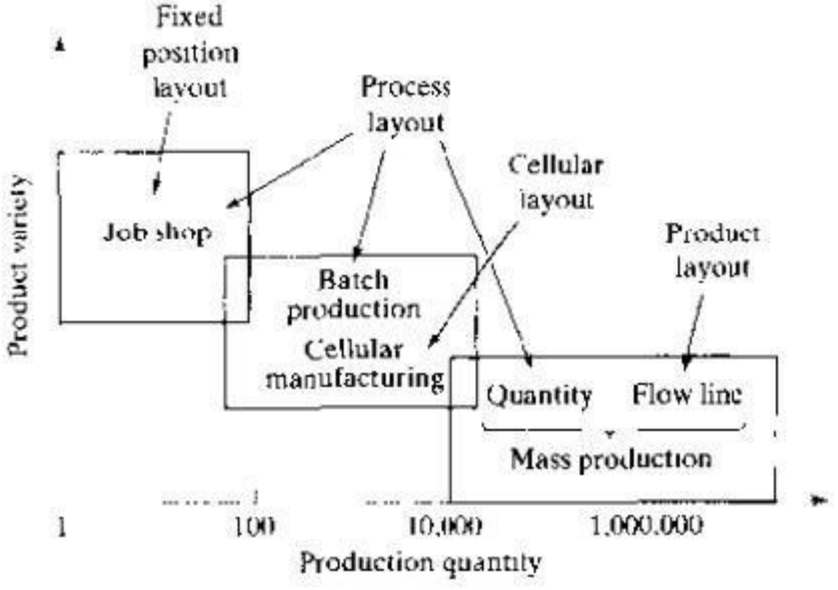


Figure 1.4 Types of facilities and layouts used for different levels of production quantity and product variety.

given product, it is often necessary to introduce model variations so that individual customers can choose the exact style and options that appeal to them. From a production viewpoint, the model differences represent a case of soft product variety. The term *mixed–model production line* applies to those situations where there is soft variety in the products made on the line. Modern automobile assembly is an example. Cars coming off the assembly line have variations in options and trim representing different models (and, in many cases, different nameplates) of thesame basic car design.

Much of our discussion of the types of production facilities is summarized in Figure 1.4, which adds detail to Figure 1.2 by identifying the types of production facilities and plant layouts used. As the figure shows, some overlap exists among the different facility types.

MANUFACTURING SUPPORT SYSTEMS

To operate the production facilities efficiently, a company must organize itself to design the processes and equipment, plan and control the production orders, and satisfy product quality requirements. These functions are accomplished by manufacturing support systems – people and procedures by which a company manages its production operations. Most of these support systems do not directly contact the product, but they plan and control its progress through the factory.

Manufacturing support involves a cycle of information processing activities, as illustrated in Figure 1.5. The production system facilities described in Section 1.1 are pictured in the center of the figure. The information processing cycle, represented by the outer ring, can be described as consisting of four functions:

(1) business functions, (2) product design,

(3) manufacturing planning, and (4) manufacturing control.

Business Functions. The business functions are the principal means of communicating with the customer. They are, therefore, the beginning and the end of the information processing cycle. Included in this category are sales and marketing, sales forecasting, order entry, cost accounting, and customer billing.

The order to produce a product typically originates from the customer and proceeds into the company through the sales and marketing department of the firm. The production order will be in one of the following forms: (1) an order to manufacture an item to the customer’s specifications, (2) a customer order to buy one or more of the manufacturer’s proprietary products, or (3) an internal company order based on a forecast of future demand for a proprietary product.

Product Design. If the product is to be manufactured to customer *design*, the design will have been provided by the customer. The manufacturer’s product design department will not be involved. If the product is to be produced to customer *specifications*, the manufacturer’s product design department may be contracted to do the design work for the product as well as to manufacture it.

If the product is proprietary, the manufacturing firm is responsible for its development and design. The cycle of events that initiates a new product design often originates in the sales and marketing department; the information flow is indicated in Figure 1.5. The departments of the firm that are organized to accomplish product design might include research and development, design engineering, drafting, and perhaps a prototype shop.

Manufacturing Planning. The information and documentation that constitute the product design flows into the manufacturing planning function. The information processing activities in manufacturing planning include process planning, master scheduling, requirements planning, and capacity planning. *Process planning* consists of determining the sequence of individual processing and assembly operations needed to produce the part. The manufacturing engineering and industrial engineering departments are responsible for planning the processes and related technical details.

Manufacturing planning includes logistics issues, commonly known as production planning. The authorization to produce the product must be translated into the master production schedule. The *master production schedule* is a listing of the products to be made, when they are to be delivered, and in what quantities. Months are traditionally used to specify deliveries in the master schedule. Based on this schedule, the individual components and subassemblies that make up each product must be planned. Raw materials must be purchased or requisitioned from storage, purchased parts must be ordered from suppliers, and all of these items must be planned so that they are available when needed. This entire task is called *material requirements planning*. In addition, the master schedule must not list more quantities of products than the factory is capable of producing each month with its given number of machines and manpower. A function called *capacity planning* is concerned with planning the manpower and machine resources of the firm.

Manufacturing Control. Manufacturing control is concerned with managing and controlling the physical operations in the factory to implement the manufacturing plans. The flow of information is from planning to control as indicated in Figure 1.5. Information also flows back and forth between manufacturing control and the factory operations. Included in the manufacturing control function are shop floor control, inventory control, and quality control.

Shop floor control deals with the problem of monitoring the progress of the product as it is being processed, assembled, moved, and inspected in the factory. Shop floor control is concerned with inventory in the sense that the materials being processed in the factory are work in process inventory. Thus, shop floor control and inventory control overlap to some extent. *Inventory control* attempts to strike a proper balance between the danger of too little inventory (with possible stockouts of materials) and the carrying cost of too much inventory. It deals with such issues as deciding the right quantities of materials to order and when to reorder a given item when stock is low.

The mission of *quality control* is to ensure that the quality of the product andits components meet the standards specified by the product designer. To accomplish its mission, quality control depends on inspection activities performed in the factory at various times during the manufacture of the product. Also, raw materials and component parts from outside sources are sometimes inspected when they are received, and final inspection and testing of the finished product is performed to ensure functional quality and appearance.

AUTOMATION IN PRODUCTION SYSTEMS

Some elements of the firm's production system are likely to be automated, whereas others will be operated manually or clerically. For our purposes here, *automation* can be defined as a technology concerned with the application of mechanical, electronic, and computer based systems to operate and control production.

The automated elements of the production system can be separated into two categories: (1) automation of the manufacturing systems in the factory and (2) computerization of the manufacturing support systems. In modern production systems, the two categories overlap to some extent, because the automated manufacturing systems operating on the factory floor are themselves often implemented by computer systems and connected to the computerized manufacturing support systems and management information system operating at the plant and enterprise levels. The term computerintegrated manufacturing is used to indicate this extensive use of computers in production systems. The two categories of automation are shown in Figure 1.6 as an overlay on Figure 1.1.

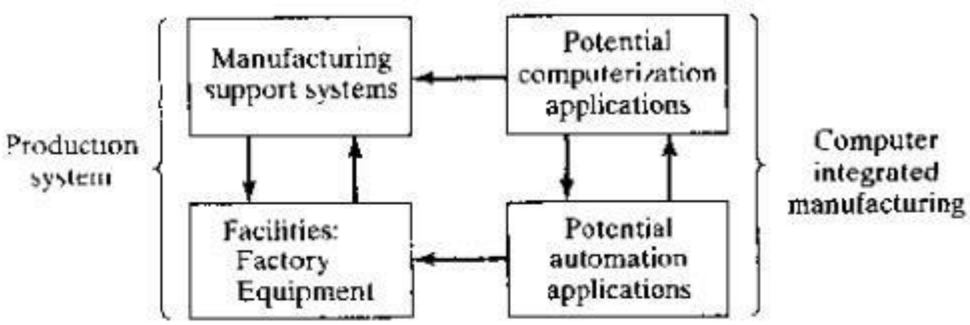


Figure 1.6 Opportunities of automation and computerization in a production system.

1. Automated Manufacturing Systems

Automated manufacturing systems operate in the factory on the physical product. They perform operations such as processing, assembly, inspection, or material handling, in some cases accomplishing more than one of these operations in the same system. They are called automated because they perform their operations with a reduced level of human participation compared with the corresponding manual process. In some highly automated systems, there is virtually no human participation. Examples of automated manufacturing systems include:

- automated machine tools that process parts
- transfer lines that perform a series of machining operations
- automated assembly systems
- manufacturing systems that use industrial robots to perform processing or assembly operations
- automatic material handling and storage systems to integrate manufacturing operations
- automatic inspection systems for quality control

Automated manufacturing systems can be classified into three basic types

(1) fixed automation, (2) programmable automation, and (3) flexible automation.

Fixed Automation. Fixed automation is a system in which the sequence of processing (or assembly) operations is fixed by the equipment configuration. Each of the operations in the sequence is usually simple, involving perhaps a plain linear or rotational motion or an uncomplicated combination of the two; for example, the feeding of a rotating spindle. It is the integration and coordination of many such operations into one piece of equipment that makes the system complex. Typical features of fixed automation are:

- high initial investment for custom engineered equipment
- high production rates
- relatively inflexible in accommodating product variety

The economic justification for fixed automation is found in products that are produced in very large quantities and at high production rates. The high initial cost of the equipment can be spread over a very large number of units, thus making the unit cost attractive compared with alternative methods of production. Examples of fixed automation include machining transfer lines and automated assembly machines.

Programmable Automation. In *programmable automation*, the production equipment is designed with the capability to change the sequence of operations to accommodate different product configurations. The operation sequence is controlled by a *program*, which is a set of instructions coded so that they can be read and interpreted by the system. New programs can be prepared and entered into the equipment to produce new products. Some of the features that characterize programmable automation include:

- high investment in general purpose equipment
- lower production rates than fixed automation
- flexibility to deal with variations and changes in product configuration
- most suitable for batch production

Programmable automated production systems are used in low and medium volume production. The parts or products are typically made in batches. To produce each new batch of a different product, the system must be reprogrammed with the set of machine instructions that correspond to the new product. The physical setup of the machine must also be changed: Tools must be loaded, fixtures must be attached to the machine table, and the required machine settings must be entered. This changeover procedure takes time. Consequently, the typical cycle for a given product includes a period during which the setup and reprogramming takes place, followed by a period in which the batch is produced. Examples of programmable automation include numerically controlled (NC) machine tools, industrial robots, and programmable logic controllers.

Flexible Automation. Flexible automation is an extension of programmable automation. A flexible automated system is capable of producing a variety of parts (or products) with virtually no time lost for changeovers from one part style to the next. There is no lost production time while reprogramming the system and altering the physical setup (tooling, fixtures, machine settings). Consequently, the system can produce various combinations and schedules of parts or products instead of requiring that they be made in batches. What makes flexible automation possible is that the differences between parts processed by the system are not significant. It is a case of soft variety, so that the amount of changeover required between styles is minimal. The features of flexible automation can be summarized as follows

- high investment for a custom engineered system
- continuous production of variable mixtures of products
- medium production rates
- flexibility to deal with product design variations

Examples of flexible automation are the flexible manufacturing systems for performing machining operations that date back to the late 1960s.

The relative positions of the three types of automation for different production volumes and product varieties are depicted in Figure 1.7. For low production quantities and new product introductions, manual production is competitive with programmable automation, as we indicate in the figure and discuss in Section 1.4.1.

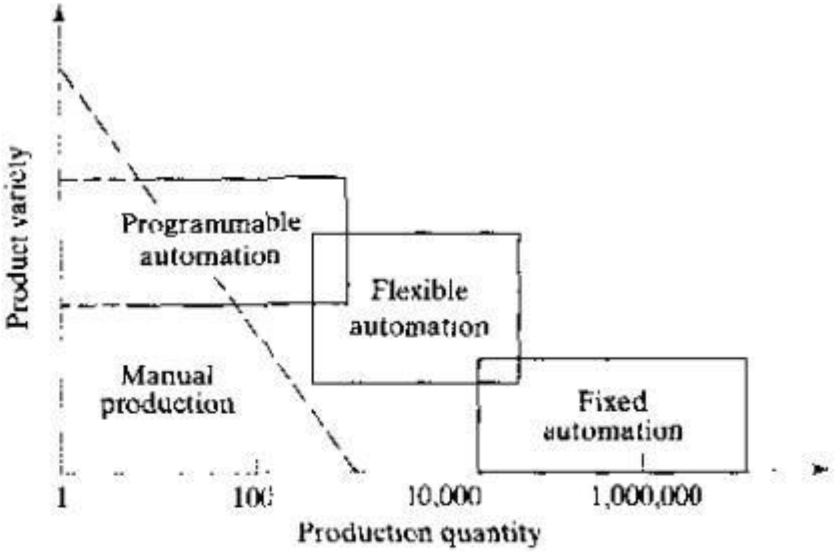


Figure 1.7 Three types of automation relative to production quantity and product variety.

2. Computerized Manufacturing Support Systems

Automation of the manufacturing support systems is aimed at reducing the amount of manual and clerical effort in product design, manufacturing planning and control, and the business functions of the firm. Nearly all modern manufacturing support systems are implemented using computer systems. Indeed, computer technology is used to implement automation of the manufacturing systems in the factory as well. The term *computer— integrated manufacturing* (CIM) denotes the pervasive use of computer systems to design the products, plan the production, control the operations, and perform the various business—related functions neededin a manufacturing firm. True CIM involves integrating all of these functions inone system that operates throughout the enterprise. Other terms are used to identifyspecific elements of the CIM system. For example, *compute raided design* (CAD) denotes the use of computer systems to support the product design function. *Computer aided manufacturing* (CAM) denotes the use of computer systems to perform functions related to manufacturing engineering, such as processplanning and numerical control part programming. Some computer systems perform both CAD and CAM, and so the term *CAD/CAM* is used to indicate the integration of the two into one system. Computer—integrated manufacturing includes CAD/CAM, but it also includes the firm’s business functions that are related to manufacturing.

Let us attempt to define the relationship between automation and CIM by developing a conceptual model of manufacturing. In a manufacturing firm, the physical production activities that take place in the factory can be distinguished from the information—processing activities, such as product design and production planning, that usually occur in an office environment. The physical activities include all of the processing, assembly, material handling, and inspection operations that are performed on the product in the factory. These operations come in direct contact with the product during manufacture. The relationship between the physical activities and the information—processing activities in our model is depicted in Figure 1.8. Raw materials flow into one end of the factory and finished products flow out the other end. The physical activities take place inside the factory. In our model, the information—processing activities form a ring that surrounds the factory, providing the data and knowledge required to successfully produce the product. These in

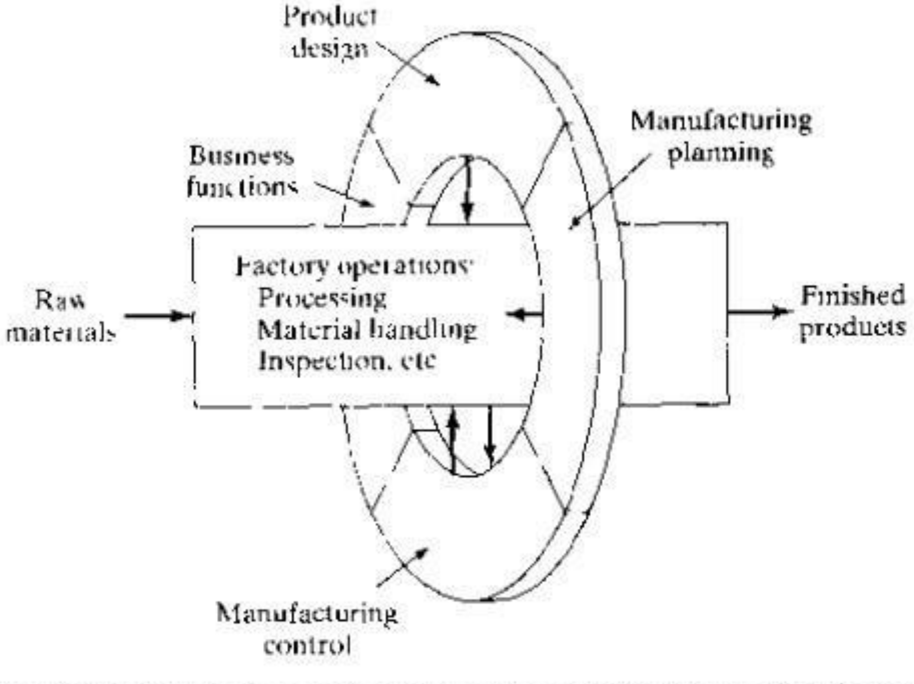


Figure 1.8 Model of manufacturing showing factory operations and the information-processing activities for manufacturing support.

formation—processing activities are accomplished to implement the four basic manufacturing support functions identified earlier: (1) business functions, (2) product design, (3) manufacturing planning, and (4) manufacturing control. These four functions form a cycle of events that must accompany the physical production activities but do not directly touch the product.

3. Reasons for Automating

Companies undertake projects in manufacturing automation and computer integrated manufacturing for a variety of good reasons. Some of the reasons used to justify automation are the following:

1. *To increase labor productivity*. Automating a manufacturing operation usually increases production rate and labor productivity. This means greater output per hour of labor input.
2. *To reduce labor cost*. Ever increasing labor cost has been and continues to be the trend in the world’s industrialized societies. Consequently, higher investment in automation has become economically justifiable to replace manual operations. Machines are increasingly being substituted for human labor to reduce unit product cost.
3. *To mitigate the effects of labor shortages*. There is a general shortage of labor in many advanced nations, and this has stimulated the development of automated operations as a substitute for labor.
4. *To reduce or eliminate routine manual and clerical tasks*. An argument can be put forth that there is social value in automating operations that are routine, boring, fatiguing, and possibly irksome. Automating such tasks serves a purpose of improving the general level of working conditions.
5. *To improve worker safety*. By automating a given operation and transferring the worker from active participation in the process to a supervisory role, the work is made safer. The safety and physical wellbeing of the worker has become a national objective with the enactment of the Occupational Safety and Health Act (OSHA) in 1970. This has provided an impetus for automation.

6. *To improve product quality*. Automation not only results in higher production rates than manual operations; it also performs the manufacturing process with greater uniformity and conformity to quality specifications. Reduction of fraction defect rate is one of the chief benefits of automation.
7. *To reduce manufacturing lead time*. Automation helps to reduce the elapsed time between customer order and product delivery, providing a competitive advantage to the manufacturer for future orders. By reducing manufacturing lead time, the manufacturer also reduces work in process inventory.
8. *To accomplish processes that cannot be done manually*. Certain operations cannot be accomplished without the aid of amachine. These processes have requirements for precision, miniaturization, or complexity of geometry, that cannot be achieved manually. Examples include certain integrated circuit fabrication operations, rapid prototyping processes based on computer graphics (CAD) models, and the machining of complex, mathematically defined surfaces using computer numerical control. These processes can only be realized by computer controlled systems.
9. *To avoid the high cost of not automating*. There is a significant competitive advantage gained in automating a manufacturing plant. The advantage cannot easily be demonstrated on a company’s project authorization form. The benefits of automation often show up in unexpected and intangible ways, such as in improved quality, higher sales, better labor relations, and better company image. Companies that do not automate are likely to find themselves at a competitive disadvantage with their customers, their employees, and the general public.

MANUAL LABOR IN PRODUCTION SYSTEMS

Is there a place for manual labour in the modern production system? The answer is certainly yes. Even in a highly automated production system, humans are still a necessary component of the manufacturing enterprise. For the foreseeable future, people will be required to manage and maintain the plant, even in those cases where they do not participate directly in its manufacturing operations. Let us separate our discussion of the labour issue into two parts, corresponding to our previous distinction between facilities and manufacturing support: (1) manual labour in factory operations and (2) labour in the manufacturing support systems.

1. Manual Labour in Factory Operations

There is no denying that the long term trend in manufacturing is toward greater use of automated machines to substitute for manual labour. This has been true throughout human history, and there is every reason to believe the trend will continue. It has been made possible by applying advances in technology to factory operations. In parallel, and sometimes in conflict, with this technologically driven trend are issues of economics that continue to find reasons for employing manual labour in manufacturing operations.

Certainly one of the current economic realities in the world is that there are countries whose average hourly wage rates are sufficiently low that most automation projects are impossible to justify strictly on the basis of cost reduction. At time of writing, these countries include Mexico, China, and most of the countries of Southeast Asia. With the recent passage of the North American Free Trade Agreement (NAFTA), the North American continent has become one large labour pool. Within this pool, Mexico's labour rate is an order of magnitude less than that in the United States. For U.S. corporate executives making decisions on a factory location or the outsourcing of work, this is an economic reality that must be reckoned with.

In addition to the labour rate issue, there are other reasons, ultimately based on economics, that make the use of manual labour a feasible alternative to automation. Humans possess certain attributes that give them an advantage over machines in certain situations and certain kinds of tasks. Table 1.1 lists the relative strengths and attributes of humans and machines. A number of situations can be listed in which manual labour is usually preferred over automation:

- *Task is too technological difficulty to automated*. Certain tasks are very difficult (either technologically or economically) to automate. Reasons for the difficulty include:

(1) problems with physical access to the work location, (2) adjustments required in the task, (3) manual dexterity requirements, and (3) demands on hand eye coordination. Manual labour is used to perform the tasks in these cases. Examples include automobile final assembly lines where many final trim operations are accomplished by human workers.

- *Short product life cycle*. If the product must be designed and introduced in a short period of time to meet a near term window of opportunity in the marketplace, or if the product is anticipated to be on the market for a relatively short period, then a manufacturing method designed around manual labour allows for a much faster product launch than does an automatedmethod. Tooling for manual production can be fabricated in much less time and at much lower cost than comparable automation tooling.
- *Customized product*. If the customer requires a one of a kind item with unique features, manual labour may have the advantage as the appropriate production resource because of its versatility and adaptability. Humans are more flexible than any automated machine.

- *To cope with ups and downs in demand*. Changes in demand for a product necessitate changes in production output levels. Such changes are more easily made when manual labour is used as the means of production. An automated manufacturing system has a fixed cost associated with its investment. If output is reduced, that fixed cost must be spread over fewer units, driving up the unit cost of the product. On the other hand,

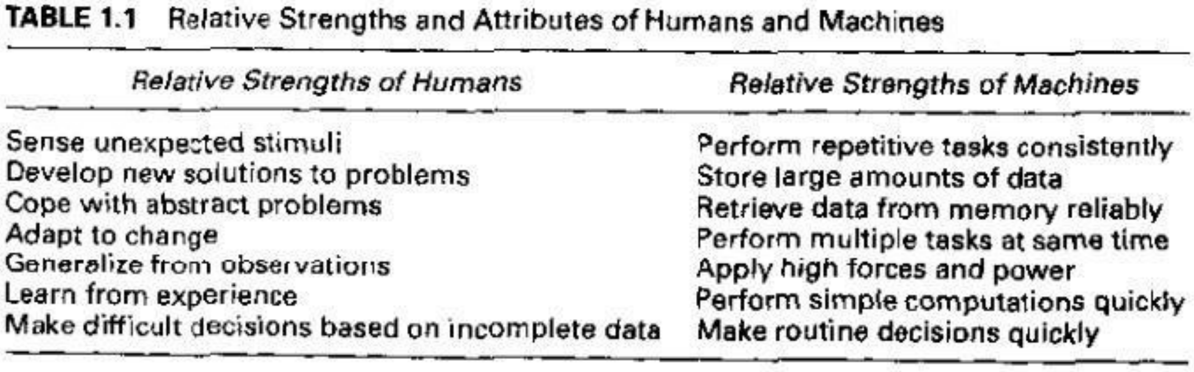


TABLE 1.1 Relative Strengths and Attributes of Humans and Machines

Relative Strengths of Humans	*Relative Strengths of Machines*
Sense unexpected stimuli	Perform repetitive tasks consistently
Develop new solutions to problems	Store large amounts of data
Cope with abstract problems	Retrieve data from memory reliably
Adapt to change	Perform multiple tasks at same time
Generalize from observations	Apply high forces and power
Learn from experience	Perform simple computations quickly
Make difficult decisions based on incomplete data	Make routine decisions quickly

an automated system has an ultimate upper limit on its output capacity. It cannot produce more than its rated capacity. By contrast, manual labour can be added or reduced as needed to meet demand, and the associated cost of the resource is in direct proportion to its usage. Manual labor can be used to augment the output of an existing automated system during those periods when demand exceeds the capacity of the automated system.

- *To reduce risk of product failure*. A company introducing a new product to the market never knows for sure what the ultimate success of that product will be. Some products will have long life cycles, while others will be on the market for relatively short lives. The use of manual labour as the productive resourceat the beginning of the product’s life reduces the company’srisk of losing a significant investment in automation if the product fails to achieve a long market life. In Section 1.5.3, we discuss an automation migration strategy that is suitable for introducing a new product.

2. Labour in Manufacturing Support Systems

In manufacturing support functions, many of the routine manual and clerical tasks can be automated using computer systems. Certain production planning activities are better accomplished by computer than by clerks. Material requirements planning (MRP, Section 26.2) is an example: In material requirements planning, order releases are generated for component parts and raw materials based on the master production schedule for final products. This requires a massive amount of data processing that is best suited to computer automation. Many commercial software packages are available to perform MRP. With few exceptions, companies that need to accomplish MRP rely on the computer. Humans are still required to interpret and implement the output of these MRP computations and to otherwise manage the production planning function.

In modern production systems, the computer is used as an aid in performing virtually all manufacturing support activities. Computer aided design systems are used in product design. The human designer is still required to do the creative work. The CAD system is a tool that assists and amplifies the designer’s creative talents. Computer aided process planning systems are used by manufacturing engineers to plan the production methods and routings. In these examples, humans are integral components in the operation of the manufacturing support functions, and the computer aided systems are tools to increase productivity and improve quality. CAD and CAM systems rarely operate completely in automatic mode.

It is very unlikely that humans will never be needed in manufacturing support systems, no matter how automated the systems are. People will be needed to do the decision making, learning, engineering, evaluating, managing, and other functions for which humans are much better suited than are machines, according to Table 1.1.

Even if all of the manufacturing systems in the factory are automated, there will still be a need for the following kinds of work to be performed:

- *Equipment maintenance*. Skilled technicians will be required to maintain and repair the automated systems in the factory when these systems break down.To improve the reliability of the automated systems, preventive maintenance will have to be carried out.
- *Programming and computer operation*. There will be a continual demand to upgrade software, install new versions of software packages, and execute the programs. It is anticipated that much of the routine process planning, numerical control part programming, and robot programming may be highly automated using artificial intelligence in the future.
- *Engineering project work*. The computer automated and integrated factory is likely never to be finished. There will be a continual need to upgrade production machines, design tooling, and undertake continuous improvement projects. These activities require the skills of engineers working in the factory.

- *Plant management*. Someone must be responsible for running the factory. There will be a limited staff of professional managers and engineers who are responsible for plant operations. There is likely to be an increased emphasis on managers' technical skills rather than in traditional factory management positions, where the emphasis is on personnel skills.

USA PRINCIPLE AND TEN STRATEGIES FOR AUTOMATION SYSTEM

Understand, simplify and automate the process

Following the USA Principle is a good first step in any automation project. The USA Principle is a common sense approach to automation projects. Similar procedures have been suggested in the manufacturing and automation trade literature, but none has a more captivating title than this one.

USA stands for:

1. Understand the existing process
2. Simplify the process
3. Automate the process.

It may turn out that automation of the process is unnecessary or cannot be cost justified after it has been simplified.

1. Specialization of operations

The first strategy involves the use of special-purpose equipment designed to perform **one operation with the greatest possible efficiency**.

This is analogous to the concept of labor specialization, which is employed ***to improve labor productivity***.

2. Combined operations

Production occurs as a sequence of operations.
Complex parts may require dozens, or even hundreds, of processing steps. The strategy of combined operations involves reducing the number of distinct production machines or workstations through which the part must be routed.

Since each machine typically involves a setup, setup time can usually be saved as a consequence of this strategy. Material handling effort and non-operation time are also reduced.

*Manufacturing lead time is reduced **for better customer service**.*

3. Simultaneous operations

A logical extension of the combined operations strategy is **to simultaneously perform the operations** that are combined at one workstation. In effect, two or more processing (or assembly) operations are being performed simultaneously on the same workpart, thus reducing total processing time.

4. Integration of operations

Another strategy is **to link several workstations together into a single integrated mechanism**, using automated work handling devices to transfer parts between stations. In effect, this reduces the number of separate machines through which the product must be scheduled.

*With more than one workstation, several parts can be processed simultaneously, thereby **increasing the overall output of the system**.*

5. Increased flexibility

This strategy attempts **to achieve maximum utilization of equipment** for job shop and medium volume situations by using the same equipment for a variety of parts or products. It involves the use of the flexible automation concepts.

6. Improved material handling and storage

A great opportunity for reducing nonpro-ductive time exists in the use of automated material handling and storage systems.

*Typical benefits include **reduced work-in-process** and **shorter manufacturing lead times**.*

7. On-line inspection

Inspection for quality of work is traditionally performed **after the process is completed**. This means that any poor quality product has already been produced by the time it is inspected. Incorporating inspection into the manufacturing process permits corrections to the process as the product is being made.

*This **reduces scrap** and **brings the overall quality** of product closer to the nominal specifications intended by the designer.*

8. Process control and optimization

This includes a wide range of control schemes **intended to operate the individual processes** and associated equipment more efficiently. By this strategy, the individual process times can be reduced and product quality improved.

9. Plant operations control

Whereas the previous strategy was concerned with the control of the individual manufacturing process, this strategy is concerned with **control at the plant level**. It attempts to manage and coordinate the aggregate operations in the plant more efficiently.

*Its implementation usually involves **a high level of computer networking** within the factory.*

10. Computer-integrated manufacturing (CIM)

Taking the previous strategy one level higher, we have the **integration of factory operations with engineering design** and the business functions of the firm.

CIM involves extensive use of:

1. Computer applications,
2. Computer data bases, and
3. Computer networking throughout the enterprise.

AUTOMATION MIGRATION STRATEGY

Phase 1 – Manual production

Manual production using single station manned cells operating independently.This is used for introduction of the new product for reasons already mentioned: **quick and low cost tooling to get started**.

Phase 2 – Automated production

Automated production using **single station automated cells** operating independently. As demand for the product grows, and it becomes clear that automation can be justified, then the single stations are automated to reduce labor and increase production rate.

Phase 3 – Automated integrated production

Automated integrated production using **a multistation automated system** with serial operations and automated transfer of work units between stations.

When the company is certain that the product will be produced in mass quantities and for several years, then integration of the single station automated cells is warranted to **further reduce labor** and **increase production rate**.

MANUFACTURING INDUSTRIES AND PRODUCTS

Manufacturing is an important commercial activity, carried out by companies that sell products to customers. The type of manufacturing performed by a company depends on the kinds of products it makes. Let us first take a look at the scope of the manufacturing industries and then consider their products.

Manufacturing Industries. Industry consists of enterprises and organizations that produce and/or supply goods and/or services. Industries can be classified as primary, secondary, and tertiary. *Primary industries* are those that cultivate and exploit natural resources, such as agriculture and mining. *Secondary industries* convert the outputs of the primary industries into products. Manufacturing is the principal activity in this category, but the secondary industries also include construction and power utilities. *Tertiary industries* constitute the service sector of the economy. A list of specific industries in these categories is presented in Table 2.1.

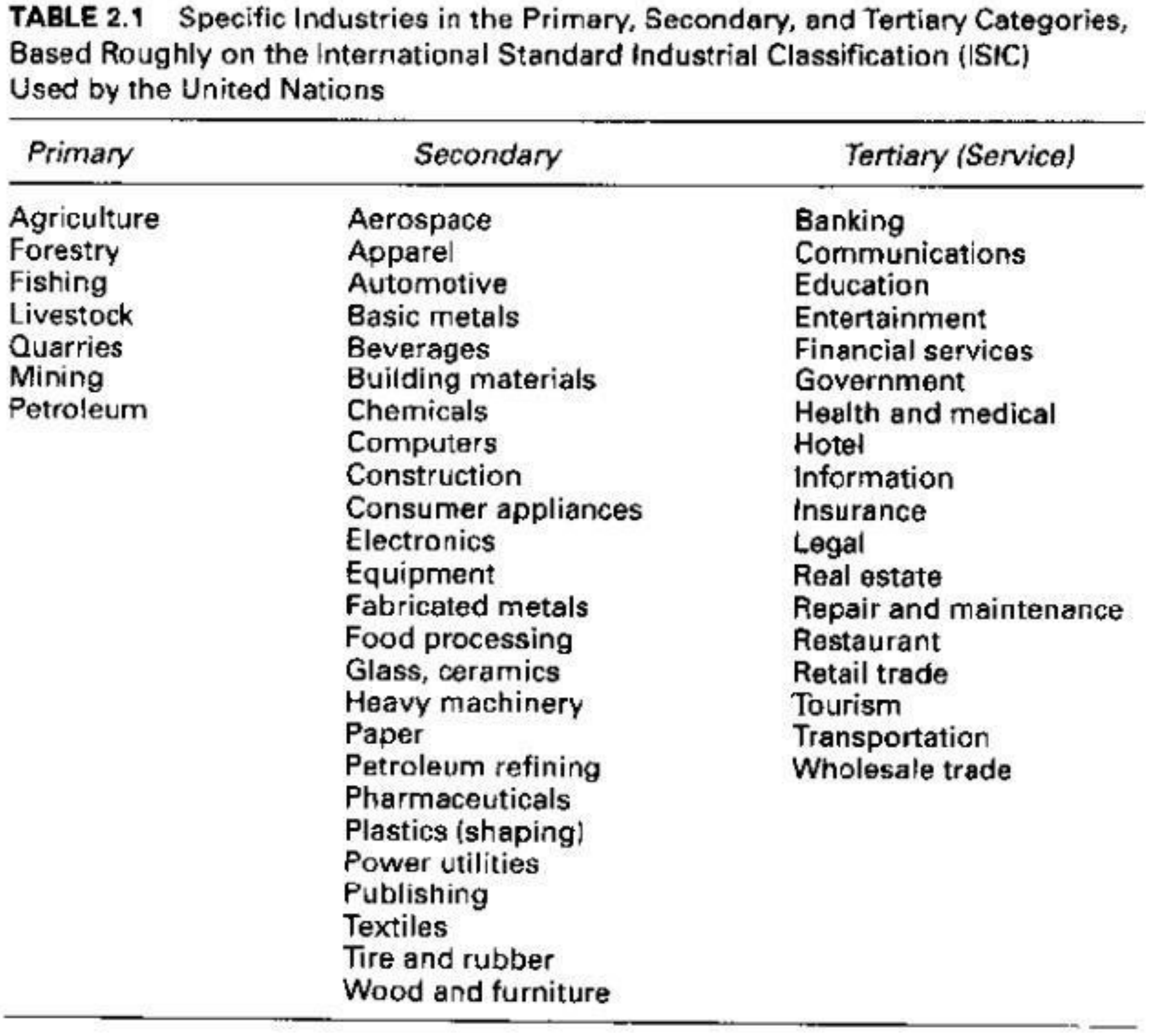


TABLE 2.1 Specific Industries in the Primary, Secondary, and Tertiary Categories, Based Roughly on the International Standard Industrial Classification (ISIC) Used by the United Nations

Primary	*Secondary*	*Tertiary (Service)*
Agriculture	Aerospace	Banking
Forestry	Apparel	Communications
Fishing	Automotive	Education
Livestock	Basic metals	Entertainment
Quarries	Beverages	Financial services
Mining	Building materials	Government
Petroleum	Chemicals	Health and medical
	Computers	Hotel
	Construction	Information
	Consumer appliances	Insurance
	Electronics	Legal
	Equipment	Real estate
	Fabricated metals	Repair and maintenance
	Food processing	Restaurant
	Glass, ceramics	Retail trade
	Heavy machinery	Tourism
	Paper	Transportation
	Petroleum refining	Wholesale trade
	Pharmaceuticals	
	Plastics (shaping)	
	Power utilities	
	Publishing	
	Textiles	
	Tire and rubber	
	Wood and furniture	

In this book, we are concerned with the secondary industries (middle columnin Table 2.1), which are composed of the companies engaged in manufacturing. Itis useful to distinguish the process industries from the industries that make discrete parts and products. The process industries include chemicals, pharmaceuticals, petroleum, basic metals, food, beverages, and electric power generation. The discrete product industries include automobiles, aircraft, appliances, computers, machinery, and the component parts that these products are assembled from. The International Standard Industrial Classification (ISIC) of industries according to types of products manufactured is listed in Table 2.2. In general, the process industries are included within ISIC codes 31–37, and the discrete product manufacturing industries are included in ISIC codes 38 and 39. However, it must be acknowledged that many of the products made by the process industries are finally sold to the consumer in discrete units. For example, beverages are sold in bottles and cans. Pharmaceuticals are often purchased as pills and capsules.

Production operations in the process industries and the discrete product industries can be divided into continuous production and batch production.The differences are shown in Figure 2.2. *Continuous production* occurs when the production equipment is used exclusively for the given product, and the output of the product is uninterrupted. In the process industries, continuous production means that the process is carried out on a continuous stream of material, with no interruptions in the output flow, as suggested by Figure 2.2(a) Once operating in steady state, the process does not depend on the length of time it is operating. The material being processed is likely to be in the form of a liquid, gas, powder, or similar physical state. In the discrete manufacturing industries, continuous production means 100% dedication of the production equipment to the part or product, with no breaks for product changeovers. The individual units of production are identifiable, as in Figure 2.2(b).

Batch production occurs when the materials are processed in finite amounts or quantities. The finite amount or quantity of material is called a *batch* in both the process and discrete manufacturing industries. Batch production is discontinuous because there are interruptions in production between batches. The reason for using batch production is

TABLE 2.2 International Standard Industrial Classification (ISIC) Codes for Various Industries in the Manufacturing Sector

TABLE 2.2 International Standard Industrial Classification (ISIC) Codes for Various Industries in the Manufacturing Sector

Basic Code	*Products Manufactured*
31	Food, beverages (alcoholic and nonalcoholic), tobacco
32	Textiles, wearing apparel, leather goods, fur products
33	Wood and wood products (e.g., furniture), cork products
34	Paper, paper products, printing, publishing, bookbinding
35	Chemicals, coal, petroleum, plastic, rubber, products made from these materials, pharmaceuticals
36	Ceramics (including glass), nonmetallic mineral products (e.g., cement)
37	Basic metals (e.g., steel, aluminum, etc.)
38	Fabricated metal products, machinery, equipment (e.g., aircraft, cameras, computers and other office equipment, machinery, motor vehicles, tools, televisions)
39	Other manufactured goods (e.g., jewelry, musical instruments, sporting goods, toys)

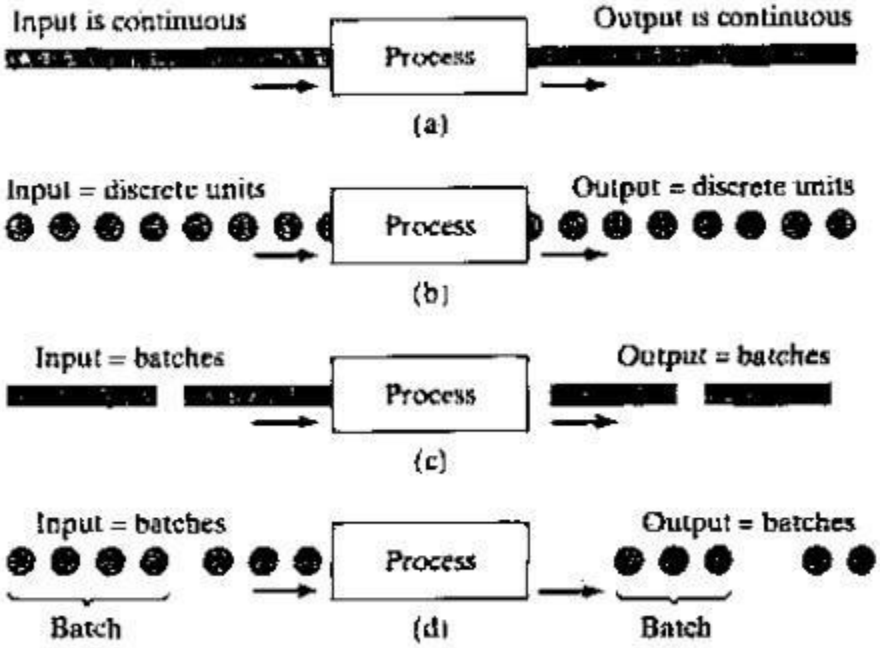


Figure 2.2 Continuous and batch production in the process and discrete manufacturing industries: (a) continuous production in the process industries, (b) continuous production in the discrete manufacturing industries, (c) batch production in the process industries, and (d) batch production in the discrete manufacturing industries.

because the nature of the process requires that only a finite amount of material can be accommodated at one time (e.g., the amount of material might be limited by the size of the container used in processing) or because there are differences between the parts or products made in different batches (e.g., a batch of 20 units of part A followed by a batch of 50 units of part B in a machining operation, where a setup changeover is required between batches because of differences in tooling and fixturing required). The differences in batch production between the process and discrete manufacturing industries are portrayed in Figure 2.2(c) and (d). Batch production in the process industries generally means that the starting materials are in liquid or bulk form, and they are processed altogether as a unit. By contrast, in the discrete manufacturing industries, a batch is a certain quantity of work units, and the work units are usually processed one at a time rather than altogether at once. The number of parts in a batch can range from as few as one to as many as thousands of units.

Manufactured Products. As indicated in Table 2.2, the secondary industries include food, beverages, textiles, wood, paper, publishing, chemicals, and basic metals (ISIC codes 31–39). The scope of our book is primarily directed at the industries that produce discrete products (ISIC codes 38 and 39). The two groups interact with each other, and many of the concepts and systems discussed in the book are applicable to the process industries, but our attention is mainly on the production of discrete hardware, which ranges from nuts and bolts to cars, airplanes, and digital computers. Table 2.3 lists the manufacturing industries and corresponding products for which the production systems in this book are most applicable.

Final products made by the industries listed in Table 2.3 can be divided into two major classes: consumer goods and capital goods. *Consumer goods* are products purchased directly by consumers, such as cars, personal computers, TVs, tires, toys, and tennis rackets. *Capital goods* are products purchased by other companies to produce goods and supply services. Examples of capital goods include commercial aircraft, mainframe computers, machine tools, railroad equipment, and construction machinery.

In addition to final products, which are usually assembled, there are companies in industry whose business is primarily to produce *materials, components*, and *supplies* for the companies that make the final products. Examples of these items include sheet steel, bar stock, metal stampings, machined parts, plastic moldings and extrusions, cutting tools, dies, molds, and lubricants. Thus, the manufacturing industries consist of a complex infrastructure with various categories and layers of intermediate suppliers that the final consumer never deals with.

MANUFACTURING OPERATIONS

There are certain basic activities that must be carried out in a factory to convert raw materials into finished products. Limiting our scope to a plant engaged in making discrete products, the factory activities are: (1) processing and assembly operations, (2) material handling, (3) inspection and test, and (4)coordination and control.

The first three activities are the physical activities that ―touch‖ the product as it is being made. Processing and assembly operations alter the geometry, properties, and/or appearance of the work unit. They add value to the product. The product must be moved from one operation to the next in the manufacturing sequence, and it must be inspected and/or tested to insure high quality. It is sometimes argued that these material handling and inspection activities not add value to the product. However, our viewpoint is that value is added through the totality of manufacturing operations performed on the product. Unnecessary operations, whether they are processing, assembly, material handling, or inspection, must be eliminated from the sequence of steps performed to complete a given product.

1 Processing and Assembly Operations

Manufacturing processes can be divided into two basic types: (1) processing operations and (2) assembly operations. A *processing operation* transforms a work material from one state of completion to a more advanced state that is closer to the final desired part or product. It adds value by changing the geometry, properties, or appearance of the starting material. In general, processing operations are performed on discrete work parts, but some processing operations are also applicable to assembled items, for example, painting a welded sheet metal car body. An *assembly operation* joins two or more components to create a new entity, which is called an assembly, subassembly, or some other term that refers to the specific joining process.

Processing Operations. A processing operation uses energy to alter a work part’s shape, physical properties, or appearance to add value to the material. The forms of energy include mechanical, thermal, electrical, and chemical. The energy is applied in a controlled way by means of machinery and tooling. Human energy may also be required, but human workers are generally employed to control the machines, to oversee the operations, and to load and unload parts before and after each cycle of operation. A general model of a processing operation is illustrated in Figure 2.1(a). Material is fed into the process, energy is applied by the machinery and tooling to transform the material, and the completed workpart exits the process. As shown in our model, most production operations produce waste or scrap, either as a natural byproduct of the process (e.g., removing material as in machining) or in the form of occasional defective pieces. An important objective in manufacturing is to reduce waste in either of these forms.

More than one processing operation are usually required to transform the starting material into final form. The operations are performed in the particular sequence to achieve the geometry and/or condition defined by the design specification.

Three categories of processing operations are distinguished: (1) shaping operations,

(2) property–enhancing operations, and (3) surface processing operations. *Shaping operations* apply mechanical force or heat or other forms and combinations of energy to effect a change in geometry of the work material.There are various ways to classify these processes. The classification used here is based on the state of the starting material, by which we have four categories:

1. *Solidification processes*. The important processes in this category are *casting* (for metals) and *moulding* (for plastics and glasses), in which the starting material is a heated liquid or semifluid, in which state it can be poured or otherwise forced to flow into a mould cavity where it cools and solidifies, taking a solid shape that is the same as the cavity.

2. *Particulate processing*. The starting material is a powder. The common technique involves *pressing* the powders in a die cavity under high pressure to cause the powders to take the shape of the cavity. However, the compacted work part lacks sufficient strength for any useful application. To increase strength, the part is then *sintered*— heated to a temperature

below the melting point, which causes the individual particles to bond together. Both metals (powder metallurgy) andceramics can be formed by particulate processing.

3. *Deformation processes*. In most cases, the starting material is a ductile metal that is shaped by applying stresses that exceed the metal's yield strength. To increase ductility, the metal is often heated prior to forming. Deformation processes include *forging*, *extrusion*, and *rolling*. Also included in this category are sheet metal processes such as *drawing*, *forming*, and *bending*.

4. *Material removal processes*. The starting material is solid (commonly a metal, ductile or brittle), from which excess material is removed from the starting workpiece so that the resulting part has the desired geometry. Most important in this category are *machining* operations such as *turning*, *drilling*, and *milling*, accomplished using cutting tools that are harder and stronger than the work metal. *Grinding* is another common process in this category, in which an abrasive grinding wheel is used to remove material. Other material removal processes are known as *nontraditional processes* because they do not use traditional cutting and grinding tools. Instead, they are based on lasers, electron beams, chemical erosion, electric discharge, or electrochemical energy.

Property–enhancing operations are designed to improve mechanical or physical properties of the work material. The most important property–enhancing operations involve *heat treatments*, which include various temperatureinduced strengthening and/or toughening processes for metals and glasses. *Sintering* of powdered metals and ceramics, mentioned previously, is also a heat treatment, which strengthens a pressed powder workpart. Propertyenhancing operations do not alter part shape, except unintentionally in some cases, for example, warping of a metal part during heat treatment or shrinkage of a ceramic part during sintering.

Surface processing operations include: (1) cleaning, (2) surface treatments, and (3) coating and thin film deposition processes. *Cleaning* includes both chemical and mechanical processes to remove dirt, oil, and other contaminants from the surface. *Surface* *treatments* include mechanical working, such as shot peening and sand blasting, and physical processes, like diffusion and ion implantation. *Coating* and *thin film deposition* processes apply a coating of material to the exterior surface of the work part. Common coating processes include *electroplating*, *anodizing* of aluminum, and organic *coating* (call it *painting*). Thin film deposition processes include *physical vapor deposition* and *chemical vapor deposition* to form extremely thin coatings of various substances. Several surface processing operations have been adapted to fabricate semiconductor materials (most commonly silicon) into integrated circuits for microelectronics. These processes include chemical vapor deposition, physical vapor deposition, and oxidation. They are applied to very localized areas on the surface of a thin wafer of silicon (or other semiconductor material) to create the microscopic circuit.

3. *Assembly Operations.* The second basic type of manufacturing operation is assembly, in which two or more separate parts are joined to form a new entity. Components of the new entity are connected together either permanently or semi permanently. Permanent joining processes include *welding*, *brazing*, *soldering*, and *adhesive bonding*. Theycombine parts by forming a joint that cannot be easily disconnected. *Mechanical assembly* methods are available to fasten two (or more) parts together in a joint that can be conveniently disassembled. The use of *threaded fasteners* (e.g., screws, bolts, nuts) are important traditional methods in this category. Other mechanical assembly techniques that form a permanent connection include *rivets*, *press fitting*, and *expansion fits*. Special assembly methods are used in electronics. Some of the methods are identical to or adaptations of the above techniques. For example, soldering is widely used in electronics assembly. Electronics assembly is concerned primarily with the assembly of components (e.g., integrated circuit packages) to printed circuit boards to produce the complex circuits used in so many of today’s products.

2 Other Factory Operations

Other activities that must be performed in the factory include material handling and storage, inspection and testing, and coordination and control.

Material Handling and Storage. A means of moving and storing materials between processing and/or assembly operations is usually required. In most manufacturing plants, materials spend more time being moved and stored than being processed. In some cases, the majority of the labor cost in the factory is consumed in handling, moving, and storing materials. It is important that this function be carried out as efficiently as possible. In Part II of our book, we consider the material handling and storage technologies that are used in factory operations.

Eugene Merchant, an advocate and spokesman for the machine tool industry for many years, observed that materials in a typical metal machining batch factory or job shop spend more time waiting or being moved than in processing [3]. His observation is illustrated in Figure 2.3. About 95% of a part's time is spent either moving or waiting (temporary storage). Only 5% of its time is spent on the machine tool. Of this 5%, less than 30% of the time on the machine (1.5% of the total time of the part) is time during which actual cutting is taking place. The remaining 70% (3.5% of the total) is required for loading and unloading, part handling and positioning, tool positioning, gaging, and other elements of nonprocessing time. These time proportions provide evidence of the significance of material handling and storage in a typical factory.

Inspection and Test. Inspection and test are quality control activities. The purpose of *inspection* is to determine whether the manufactured product meets the established design standards and specifications. For example, inspection examines whether the actual dimensions of a mechanical part are within the tolerances indicated on the engineering drawing for the part. *Testing* is generally concerned with the functional specifications of the final product rather than with the individual parts that go into the product. For example, final testing of the product ensures that it functions and operates in the manner specified by the product designer. In Part IV of this text, we examine the inspection and testing function.

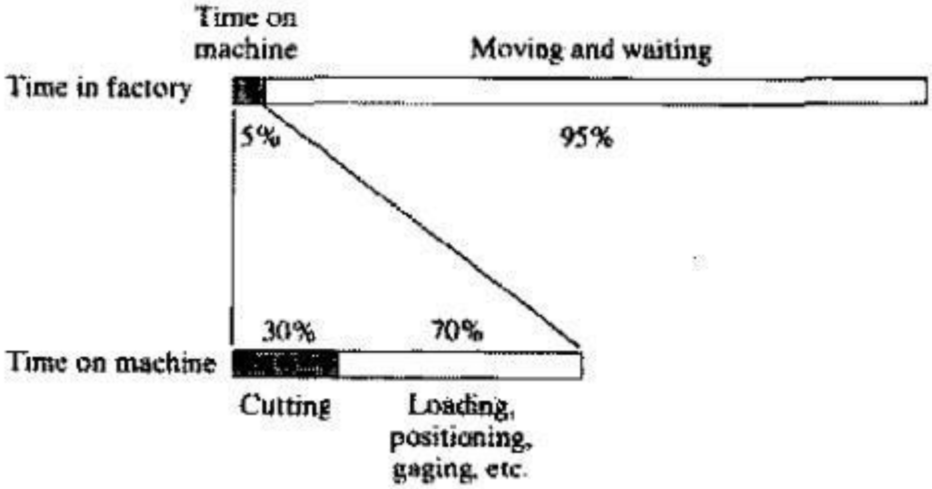


Figure 2.3 How time is spent by a typical part in a batch production machine shop [3].

Coordination and Control. Coordination and control in manufacturing includes both the regulation of individual processing and assembly operations as well as the management of plant level activities. Control at the process level involves the achievement of certain performance objectives by properly manipulating the inputs and other parameters of the process. Control at the process level is discussed in Part I of the book.

Control at the plant level includes effective use of labour, maintenance of the equipment, moving materials in the factory, controlling inventory, shipping products of good quality on schedule, and keeping plant operating costs at a minimum possible level..The manufacturing control function at the plant level represents the major point of intersection between the physical operations in the factory and the information processing activities that occur in production. We discuss many of these plant and enterprise level control functions in Parts IV and V.

PRODUCT/PRODUCTION RELATIONSHIPS

Companies organize their manufacturing operations and production systems as a function of the particular products they make. It is instructive to recognize that there are certain product parameters that are influential in determining how the products are manufactured. Let us consider four key parameters: (1) production quantity, (2) product variety, (3) complexity of assembled products, and (4) complexity of individual parts.

1 Production Quantity and Product Variety

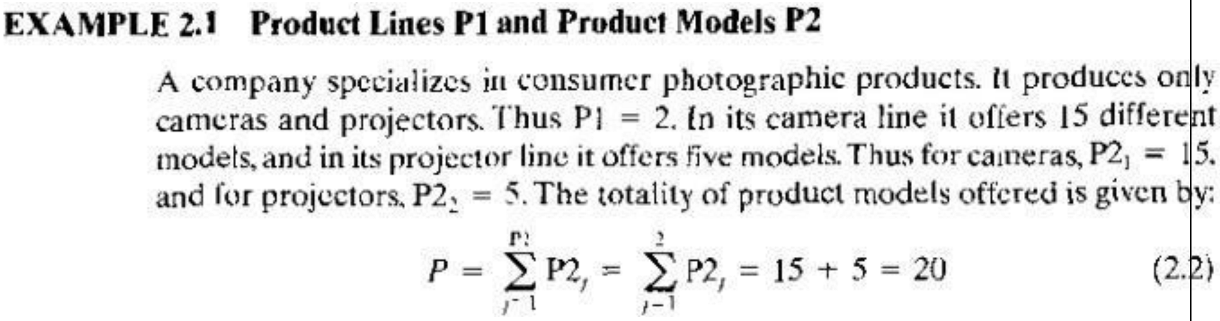
We previously discussed production quantity and product variety in Chapter 1 (Section 1.1). Let us develop a set of symbols to represent these important parameters. First, let Q=production quantity and P=product variety. Thus we can discuss product variety and production quantity relationships as PQ relationships.

Q refers to the number of units of a given part or product that are produced annually by a plant. Our interest includes both the quantities of each individual part or product style and the total quantity of all styles. Let us identify each part or product style by using the subscript j, so that Q_j=annual quantity of style j. Then let Q_f=total quantity of all parts or products made in the factory. Q_j and Q_f are related as follows:

$$Q_f = \sum_{j=1}^{P} Q_j \qquad (2.1)$$

where P=total number of different part or product styles, and j is a subscript to identify products, j=1, 2, ***p*** , P.

P refers to the different product designs or types that are produced in a plant. It is a parameter that can be counted, and yet we recognize that the difference between products can be great or small. In Chapter 1, we distinguished between hard product variety and soft product variety. *Hard product variety* is when the products differ substantially. *Soft product variety* is when there are only small differences between products. Let us divide the parameter P into two levels, as in a tree structure. Call them P1 and P2. P1 refers to the number of distinct product lines produced by the factory, and P2 refers to the number of models in a product line. P1 represents hard product variety, and P2 is for soft variety.



EXAMPLE 2.1 Product Lines P1 and Product Models P2

A company specializes in consumer photographic products. It produces only cameras and projectors. Thus P1 = 2. In its camera line it offers 15 different models, and in its projector line it offers five models. Thus for cameras, $P2_1 = 15$, and for projectors, $P2_2 = 5$. The totality of product models offered is given by:

$$P = \sum_{j=1}^{P1} P2_j = \sum_{j=1}^{2} P2_j = 15 + 5 = 20 \qquad (2.2)$$

2 Product and Part Complexity

How complex is each product made in the plant? Product complexity is a complicated issue. It has both qualitative and quantitative aspects. Let us deal with it using quantitative measures. For an assembled product, one possible indicator of *product complexity* is its number of components—the more parts, the more complex the product is. This is easily demonstrated by comparing the numbers of components in various assembled products, as in Table 2.4. Our list demonstrates that the more components a product has, the more complex it tends to be.

For a fabricated component, a possible measure of *part complexity* is the number of processing steps required to produce it. An integrated circuit, which is technically a monolithic silicon chip with localized alterations in its surface chemistry, requires hundreds of processing steps in its fabrication. Although it may measure only 9 mm (3 8 inch) on a side and is 0.5 mm (0.020 inch) thick, its complexity is orders of magnitude greater than a round washer of 9 mm (3 8 inch) outside diameter, stamped out of 0.80mm (1 32inch) thick stainless steel in one step. In Table 2.5, we have compiled a list of manufactured parts with the typical number of processing operations that would be required for each.

So, we have complexity of an assembled product defined as the number of distinct components; let n_p= the number of parts per product. And we have processing complexity of each part as the number of operations required to make it; let n_o= the number of operations or processing steps to make a part.We can draw some distinctions among production plants on the basis of n_p and n_o.As defined in Table 2.6, three different types of plant can be identified: parts producers, pure assembly plants, and vertically integrated plants.

TABLE 2.4 Typical Number of Separate Components in Various Assembled Products (Compiled from [2], [4], and Other Sources)

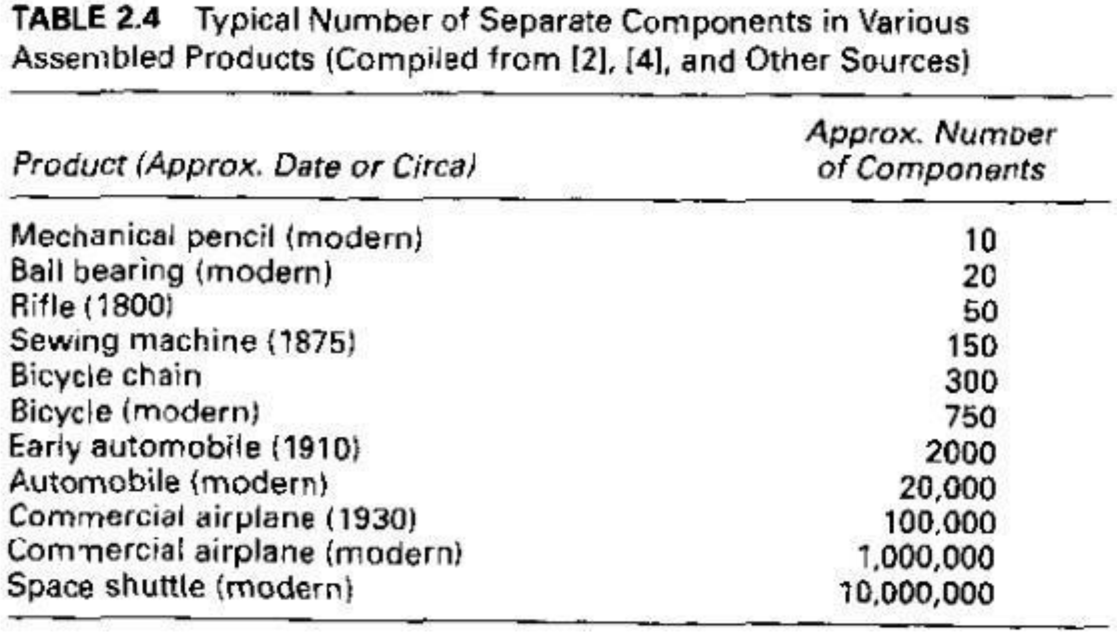
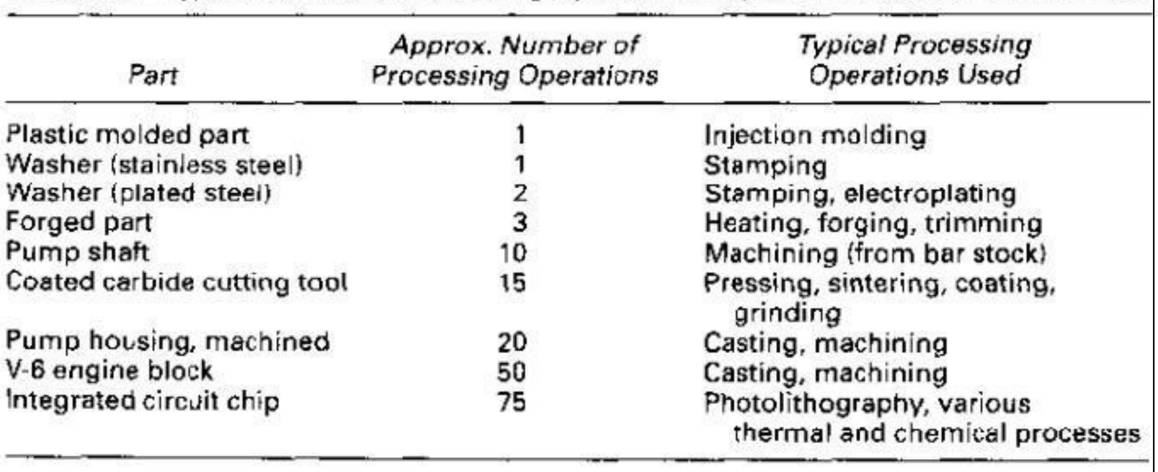


TABLE 2.4 Typical Number of Separate Components in Various Assembled Products (Compiled from [2], [4], and Other Sources)

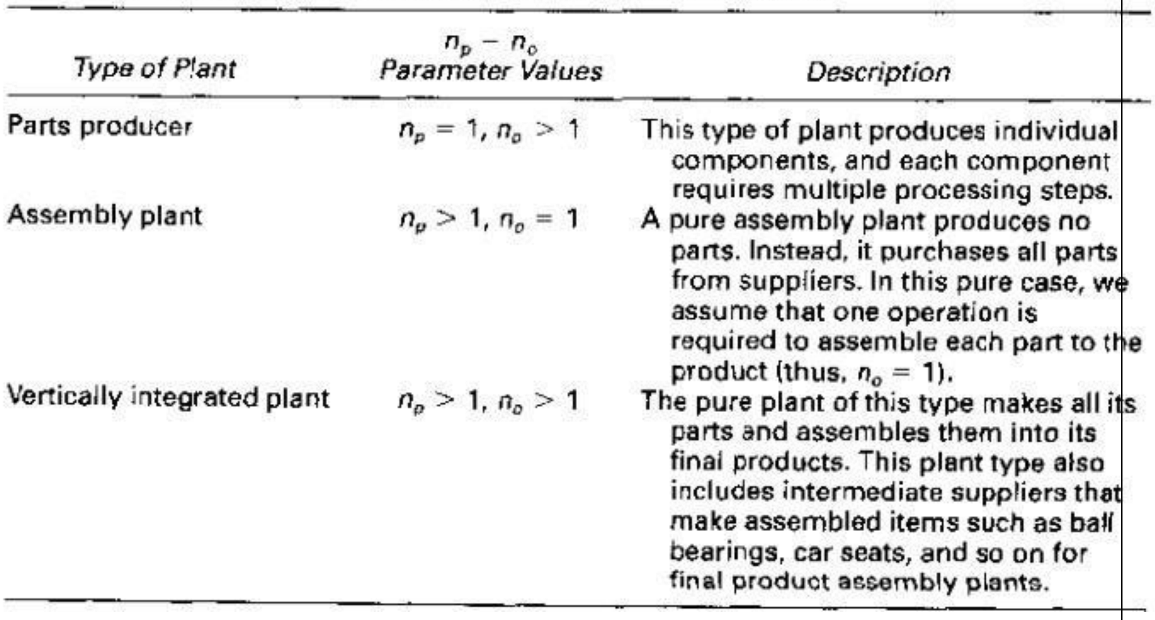
Product (Approx. Date or Circa)	*Approx. Number of Components*
Mechanical pencil (modern)	10
Ball bearing (modern)	20
Rifle (1800)	50
Sewing machine (1875)	150
Bicycle chain	300
Bicycle (modern)	750
Early automobile (1910)	2000
Automobile (modern)	20,000
Commercial airplane (1930)	100,000
Commercial airplane (modern)	1,000,000
Space shuttle (modern)	10,000,000

TABLE 2.5 Typical Number of Processing Operations Required To Fabricate Various Parts



Part	*Approx. Number of Processing Operations*	*Typical Processing Operations Used*
Plastic molded part	1	Injection molding
Washer (stainless steel)	1	Stamping
Washer (plated steel)	2	Stamping, electroplating
Forged part	3	Heating, forging, trimming
Pump shaft	10	Machining (from bar stock)
Coated carbide cutting tool	15	Pressing, sintering, coating, grinding
Pump housing, machined	20	Casting, machining
V-6 engine block	50	Casting, machining
Integrated circuit chip	75	Photolithography, various thermal and chemical processes

TABLE 2.6 Production Plants Distinguished by n_p and n_o Values



Type of Plant	$n_p - n_o$ *Parameter Values*	*Description*
Parts producer	$n_p = 1, n_o > 1$	This type of plant produces individual components, and each component requires multiple processing steps.
Assembly plant	$n_p > 1, n_o = 1$	A pure assembly plant produces no parts. Instead, it purchases all parts from suppliers. In this pure case, we assume that one operation is required to assemble each part to the product (thus, $n_o = 1$).
Vertically integrated plant	$n_p > 1, n_o > 1$	The pure plant of this type makes all its parts and assembles them into its final products. This plant type also includes intermediate suppliers that make assembled items such as ball bearings, car seats, and so on for final product assembly plants.

Let us develop some simple relationships among the parameters P, Q, n_p, and n_o that indicate the level of activity in a manufacturing plant.We will ignore the differences between P1 and P2 here. The totalnumber of products made annually in a plant is the sum of the quantities of the individual product designs, as expressed in previous Eq. (2.1). Assuming that the products are all assembled and that all component parts used in these products are made in the plant (no purchased components), then the total number of parts manufactured by the plant per year is given by:

$$n_{pf} = \sum_{j=1}^{P} Q_j n_{pj} \qquad (2.3)$$

where n_{pf}=total number of parts made in the factory (pc yr), Q_j=annual quantity of product style j (products yr), and n_{pj}=number of parts in product j (pc product).

Finally, if all parts are manufactured in the plant, then the total number of processing operations performed by the plant is given by:

$$n_{of} = \sum_{j=1}^{P} Q_j n_{pj} \sum_{k=1}^{n_{pj}} n_{ojk} \qquad (2.4)$$

where n_{of}=total number of operation cycles performed in the factory (ops yr), and n_{ojk}=number of processing operations for each part k, summed over the number of parts in product j, n_{pj}. Parameter n_{of} provides a numerical value for the total activity level in the factory.

We might try to simplify this to better conceptualize the situation by assuming that the number of product designs P are produced in equal quantities Q, all products have the same number of components n_p, and all components require an equal number of processing steps n_o. In this case, the total number of product units produced by the factory is given by:

$$Q_f = PQ \qquad (2.5)$$

The total number of parts produced by the factory is given by:

$$n_{pf} = PQn_p \qquad (2.6)$$

And the total number of manufacturing operation cycles performed by the factory is given by:

$$n_{of} = PQn_pn_o \qquad (2.7)$$

Using these simplified equations, consider the following example.

EXAMPLE 2.2 A Manufacturing Operations (and Production Systems) Problem

> Suppose a company has designed a new product line and is planning to build a new plant to manufacture this product line. The new line consists of 100 different product types, and for each product type

the company wants to produce 10,000 units annually. The products average 1000 components each, and the average number of processing steps required for each component is 10. All parts will be made in the factory. Each processing step takes an average of 1 min. Determine: (a) how many products, (b) how many parts, and
(c) how many production operations will be required each year, and
(d) how many workers will be needed for the plant, if it operates one shift for 250 day yr?

Solution: The total number of units to be produced by the factory is given by Eq (2.5):

Q=PQ=100*10,000=1,000,000 products annually.

The total number of parts produced is:

n_{pf}=PQn_p=1,000,000*1000=*1,000,000,000 parts annually*.

The number of distinct production operations is:

n_{of}=PQ$n_p n_o$=1,000,000,000*10=*10,000,000,000 operations*.

Let us try to estimate the number of workers required. First consider the total time to perform these operations. If each operation takes 1 min (1 60 hr),

Total time=10,000,000,000*1 60=166,666,667 hr

If each worker works 2000 hr yr (40 hr wk*50 wk yr), then the total number of workers required is:

$$w = \frac{166{,}666{,}667}{2000} = 83{,}333 \text{ workers.}$$

The factory in our example is a fully integrated factory. It would be abig factory. The number of workers we have calculated only includes direct labor. Add indirect labor, staff, and management, and the number increases to well over 100,000 employees. Imagine the parking lot. And inside the factory, the logistics problems of dealing with all of the products, parts, and operations would be overwhelming. No organization in its right mind would consider building or operating such a plant today—not even the federal government.

3 Limitations and Capabilities of a Manufacturing Plant

Companies do not attempt the kind of factory in our example. Instead, today’s factory is designed with a much more specific mission. Referred to as a *focused factory* [5], it is a plant which concentrates ―on a limited, concise, manageable set of products, technologies, volumes, and markets.‖ It is a recognition that a manufacturing plant cannot do everything. It must limit its mission only to a certain scope of products and activities in which it can best compete. Its size is typically limited to about 500 workers, althoughthat number may vary widely for different types of products and manufacturing operations.

Let us consider how a plant, or its parent company, limits the scope of its manufacturing operations and production systems. In limiting its scope, the plant in effect makes a set of deliberate decisions about what it will not try to do. Certainly one way to limit a plant’s scope is by avoiding being a fully integrated factory, at least to the extent of our Example 2.2. Instead, it specializes in being either a parts producer or an assembly plant. Just as it decides what it will not do, the plant must also decide on the specific technologies, products, and volumes in which it will specialize. These decisions define the plant’s intended manufacturingcapability. *Manufacturing capability* refers to the technical and physical limitations of a manufacturing firm and each of its plants. We can identify several dimensions of this capability: (1) technological processing capability, (2) physical size and weight of product, and (3) production capacity.

Technological Processing Capability. The technological processing capability of a plant (or company) is its available set of manufacturing processes. Certain plants perform machining operations, others roll steel billets into sheet stock, and others build automobiles. A machine shop cannot roll steel, and a rolling mill cannot build cars. The underlying feature that distinguishes these plants is the set of processes they can perform. Technological processing capability is closely related to the material being processed. Certain manufacturing processes are suited to certain materials, while other processes are suited to other materials. By specializing in a certain process or group of processes, the plant is simultaneously specializing in a certain material type or range of materials.

Technological processing capability includes not only the physical processes, but also the expertise possessed by plant personnel in these processing technologies. Companies are limited by their available processes.They must focus on designing and manufacturing products for which their technological processing capability provides a competitive advantage.

Physical Product Limitations. A second aspect of manufacturing capability is imposed by the physical product. Given a plant with a certain set of processes, there are size and weight limitations on the products thatcan be accommodated in the plant. Big, heavy products are difficult to move.To move products about, the plant must be equipped with cranes of large load capacity. Smaller parts and products made in large quantities can be moved by conveyor or fork lift truck.The limitation on product size and weight extends to the physical capacity of the manufacturing equipment as well. Production machines come in different sizes. Larger machines can be used to process larger parts. Smaller machines limit the size of the work that can be processed. The set of production equipment, material handling, storage capability, and plant size must be planned for products that lie withina certain size and weight range.

Production Capacity. A third limitation on a plant's manufacturing capability is the production quantity that can be produced in a given time period (e.g., month or year). This quantity limitation is commonly called *plant capacity*, or *production capacity*, which is defined as the maximum rate of production per period that a plant can achieve under assumed operating conditions. The operating conditions refer to number of shifts per week, hours per shift, direct labor manning levels in the plant, and similar conditions under which the plant has been designed to operate. Thesefactors represent inputs to the manufacturing plant. Given these inputs, how much output can the factory produce?

Plant capacity is often measured in terms of output units, such as annual tons of steel produced by a steel mill, or number of cars produced by a final assembly plant. In these cases, the outputs are homogeneous, more or less.In cases where the output units are not homogeneous, other factors may be more appropriate measures, such as available labor hours of productive capacity in a machine shop that produces a variety of parts.

MODULE 2

BASIC ELEMENTS OF *AN AUTOMATED SYSTEM*

An automated system consists of three basic elements: (1) *power* to accomplish the process and operate the system. (2) a *program of instructions* to direct the process, and (3) a *control system* to actuate the instructions. The relationship amongst these elements is illustrated in Figure
3.2. All systems that qualify as being automated include these three basic elements in one form or another.

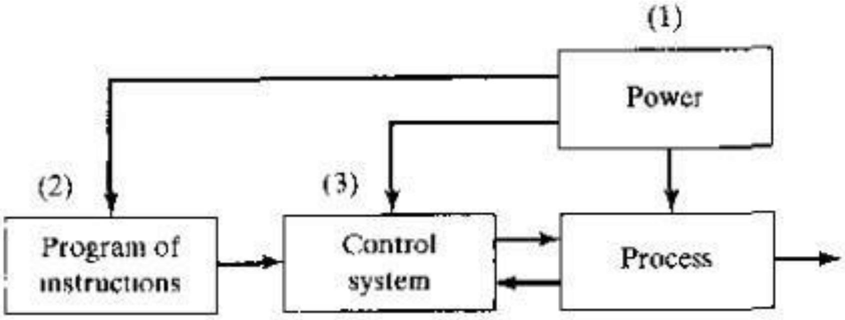


Figure 3.2 Elements of an automated system: (1) power, (2) program of instructions, and (3) control systems.

Power to Accomplish the Automated Process

An automated system is used to operate some process, and power is required to drive the system!.'; as well as the controls. The principal source of power in automated systems is electricity. Electric power has many advantages in automated as well as non automated processes

Electrical power is widely "used at moderate cost. It is an important part of our industrial infrastructure

Electrical power can be readily converted 10 alternative energy forms: mechanical, thermal, light, acoustic, hydraulic, and pneumatic.

Electrical power at low levels can be used to accomplish functions such as sigl1al transmission, information processing, and data storage and communication.

Electrical energy can be stored in longlife batteries for use in locations where an external source of electrical power is not conveniently available.

Alternative power sources include fossil fuels, solar energy, water, andwind. However, their exclusive use is rare in automated systems. In many cases when alternative power sources are used to drive the process itself, electrical power is used for the controls that automate the operation. For example, in casting or heat treatment, the furnace may be heated by fossil fuels. but the control system to regulate temperature and time cycle is electrical.

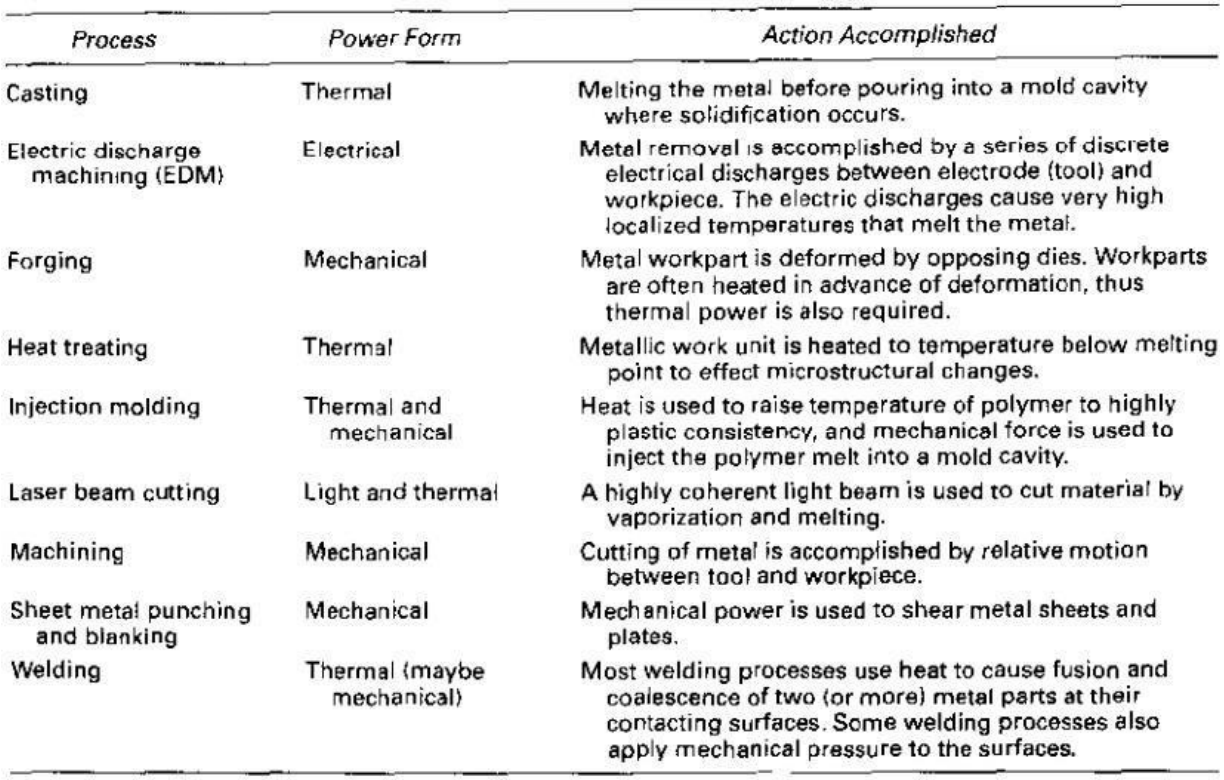
In other cases, the energy from these alternative sources is converted to electric power to operate both the process and its automation. When solar energy is used as a power source for an automated system. it is generally converted in this way.

Power for the Process. In production, the term *process* refers to the manufacturing operation that is performed on a work unit. In Table 3.1, a list of common manufacturing processes is compiled along with the form of power required and the resulting action on the work unit. Most of the power in manufacturing plants is consumed by these kinds of operations, The "power form" indicated in the middle column of the table refers to the energy that is applied directly to the process. As indicated above, the power source for each operation is usually converted from electricity.

In addition to driving the manufacturing process itself, power is also required for the following material handling functions'

Loading and unloading the work unit. All of the processes listed in Table 3.1 are accomplished on discrete parts. These parts must be moved into the proper position

TABLE 3.1 Common Manufacturing Processes and Their Power Requirements



Process	*Power Form*	*Action Accomplished*
Casting	Thermal	Melting the metal before pouring into a mold cavity where solidification occurs.
Electric discharge machining (EDM)	Electrical	Metal removal is accomplished by a series of discrete electrical discharges between electrode (tool) and workpiece. The electric discharges cause very high localized temperatures that melt the metal.
Forging	Mechanical	Metal workpart is deformed by opposing dies. Workparts are often heated in advance of deformation, thus thermal power is also required.
Heat treating	Thermal	Metallic work unit is heated to temperature below melting point to effect microstructural changes.
Injection molding	Thermal and mechanical	Heat is used to raise temperature of polymer to highly plastic consistency, and mechanical force is used to inject the polymer melt into a mold cavity.
Laser beam cutting	Light and thermal	A highly coherent light beam is used to cut material by vaporization and melting.
Machining	Mechanical	Cutting of metal is accomplished by relative motion between tool and workpiece.
Sheet metal punching and blanking	Mechanical	Mechanical power is used to shear metal sheets and plates.
Welding	Thermal (maybe mechanical)	Most welding processes use heat to cause fusion and coalescence of two (or more) metal parts at their contacting surfaces. Some welding processes also apply mechanical pressure to the surfaces.

and orientation for the process 10 be performed and power required for this transport and placement function. At the conclusion of the process, the work unit must similarly be removed. If the process is completely automated, then some form of mechanized power is used. If the process is manually operated or serni autornated, then human power may be used to position and locate the work unit *Materia! transport be/ween operations.* In addition 10 loading and unloading at a given operation. the work units must be moved between operations.

Power for Automation. Above and beyond the basic power requirements for the manufacturing operation, additional power is required for automation. The additional power is used for the following functions:

Control unit. Modern industrial controllers are based on digital computers, which require electrical power to read the program of instructions, make the control calculations, and execute the instructions by transmitting the propercommands to the actuating devices.

PnweT to nell/are the control signals. The commands sent by the controller unit are carried out by means of electromechanical devices, such as switches and motors, called *actuators* (Section 5.2). The commands are generally transmitted by means of low voltage control signals. To accomplish the commands, the actuators require more power,

and so the control signals must he amplified to provide the proper power level for the actuating device

Data acquisition and information processing. In most control systems, data must be collected from the process and used as input to the control algorithms. In addition, a requirement of the process may include keeping records of process performance or product quality. These data acquisition and record keeping functions require power, although in modest amounts.

Program of Instructions

The actions performed b) an automated process arc defined by a program of instructions Whether the manufacturing operation involves low, medium, or high production (Section 1.1), each part or product style made in the operation requires one or more processing steps that are unique to that style, These processing steps are performed during a work cycle. A new part is completed during each work cycle (in some manufacturing operations, morethan one part is produced during the work cycle; e.g., a plastic injection molding operation may produce multiple parts each cyde using a multiple cavity mold). The particular processing steps for the work cycle are specified in a *work cycle program.* Work cycle programs are called *part programs* in numerical control (Chapter 6). Other process control applications use different names for this type of program.

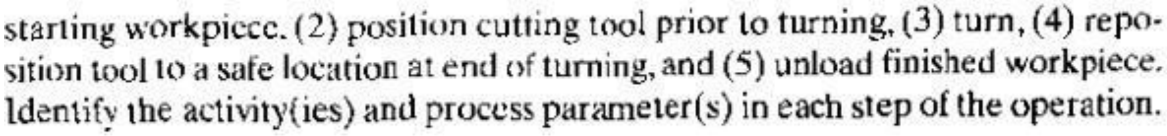
Work Cycle Programs. In the simplest automated processes, the work cycle consists of essentially one step, which is to maintain a single process parameter at a defined level, for example, maintain the temperature of a furnace at a designated value for the duration of a heat treatment cycle. (We assume that loading and unloading of the work units into and from the furnace is performed manually and is therefore not part of the automatic cycle.) In this case, programming simply involves sening the temperature dial on the furnace, 'Io change the program, the operator simply changes the temperature setting. An extension of this simple case is when the single step process is defined by more than one process parameter, for example, a furnace in which both temperature and atmosphere are controlled

In more complicated systems, the process involves a work cycle consisting of multiple steps that are repeated with no deviation from one cycle to the next. Most discrete part manufacturing operations are in this category A typical sequence of steps (simplified) is:

(1) load the part into the production machine, (2) perform the process, and (3) unload the part. During each step, there are one or more activities that involve changes in one or more process parameters. *Process parameters* are mputs to the process. such as temperature setting of a furnace, coordinate axis value in a positioning system, valve opened or closed in a fluid flow system, and motor on or off. Process parameters are distinguished from *process variables*, which are outputs from the process; for example, the actual temperature of the furnace, the actual position of the axis, the actual flow rate of the fluid in the pipe, and the rotational speed of the motor. As our list of examples suggests, the changes in process parameter values may be continuous (gradual changes during the processing step; for example, gradually increasing temperature during a heat treatment cycle) or discrete (stepwise changes; for example, on/off). Different process parameters filly be involved in each step.

EXAMPLE 3.1 An Automated Turning Operation

Consider an automated turning operation in which a cone shaped geometry is generated. Assume the system is automated and that a robot is used to load and unload the work unit. The work cycle consists of the following steps: (1) load



starting workpiece. (2) position cutting tool prior to turning, (3) turn, (4) reposition tool to a safe location at end of turning, and (5) unload finished workpiece. Identify the activity(ies) and process parameter(s) in each step of the operation.

Solution' In step (1). the activities consist of the robot manipulator reaching for the raw workpart Iifting and positioning the part into the chuck jaws of the lathe, then removing the manipulator to a safe position to await unloading. The process parameters for these activities are the axis values of the robot manipulator (which change continuously). the gripper value (open or closed).and the chuck jaw value (open or closed)

In step (2). the activity involves the movement of the cutting tool to a "ready' position, The process parameters associated with this activity are the rand zaxis position of the tool

Step (3) is the turning operation. It requires the simultaneous control of three process parameters: rotational speed of the workpiece (rev/min), feed (rnrn/rev), and radial distance of the cutting tool from the axis of rotation. To cut the conical shape, radial distance must be changed continuously at a constant rate for each revolution of the workpiece For a consistent finish on the surface, the rotational speed must be continuously adjusted to maintain a constant surface speed (m/min); and [or equal feed marks on the surface, the feed mll~tbe set at a constant value. Depending on the angle of the cone, multiple turning passes may be required to gradually generate the desired contour. Each pass represents an additional step in the sequence.

Steps (4) and (5) involve the reverse activities as steps (2) and (1), respectively, and the process parameters are the same.

Many production operations consist of multiple steps, sometimes more complicated than our turning example. Examples of these operations include automatic screw machine cycles, sheet metal stamping operations, plastic injection molding, and die casting. Each of these manufacturing processes has been used for many decades. In earlier versions of these operations. the work cycles were controlled by hardware components, such as limit switches. timers, cams, and electromechanical reteys In effect, the hardware components and their arrangements served (IS the program of instructions that directed the sequence of steps in the processing cycle. Although these devices were quite adequate in performing their sequencing function. they suffered from the following disadvantages: (I) They often required considerable time to design and fabricate, thus forcing the production equipment to be used for batch production only; (2) making even minor changes in the program was difficult and time consuming; and (3) the program was in a physical form that is not readily compatible with computer data processing and communication.

Modern controllers used in automated systems are based on digital computers. Instead of cams, timers, rclays, and other hardware devices, the programs for computer controlled equipment are contained in magnetic tape, diskettes, compact disks (CDROMs), computer memory, and other modern storage technologies. Virtnally all new equipment that perform the above mass production operations are designed with some type of computer controller to execute their respective processing cycles. The use of digital computers the process controller allows improvements and upgrades to be made In the control programs, such as the .addition of control functions not foreseen during initial equipment design. T~cse kinds ot control changes are often difficult to make with the previous hardware devices.

The work cycle may include manual steps, where the operator performs certain activities during the work cycle. and the automated system performs the rest. A common example is the loading and unloading of parts by the operator uno and from a numerical control machine between machining cycles. where the machine performs the cutting operation underpart program control. Initiation of the cutting operation of each cycle is triggered hy rbe operator activating a "start" button after the part has been loaded.

Decision Making in the Programmed Work Cycle. In our previous discussion of automated work cycles. the only two features of *the* work cycle are (I) the number and Sequence of processing steps and (2) the process parameter changes in each step. Each work cycle consists of the same steps and associated process parameter changes with no variation fromone cycle to the next. The program of instructions is repealed each work cycle without deviation. In fact, many automated manufacturing operations require decisions to be made during the programmed work cycle to cope with variations in the cycle. **10** many cases, the variations are routine elements of the cycle, and the corresponding instructions for dealing with them are incorporated into the regular part program. Base cases include:

Operator interaction. Although the program of instructions is intended to be carried out without human interaction, the controller unit may require input data from a human operation in order to function. For example, in an automated engraving operations, the operator may have 10 enter the alphanumeric characters that are to be engraved on the work unit (e.g .. plaque, trophy, belt buckle). Having entered the characters, the engraving operation is accomplished automatically by the system. (An everyday example of operator interaction with an automated system is a bank customer using an automated teller machine. The customer must enter the codes mdieating what transaction is to be accomplished by the teller machine.)

Different part or product stvles processed by the system. In this instance, the automated system is programmed to perform different work cycles on different part or product styles. An example is an industrial robot that performs a series of spot welding operations on car bodies in a final assembly plant. These plants are often designed to build different body styles on the same automated assembly line, such as two door and four door sedans. As each car body enters a given welding station on the line, sensors identify which style it is, and the robot performs the correct series of welds for that style.

Variations in the staning work units. In many manufacturing operations the starting work units are not consistent. A *good* example is a sand casting as the starting work unit in a machining operation. The dimensional variations in the raw castings sometimes necessitate an extra machining pass to bring the machined dimension to the specified value. The part program must be coded to allow for the additional pass when necessary.

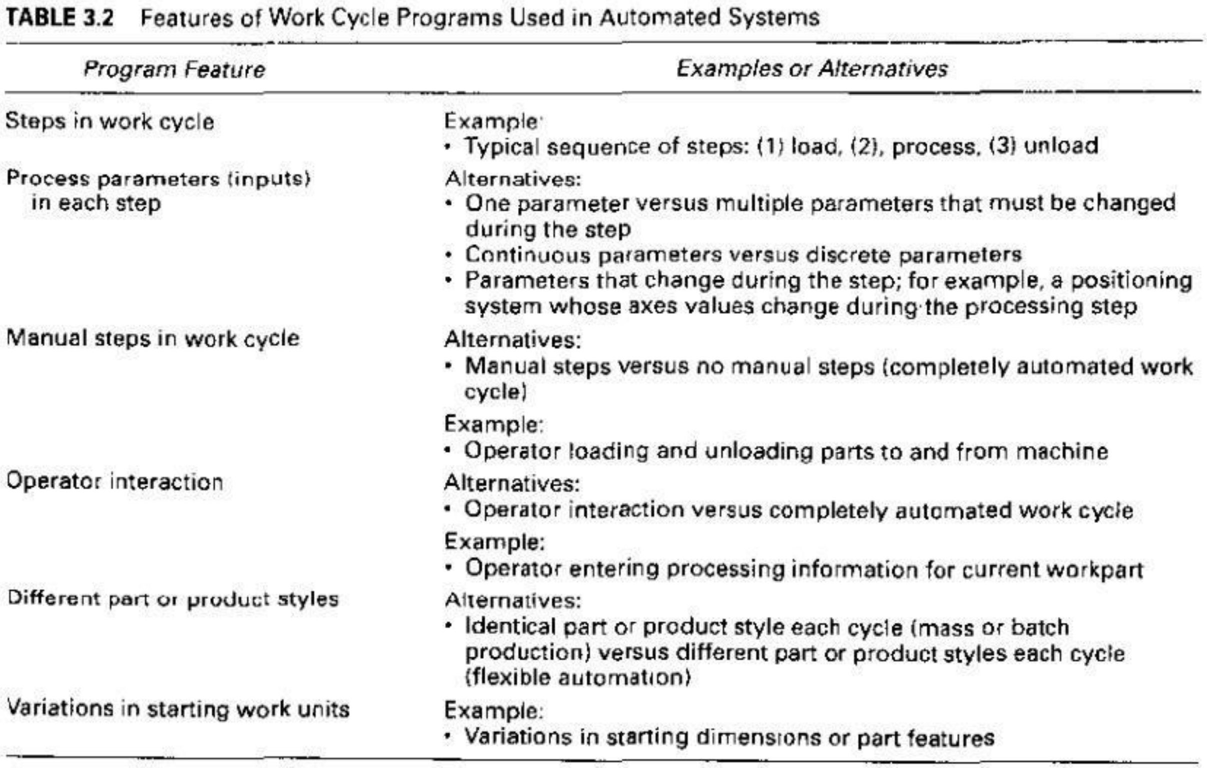


TABLE 3.2 Features of Work Cycle Programs Used in Automated Systems

Program Feature	*Examples or Alternatives*
Steps in work cycle	Example: • Typical sequence of steps: (1) load, (2), process, (3) unload
Process parameters (inputs) in each step	Alternatives: • One parameter versus multiple parameters that must be changed during the step • Continuous parameters versus discrete parameters • Parameters that change during the step; for example, a positioning system whose axes values change during the processing step
Manual steps in work cycle	Alternatives: • Manual steps versus no manual steps (completely automated work cycle) Example: • Operator loading and unloading parts to and from machine
Operator interaction	Alternatives: • Operator interaction versus completely automated work cycle Example: • Operator entering processing information for current workpart
Different part or product styles	Alternatives: • Identical part or product style each cycle (mass or batch production) versus different part or product styles each cycle (flexible automation)
Variations in starting work units	Example: • Variations in starting dimensions or part features

In all of these examples, the routine variations can be accommodated in the regular *work* cycle program. The program can be designed to respond to sensor or operator inputs by executing the appropriate subroutine corresponding to the input. **In** other cases, the variations in the work cycle are not routine at all. They are infrequent and unexpected, such as the failure of an equipment component. Itt these instances, the program must include contingency procedures or modifications in the sequence to copc with conditions that lie outside the normal routine. We discuss these measures later in the chapter in the context of advanced automation functions (Section3.2).

A variety of production situations and work cycle programs has been discussed here The features of work cycle programs (part programs) used to direct the operations of an automated system are summarized as in Table 3.2.

Control System

The control element of the automated system executes the program of instructions. The control system causes the process to accomplish its defined function. which for our purpose is to carry out some manufacturing operation. Let us provide a brief introduction to control systems here. The following chapter describes this important industrial technology in marc detail.

The controls in an automated system can be either closed loop or open loop. A *closed loup control system,* also known as a *feedback control system*. is one in which the output variable is compared with an input parameter, and any difference between the two is used to drive the output into agreement with the input.As shown in Figure 3.3. a closed loop control system consists of six basic elements: (I) input parameter, (2) process, (3) output van. able, (4) feedback sensor. (5) controller. and (0) actuator. The *input parameter*. often referred to as the *set point,* represents the desiredvalue of the output. **In** a home temperature can. trot system, the set point is the desired thermostat setting. The *process* is the operation or function beingcontrolled. In particular, it is the *output variable* that is being controlled in the Ioop.Jn the present discussion, the process of interest is usually a manufacturing operation, and the output variable is some process variable, perhaps a critical performance measure in the process, such as temperature or force or flow rate.A *sensor* is used to measure the output variable and close the loop between input and output. Sensors perform the feedback function in a closed loop control system. The controllercornpares the output with the input and makes the required adjustment in the process to reduce the difference between them. The adjustment is accomplished using one or more *actuators,* which are the hardware devices that physically carry out the control actions, such

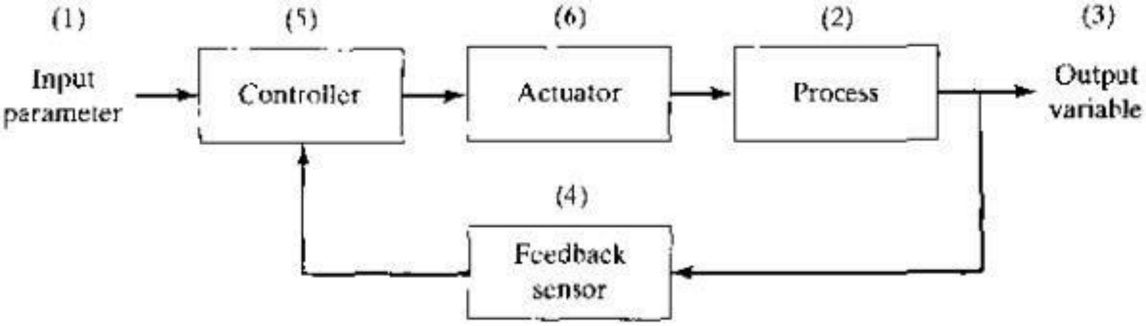


Figure 3.3 A feedback control system.

as an electric motor or a flow valve. It should be mentioned that OUT model in Figure 3.3 shows only one loop. Most industrial processes require multiple loops, one for each process variable that must be controlled

In contrast to the closed loop control system, an *open loop control system* operates without the feedback loop, as in Figure 3.4. In this case, the controls operate without measuring the output variable.so no comparison is made between the actual value of the output and the desired input parameter.The controller relies on an accurate model of the effect of its actuator 011the process variable. With an open loop system, there is always the risk that the actuator will not have the intended effect on the process, and that is the dis advantage of an open loop system.lt~ advantage is that it is generally simpler and less expensive than a closed loop system. Open loop systems are usually appropriate when the following conditions apply: (1) The actionsperformed by the control system are simple,

(2) the actuating function is very reliable, and (3) any reaction forces opposing the actuation are small enough to have no effect on the actuation. If these characteristics are not applicable, then a closed loop control system may be more appropriate.

Consider the difference between a closed loop and open loop system for the case of a positioning system. Positioning systems are common in manufacturing to locate a work part relative to a tool or workhead. Figure 3.5 illustrates the case of a closed loop positioning system.

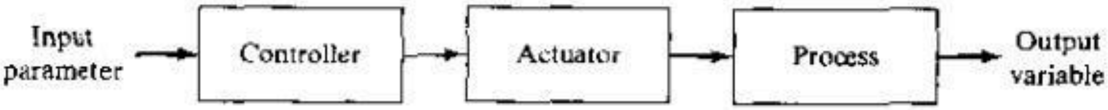


Figure 3.4 An open loop control system.

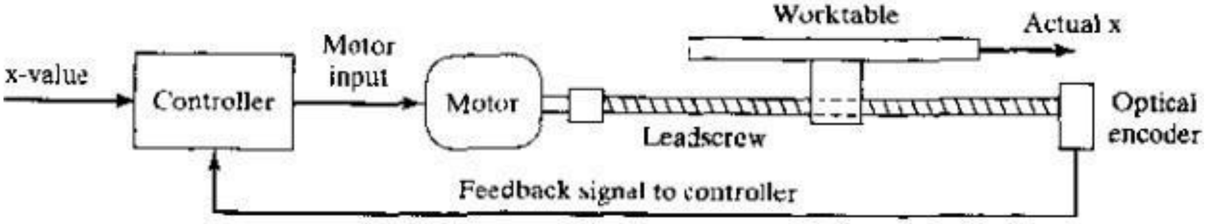


Figure 3.5 A (one-axis) positioning system consisting of a leadscrew driven by a dc servomotor.

In operation, the system is directed to move the worktable to a specified location as defined bv a coordinate value in a Cartesian (or other) coordinate system. Most positioning systems have at least two axes (e.g., an .r *y* positioning table) with a control system for each axis, but our diagram only illustrates one of these axes. A de servomotor connected to a Ieadscrew is a common actuator for each axis. A signal indicating the coordinate value (e.g .. xvalue) is sent from the controller to the motor that drives the leadscrew, whose rotation is converted into linear motion of the positioning table. As the table moves closer to the desired xco ordinate value. thedifference between the actual a position and the input .rvaluc is reduced. Theactual position is measured by a feedback sensor (e.g., an optical encoder). The controller continues to drive the motor until the actual table position corresponds to the input position value.

For the open loop case, the diagram for the positioning system would be similar to the preceding. except that no feedback loop is present and a stepper motor is used in place of the de servomotor. A stepper motor is designed to rotate a precise fraction of a tum for each pulse received from the controller. Since the motor shaft is connected to the leadscrew, and the leadscrew drives the worktable. each pulse converts into a small constant linear movement of *the* table. To move the table a desired distance. the number of pulses corresponding to thai distance is seut to the motor. Given the proper application, whose charactcrisrtcs match the preceding list of operating conditions, an open loop positioning system works with highreliability.

ADVANCED AUTOMATION FUNCTIONS

In addition to executing work cycle programs, an automated system may be capable of executing advanced functions that are nOI specific to a particular work unit. In general, the functions are concerned with enhancing the performance and safety of the equipment. Advanced automation functions include the following: (1) safety monitoring, (2) maintenance and repair diagnostics, and (3) error detection and recovery.

Advanced automation function> are made possible by special subroutines included in the program of tnsttuctluns. In some cases, the runcnons provide information only and

do not involve any physical actions by the control system, An example of this case includes reporting a list of preventive maintenance tasks that should be accomplished. Any actions taken on the basis of this report are decided by the human operators and managers of the system and not by the system itself 11\ othercases, the program of instructions must be physically executed by means of the control system using available actuators. A simple example of this case is a safety monitoring system that sounds an alarm when a human worker gets dangerously close to the automated system.

Safety Monitoring

One of the significant reasons for automating a manufacturing operation is to remove worker{s) from a hazardous working environment. An automated systemis often installed to perform a potentially dangerous operation that would otherwise be accomplished manually by human workers '.However, even in automated systems. workers are still needed *to* service the system. at periodic time intervals If not fulltime. Accordingly. it is important *that* the automated system be designed to operate safely when workers arc in attendance. In addition is essential that the automated system carry QUills proCI;:SS in a way that is not self destructive. Thus. there are two reasons for providing an automated system with a safety monitoring capability: (1) to protect human workers in the vicinity of the system ami (2) to protect the equipment associated with the system.

Safety monitoring means more than the conventional safety measures til ken in a ill: al· ufacturing operation, such as protective shields around the operation or the kinds of manual devices that might be utilized by human workers. such as emergency stop buttons. *Safety monitoring in* an automated system involves the use or sensors to track the system's operation and identify conditions and events that are unsafe or potentially unsafe. The safety monitoring system is programmed to respond to unsafe conditions in some appropriate way. Possible responses to various hazards might include one or more of the following:

complete stoppage of the automated system

sounding an alarm

reducing the operating speed of the process

taking corrective actions to recover from the safety violation

This last response is the most sophisticated and is suggestive of an intelligent machine performing some advanced strategy, This kind of response is applicable to a variety of possible mishaps, not necessarily confined to safety issues, and is called error detection and recovery (Section 3.2.3).

Sensors for safety monitoring range from very simple devices to highly sophisticated systems. The topic of sensor technology is discussed in Chapter 5 (Section 5.1). The following list suggests some of the possible sensors and their applications for safety monitoring:

Limit switches to detect proper positioning of a part in a work holding device so that the processing cycle can begin.

Photoelectric sensors triggered by the interruption of a light beam; this could be used to indicate that a part is in the proper position or to detect the presence of a human intruder into the work cell.

Temperature sensors to indicate that a metal work part is hot enough to proceed with a hot forging operation. If the work part is not sufficiently heated, then the metal's duetutty may be too low, and the forging dies might be damaged during the operation.

Heat or smoke detectors to sense fire hazards.

Pressure sensitive floor pads to detect human intruders into the work cell

Machine vision systems to supervise the automated system and its surroundings.

It should be mentioned that a given safety monitoring system is limited in its ability to respond to hazardous conditions by the possible irregularities that have been foreseen by the system designer. If the designer h as not anticipated a particular hazard, and consequently has not provided the system with the sensing capability to detect that hazard, then the safety monitoring system cannot recognize the event if and when it occurs.

Maintenance and Repair Diagnostics

Modem automated production systems are becoming increasingly complex and sophisticated, thus complicating the problem of maintaining and repairing them. *Maintenance and repair diagnostics* refers to the capabilities of an automated system to assist in the identification of the source of potential or actual malfunctions and failures of the system. Three. modes of operation are typical of a modern maintenance and repair diagnostics subsystem

Swills monitoring, **In** the status, monitoring mode, the diagnostic subsystem monitoring and records the status of key sensors and parameters of the system during normal operation. On request, the diagnostics subsystem can display any of these values and provide an interpretation of current system status, perhaps warning of an immediate failure

Failure diagnostics. The failure diagnostics mode is invoked when a malfunction or failure occurs. Its purpose is to interpret the current values of the monitored van. Ables and to analyze the recorded values preceding the failure so that the cause of the failure can be identified

3 Recommendation of repair procedure the third mode of operation. the subsystem provides a recommended procedure to the repair crew as to the steps that should be taken to effect repairs. Methods for developing the recommendations are sometimes based on the use of expert systems in which the collective judgments of many repair experts arc pooled and incorporated into a computer program that uses artificial intelligence techniques.

Status monitoring serves two important functions of machine diagnostics: (I) providing information for diagnosing a current failure and (2) providing data to predict a future malfunction or failure. first, when a failure of the equipment has occurred, it is usually difficult for the repair crew to determine the reason for the failure and what steps should be taken 10 make repairs. It is often helpful to reconstruct the events leading up to the failure. The computer is programmed to monitor *and* record the variables and to draw logical inferences from their values about the reason for the malfunction, This diagnosis helps the repair personnel make the necessary repairs and replace the appropriate components.

This is especially helpful in electronic repairs where it is often difficult to determine on the basis of visual inspection which components have failed

The second function of status monitoring is to identify signs of an impending failure, so that the affected components can be replaced before failure actually causes the system to go down. These part replacements can be made during the night shift or other time when the process is not operating. with the result that the system experiences [10loss of regular operation

Error Detection and Recovery

In the operation of any automated system, there are hardware malfunctions and unexpected events that occur during operation. These events can result in costly delays and loss of production until the problem has been corrected and regular operation is restored. Traditionally. equipment malfunctions are corrected by human workers, perhaps with the aid of a maintenance and repair diagnostics suhroutine. With the increased use of computer control for manufacturing processes, there is a trend toward using the control computer not only to diagnose the malfunctions but also to automatically take the necessary corrective action to restore the system to normal operation. The term *error detection and recovery* is used when the computer performs these functions,

Error Detection. A, indicated by the term. error detection lind recovery consists of two steps: (1) error detection and (2) error recovery. The *error defection* step uses the automated svstem's available sensor systems to determine when a deviation or malfunction has occurred, correctly interpret the sensor signal(s), and classify the error. Design of the error detection subsystem must begin with 11 classification of the possible errors that can occur during system operation. The errors in a manufacturing process tend to be very application specific. They must be anticipated in advance in order to select sensors that will enable their detection

In analyzing a given production operation, the possible errors can be classified into one of three general categories: (1) random errors, 1'2)systematic errors. and (3) aberrations, *Random errors* occur as a result of the normal stochastic nature of the process. These errors occur when the process is in statistical control (Section 21.1). Large variations in part dimensions, even when the production process is in statistical control, can cause problems in downstream operations. By detecting these deviations on a part by part basis, corrective action can be taken in subsequent operations, *Systematic errors* are those that result from some assignablecause such as a change in raw material properties or a drift in an equipment setting.These errors usually cause the product to deviate from specifications so as to be unacceptable in quality terms. Finally. the third type of error. *aberrations,* results from either an equipment failure or a human mistake. Examples of equipment failures include fracture of a mechanical shear pin, bursts in a hydraulic line, rupture of a pressure vessel, and sudden failure of a cutting tool. Examples of human mistakes include errors in the control program, improper fixture setups, andsubstitution of the wrong raw materials,

The two main design problems in error detection are: (1) to anticipate all of the possible errors that can occur in a given process and (2) to specify *the* appropriate sensor systems and associated interpretive software so that the system is capable of recognizing each error. Solving the first problem requires a systematic evaluationof the possibilities under each of the three error classifications. If the error has not been anticipated, then the error detection subsystem cannot correctly detect and identify it.

EXAMPLE 3.2 **Error Detection in an Automated Machining Cell**

Consider an automated cell consisting of a CNC machine tool, a parts storage unit, and a robot for loading and unloading the parts between the machine and the storage unit. Possible errors that might affect this system can be divided into the following categories: (1) machine and process, (2) cutting tools, (3) workholding fixture, (4) parI storage unit, and (5) load/unload robot. Develop a list of possible errors (deviations and malfunctions) that might be included in each ofthcse five categories.

Solution: A list of possible errors in the machining cell is presented in Table 3.3.

Error Recovery. *Error recovery* is concerned with applying the necessary correc*tive* action to overcome the error and bring the system back to normal operation. The problem of designing an error recovery system focuses on devising appropriate strategies and procedures that will either correct or compensate for the variety of errors that can occur in the process. Generally, a specific recovery strategy and procedure must be designed for each different error, The types of strategies can he classified as follows:

l , *Make adjustments at the end of the current work cycle.* When the current work cycle is completed. the part program branches to a corrective action subroutine specifically

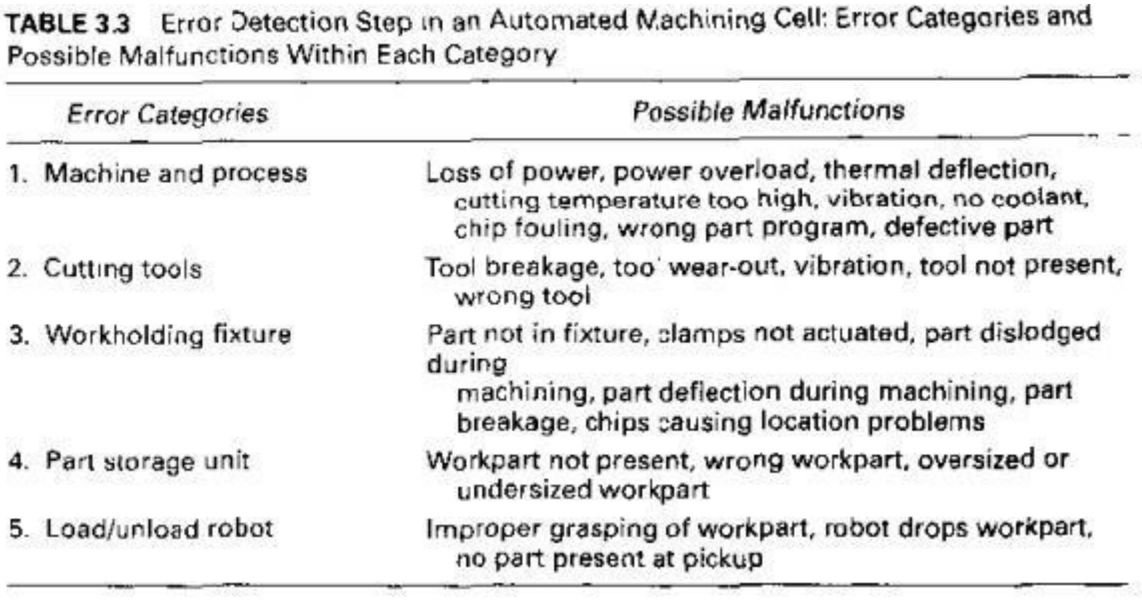


TABLE 3.3 Error Detection Step in an Automated Machining Cell: Error Categories and Possible Malfunctions Within Each Category

Error Categories	*Possible Malfunctions*
1. Machine and process	Loss of power, power overload, thermal deflection, cutting temperature too high, vibration, no coolant, chip fouling, wrong part program, defective part
2. Cutting tools	Tool breakage, tool wear-out, vibration, tool not present, wrong tool
3. Workholding fixture	Part not in fixture, clamps not actuated, part dislodged during machining, part deflection during machining, part breakage, chips causing location problems
4. Part storage unit	Workpart not present, wrong workpart, oversized or undersized workpart
5. Load/unload robot	Improper grasping of workpart, robot drops workpart, no part present at pickup

designed for the error detected, executes the subroutine, and then returns to the work cycle program. this action reflects a low level of urgency and is most commonly associated with random errors in the process.

Make udjusnnents during IIII' current cycle. I his general1y indicates a higher level of urgency than the preceding type. In this case, the action to correct or compensate for the detected error is initiated a~ soon as the error is detected. However, it must be possible to accomplish the designated corrective action while the work cycle is still being executed

- *Stop the prnc invoke corrective action.* In this case, the deviation or malfunction requires that the execution of the work cycle be suspended during corrective action. It is assumed that the system is capable of automatically recovering from the error without human assistance. At the end of the corrective action, the regular work cycle Is continued.

- *Stop (III:process and call for help.* In this case, the error requiring stoppage of the process cannot he resolved through automated recovery procedures. This situation arises because: (I) the automated cell is not enabled to correct the problem or (2) the error cannot be classified into the predefined list of errors. In either case, human assistance is required to correct the problem and restore the system to fully automated operation.

Error detection and recovery requires an interrupt system (Section 4.3.2). When an error in the process is sensed and identified, an interrupt in the current program execution is invoked to branch to the appropriate recovery subroutine, This is done either at the end of the current cycle (type 1 above) or immediately (types 2, 3,and 4).At the completion of the recovery procedure, program execution reverts back to normal operation.

LEVELS OF AUTOMATION

The concept of automated systems can be applied to various levels of factory operations. One normally associates automation with the individual production machines. However, the production machine itself 1~made up of subsystems that may themselves be automated. For example. one of tile important automation technologies we discuss in this pari of the book is numerical control (Chapter6).A modern numerical control (NC) machine tool is an automated system. However, the NC machine itself is composed of multiple control systems. Any *NC* machine has at least two axes of motion, and some machines have up to five axes. Each of these axes operates as a positioning system, as described in Section 3.1.3, and is, ineffect, itself an automated system. Similarly, a NC machine is often part of a larger manufacturing system, and the larger system may itself be automated. For example, two or three machine tools may be connected by an automated pact handling system operating under computer control. The machine tools also receive instructions (e.g., part programs) from the computer. Thus we have three levels of automation and control included here (the positioning system level, the machine toollevel, and the manufacturing system level). For our purposes in this text, we can identify five possible levels of automation in a production plant. They are defined next, and their hierarchy is depicted in Figure 3.6.

> *Device level*. This is the lowest level in our automation hierarchy. It includes the actuators, sensors, and other hardware components that comprise the machine level. The devices are combined into the individual control loops of the machine; for ex· ample, the feedback control loop for one axis of a CNC machine or one joint of an industrial robot.

Machine [ewl. Hardware at the device level is assembled into individual machines. Examples include CNC machine tools and similar production equipment, industrial roo bOIS, powered conveyors, and automated guided vehicles. Control functions at this

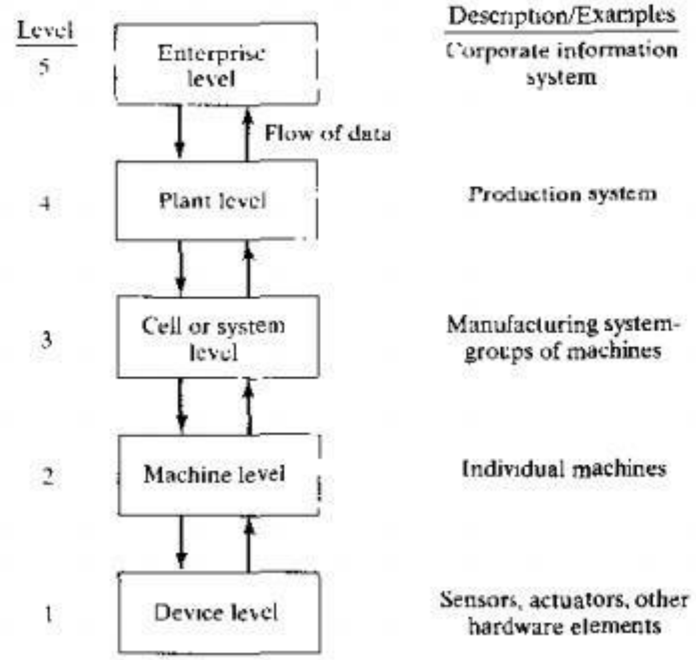


Figure 3.6 Five levels of automation and control in manufacturing.

level include performing the sequence of steps in the program of instructions in the correct order and making sure that each step is properly executed.

Cell or system level. This is the manufacturing cell or system level, which operates under instructions from the plant level. A manufacturing cell or system is a group of machines or workstations connected and supported by a material handling system, computer. and other equipment appropriate to the manufacturing process. Production lines arc included in this level. functions include part dispatching and machine loading. coordination among machines and material handling system, and collecting and cvaluatinginspection data.

Plum level. This is the factory or production systems level. It receives instructions from *(he* corporate information system and translates theminto operational plans for production. Likely functions include: order processing, process planning, inven. tory control, purchasing, material requirements planning, shop floor control, and qualiry control.

Enterprise level. This is the highest level. consisting of the corporate information system. It is concerned with all of the functions necessary to manage the company: marketing and sales, accounting, design, research, aggregate planning, and master production scheduling.

Most of the technologies discussed in this part of the book are at level 2 (the machine level), although we discuss level! automation technologies (the devices that make up a control system) in Chapter 5. The level 2 technologies include the individual controllers (e.g .. programmable logic controllers and digital computer controllers. numerical control machines. and industrial robots. The material handling equipment discussed in Part 11 abo represent technologies at level 2. although some of the handling equipment are themselves sophisticated automated systems. The automation and control issues at level2 Concerned with the basic operation of the equipment and the physical processes they perform

Controllers. machines, and material handling equipment are combined into manufacturing cells. or production lines. or similar systems, which make up level 3, considered in Part III. A *manufacturing system* is defined in this book as a collection of integrated equipment designed for some special mission, such as machining a defined part family or assembly of a certain product. Manufacturing systems also include people. Certain highly automated manufacturing systems can operate for extended periods of time without humans present to attend to their needs. But most manufacturing systems include workers as important elements of the system: for example, assembly workers on a eooveyorized production line or part loaders/unloaders in a machining cell. Thus, manufacturing systems are designed with varying degrees of automation; some are highly automated, others are completely manual, and there is a wide range between.

The manufacturing systems in a factory arc components of a larger system, which we refer to as a production system. We define a *production system* as the people, equipment, and procedures that are organized for the combination of materials and processes that comprise a company's manufacturing operations. Production systems are at level 4, the plant level, while manufacturing systems are at level 3 in our automation hierarchy. Production systems include not only the groups of machines and workstations in the factory but also the support proceduresthat make them work. These procedures include production control, inventory control, material requirements planning. shop floor control. and quality control. These systems are discussed in Parts IV and V. They are often implemented not only at the plant level but also ar the corporate level (level S).

3 Industrial Control Systems

CONTENTS

Process Industries Versus Discrete Manufacturing Industries

- Levels of Automation in the Two Industries
- Variables and Parameters in the Two Industries

Continuous Versus Discrete Control

- Continuous Control Systems
- Discrete Control Systems

Computer Process Control

- Control Requirements
- Capabilities of Computer Control
- levels of Industrial Process Control

Forms of Computer Process Control

- Computer Process Monitoring
- Direct Digital Control
- Numerical Control and Robotics
- Programmable Logic Controllers
- Supervisor Control
- Distributed Control Systems and Personal Computers

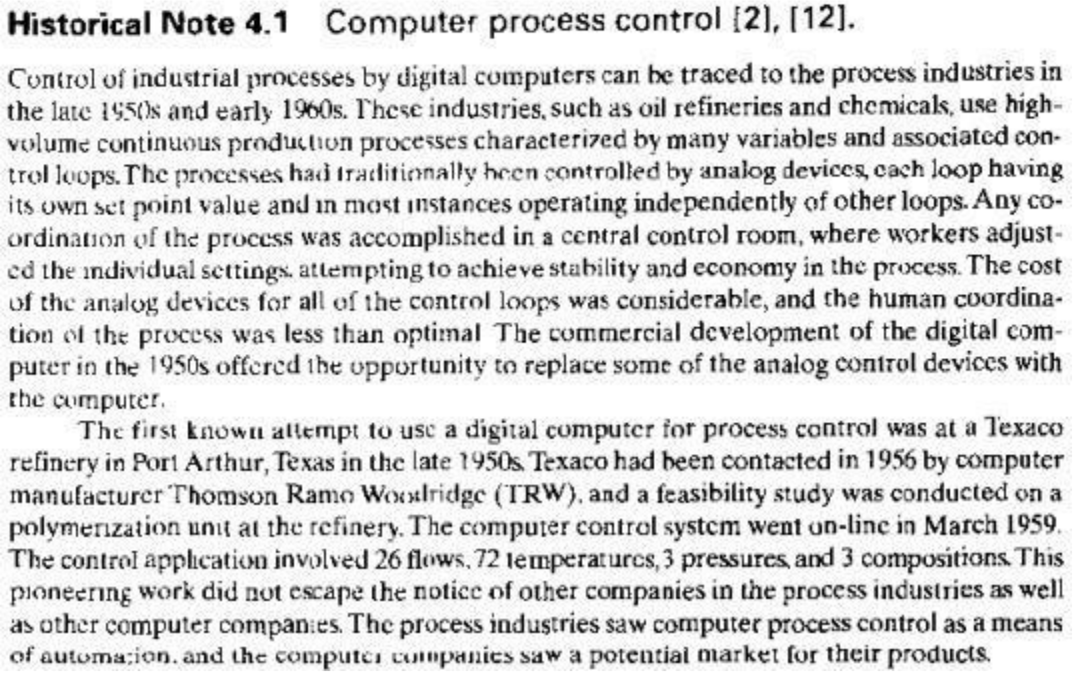
The control system is one of the three basic components of an automation system (Section 3.1). In this chapter, we examine industrial control systems, in particular how digital computers are used to implement the control function in production. Industrial control is defined here automatic regulation of unit operations and their associated equipment as well integration and coordination of the unit operations into the larger production system. In the context of our book, the term *unit operations* usually refers to manufacturing operations; however, the term also applies to the operation of material handling and other industrial equipment. Let us begin our chapter by comparing industrial control as it is applied in the processing industries and how 11is applied in the discrete manufacturing industries.

COMPUTER PROCESS CONTROL

Computer Process Control

- ***Control Requirements***
- ***Capabilities of Computer Control***
- ***levels of Industrial Process Control***

The use of digital computers to control industrial processes had its origins in the continuous process industries in the late 1950s (Historical Note 4.1). Prior to then, analog controllers were used to implement continuous control, and relay systems were used to implement discrete control. At that time, computer technology was in its infancy, and the only computers available for process control were large, expensive mainframes. Compared with today's technology, the digital computers of the 195Ch;were slow, unreliable, and not well suited to process control applications. The computers that were installed sometimes cost more than the processes they controlled. Around 1960, digital computers started replacing analog controllers in continuous process control applications; and around 1970, programmable logic controllers started replacing relay hanks in discrete control applications. Advances III computer technology Since the 1960s and 1970.~have resulted in the de:elopm~nl of the microprocessor. Today, virtually all industrial processes, certainly new installations, are controlled by digital computers based on microprocessor technology. Microprocessorbased controllers are discussed in Section 4.4.6.



Historical Note 4.1 Computer process control [2], [12].

Control of industrial processes by digital computers can be traced to the process industries in the late 1950s and early 1960s. These industries, such as oil refineries and chemicals, use high-volume continuous production processes characterized by many variables and associated control loops. The processes had traditionally been controlled by analog devices, each loop having its own set point value and in most instances operating independently of other loops. Any coordination of the process was accomplished in a central control room, where workers adjusted the individual settings, attempting to achieve stability and economy in the process. The cost of the analog devices for all of the control loops was considerable, and the human coordination of the process was less than optimal. The commercial development of the digital computer in the 1950s offered the opportunity to replace some of the analog control devices with the computer.

The first known attempt to use a digital computer for process control was at a Texaco refinery in Port Arthur, Texas in the late 1950s. Texaco had been contacted in 1956 by computer manufacturer Thomson Ramo Wooldridge (TRW), and a feasibility study was conducted on a polymerization unit at the refinery. The computer control system went on-line in March 1959. The control application involved 26 flows, 72 temperatures, 3 pressures, and 3 compositions. This pioneering work did not escape the notice of other companies in the process industries as well as other computer companies. The process industries saw computer process control as a means of automation, and the computer companies saw a potential market for their products.

The available computers In the late I950s were not reliable, and most of the subsequent process control installations operated by euher printing out instructions for the operator or by making adjustments in the set points (If analog controllers, thereby reducing the risk of process downtime due to compute: problems. The latter mode of operation was called *set point control*. By March 1%1, a total of 37 computer process control systems had been installed. Much experience was gamed from these early installations. The *interruptfeature* (Section 4.3.2). by which the computer suspends current program execution to quickly respond to a process need. was developed during this period.

The first *direct digital control* (DOC) system (Section 4.4.2), in which certain analog de" vices are replaced by the computer, was installed by Imperial

Chemical Industries in England in 1%2. In this on plementauonzza process variables were measured, and 129actuators (valves) controlled Improvements in DOC technology were made, and additional systems were installed during the 1%0s. Advantages 01 DOC noted during this time included: (1) cost savings from elimination of analog instrumentation for large systems. (2) simplified operator display pencts, and ,:3) flexibility through reprogramming capability.

Computer technology was advancing. leading to the development of the *minicomputer*

in the late 1960s.Process control applications were easier to justify using theses smaller, less expensive computers. Development of the *microcomputer* in the early 1970s continued this trend. Lower cost process control hardware and Interface equipment (such as analog to digital converters) were becoming available due to the larger markets made possible by low cost computer controllers.

Most of the developments in computer process control up to this time were biased toward the process industries rather than discrete part and product manufacturing. Just as analog devices had been used to automate process industry operations, relay banks were widely used to satisfy the discrete process control (ON/OFF) requirements in manufacturing automation.

Let us consider the requirements placed on the computer in industrial control applications. We then examine the capabilities that have been incorporated intothe control computer to address these requirements. and finally we observe the hierarchical structure of the functions performed by the control computer.

Control Requirements

Whether the application involves continuous control, discrete control. or both, there are certain basic requirements that tend to he common to nearly all process control applications. By and large, they are concerned with the

need to communicate and interact with the process on arealtime basis.A *reallime controller* is able to respond to the process within a short enough time period that process performance is not degraded. Factors that determine whether a computer controller can operate in realtime include: (1)the speed of the controller's central processing unit (CPU) and its interfaces,
(2) the controller's operating system, (3) the design of the application software, and (4) the number of different input/out. put events to which the controlier is designed to respond. Realtime control usually requires the controller to be capable of *multitasking*, which means coping with multiple tasks concurrently without the tasks interfering with one another.

There are two basic requirements that must be managed by the controller to achieve real time control:

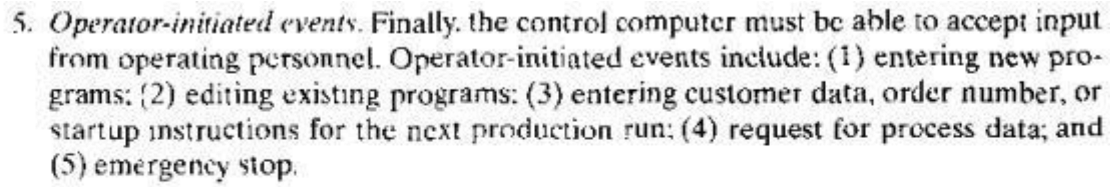
Process initiated interrupts. The controller must be able to respond to incoming signals from the process. Depending on the relative importance of the signals, the computer may need to interrupt execution of a current program to service a higher priority need of the process. A process initiated interrupt is often triggered by abnormal operating conditions, indicating that some corrective action must be taken promptly.

Timer initiated actions. The controller must be capable of executing certain actions at specified points in time. Timer initiated actions can be generated at regular time intervals, ranging from very low values (e.g., 100 j.ts) to several minutes. or they can be generated at distinct points in time. Typical timer initiated actions in process control include: (1) scanning sensor values from the process at regular sampling intervals, (2) turning on and off switches, motors, and other binary devices associated with the process at discrete points in time during the work cycle, (3) displaying performance data on the operator's console at regular times during a production run, and (4) recomputing optimal process parameter values at specified times.

These two requirements correspond to the two types of changes mentioned previously in the context of discrete control systems: (l) event driven changes and (2) time driven changes.

In addition to these basic requirements. the control computer must also deal with other types of interruptions and events. These include:

Computer commands to process. In addition to incoming signals from the process, the control computer must be able to send control signals to the process to accommodate readjust a 5ct point in *5iyrtem and program itiated IT('nts.* These are events related to the computer system itself 'havearc similar to the kinds of computer operations associated with business and engineering applications of computers. A *system initiated event* involves communications among ompl!ten and peripher<ll devices linked together in a network. In these multiple computer networks, feedback signals, control commands, and other data must be transferred back and forth among the computers in the overall control of the process.A *program initiated {'vent* is when some non process related action is called for in the program .such as the printing or display of reports on a printer or monitor. In process coutrut, vvstern and program initiated eventsgenerally occupy low level of priority compared with process interrupts, commands to the process. and timer initiated events



5. *Operator-initiated events.* Finally. the control computer must be able to accept input from operating personnel. Operator-initiated events include: (1) entering new programs; (2) editing existing programs; (3) entering customer data, order number, or startup instructions for the next production run; (4) request for process data; and (5) emergency stop.

Capabilities of Computer control

The above requirements can he satisfied by providing the controller with certain capabilities that allow it 10 interact on a real time basis with the process and the operator, The capabilities are: (1) polling, (2) interlocks. (3) interrupt system, and (4) exception handling.

Polling (Data Sampling). In computer process *control,polllNg* refers 10 the periodic ~ampling of data that indicates the status of the process. When the data consist of a continuous analog ~ignal. sampling means that the continuous slgnalrs substituted with a series of numerical values that represent the continuous signal at discrete moments in time. The same kind of substitution holds for discrete data. except that the number of possible numerical values the data can take on more limited certainly the case with binary data We discuss the techniques by which continuous and discrete datil are entered into and transmitted from the computer in Chapter 5. Other names used for polling include *sampling* and *scanning*

In some polling procedure simply requests whether any changes have the last polling cycle and then collects only the new data from shorten the cycle time required for polling. Issues related to

polling include:

1. *Polling frequency*. This is the reciprocal of the time interval between when data are collected

Polling order. The polling order is the sequence in which the different data collection points of the process are sampled.

Polling formal. This refers to the manner in which the sampling procedure is designed. The alternatives include: (a) entering all new data from all sensors and other devices ~very polling cycle; (b) updating the control system only with data that have changed since the last polling cycle; or (c) using *highlevel and towlevdscanntng.ot conditional scanning,* in which only certain key data are normally collected each polling cycle (highlevel scanning), but if the data indicates some irregularity in the process. a lowlevel scan undertaken to collect more complete data to ascertain the source of the irregularity.

These issues become increasingly critical with very dynamic processes in which changes in process S(;JIII, occur rapidly

Interlocks. An *interlock* is a safeguard mechanism for coordinating the activities of two or more devices and preventing vue device from interfering with the others. In process control. interlocks provide a means by which the controller is able to sequence the activities in a work cell, ensuring that the actions of one piece of equipment arc completed before the next piece of equipment begins its activity. Interlocks work by regulating the flow of control signals back and forth between the controller and the external devices.

There are two types of interlocks, input interlocks and output interlocks, where input and output are defined relative to the controller. An *input interlock* is a signal that originates from an external device (e.g., a limit switch, sensor, or production machine) and is sent to the controller. Input interlocks can be used for either of the following functions:

To *proceed* with the execution of the work cycle program. For example, the production machine communicates a signal to the controller that it has completed its processing of the part. This signal constitutes an input interlock indicating that the controller can now proceed to the next step in the work cycle, which is to unload the part.

To *interrupt* the execution of the work cycle program. For example, while unloading the part from the machine, the robot accidentally drops the part. The sensor in its gripper transmits an interlock signal to the controller indicating that the regular work cycle sequence should be interrupted until corrective action is taken.

An *output interlock* is a signal sent from the controller to some external device. It is used to control the activities of each external device and to coordinate its operation with that of the other equipment in the cell. For example, an output interlock can be used to send a control signal to a production machine to begin its automatic cycle after the workpart has been loaded into it.

interrupt System. Closely related to interlocks is the interrupt system. As suggested by our discussion of input interlocks, there are occasions when it becomes necessary for the process or operator to interrupt the regular controller operation to deal with more pressing matters. All computer systems are capable of being interrupted; if nothing else, by turning off the power. A more sophisticated interrupt system is required for process control applications. An *interrupt system* is a computer control feature that permits the execution of the current program to be suspended to execute another program or subroutine in response to an incoming signal indicating a higher priority event. Upon receipt of an interrupt signal, the computer system transfers to a predetermined subroutine designed to deal with the specific interrupt. The status of the current program is remembered so that its execution can be resumed when servicing of the interrupt has been completed.

Interrupt conditions can be classified as internal or external *Internal interrupts* are generated by the computer system itself. These include timer initiated events, such as polling

of data from sensors connected to the process, or sending commands to the process at specific points 10 clock time. System and program initiated interrupts are also classified as

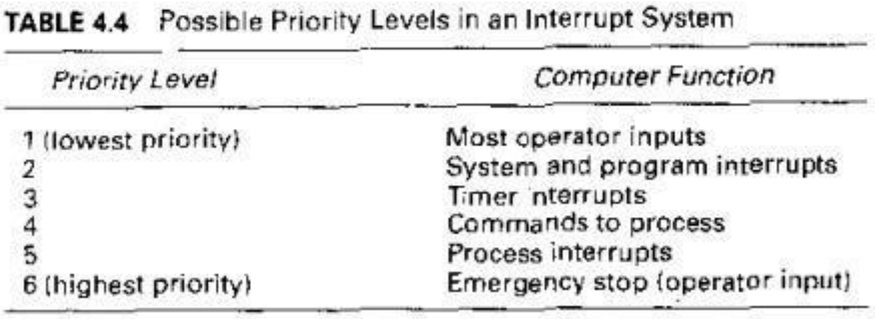
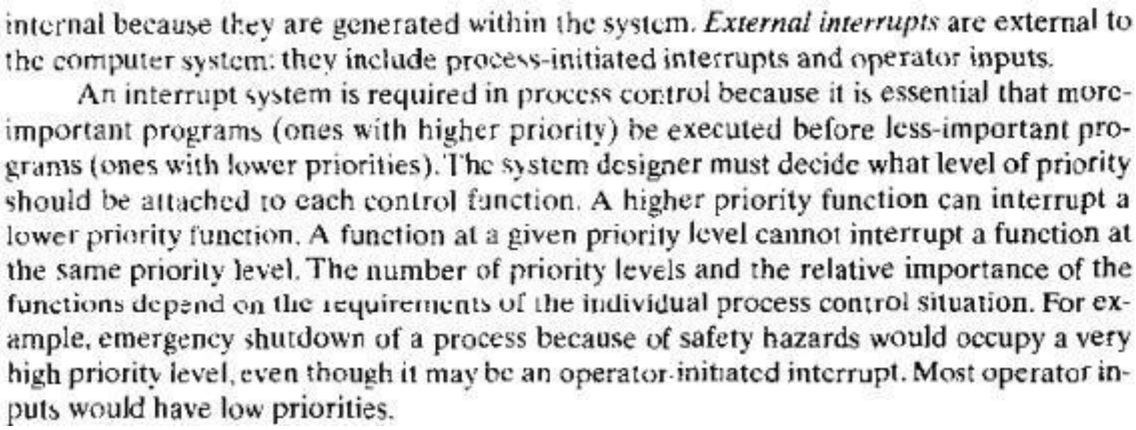


TABLE 4.4 Possible Priority Levels in an Interrupt System

Priority Level	*Computer Function*
1 (lowest priority)	Most operator inputs
2	System and program interrupts
3	Timer interrupts
4	Commands to process
5	Process interrupts
6 (highest priority)	Emergency stop (operator input)



internal because they are generated within the system. *External interrupts* are external to the computer system: they include process-initiated interrupts and operator inputs.

An interrupt system is required in process control because it is essential that more-important programs (ones with higher priority) be executed before less-important programs (ones with lower priorities). The system designer must decide what level of priority should be attached to each control function. A higher priority function can interrupt a lower priority function. A function at a given priority level cannot interrupt a function at the same priority level. The number of priority levels and the relative importance of the functions depend on the requirements of the individual process control situation. For example, emergency shutdown of a process because of safety hazards would occupy a very high priority level, even though it may be an operator-initiated interrupt. Most operator inputs would have low priorities.

important programs higher priority) Be executed before less important programs (ones with lower priorites .The system designer must decide what level of priority should be attached to each control function. A higher priority function can interrupt a lower primity function. A function at a given priority level cannot interrupt a function at the same priority level. The number of priority levels and the relative importance of the function depend on the l<:'[uir<:I1n;nl>of the individual process control situation. For example, emergency shutdown of a process because of safety hazards would occupy a very high priority level, even though it may be an operator. initiated interrupt. Most operator in" puts would have low priorities.

One possible organization of priority rankings for process control functions is shown III Table 4.4. Of course, the priority system may have more or less than the number of levcis shown here. depending on the controlsituation. For example, some process interrupts may be more important thanothers. and some system interrupts may take precedence over certain process interrupts, thus requiring more than the six levels indicated in our table

To respond 10 the various levels of priority defined for a given control application, an interrupt system can have one or more interrupt levels.A *single level interrupt system* has only two modes *of* operation: normalmode and interrupt mode. The normal mode can be interrupted, but the interrupt mode cannot. This means that overlapping interrupts arc serviced on a first come. First served basis, which have potentially hazardous consequences it an important process interrupt was forced to wait its tum while a series of less important operator and system interrupts were serviced. A *multilevel interrupt system* has a normal operating mode plus more than one interrupt level. The normal mode can be interrupted hy any interrupt level. hut the interrupt levels have relative priorities that determine which functions can interrupt others. Example 4.1 illustrates the difference between the single level and multilevel interrupt systems.

EXAMPLE 4.1 Single Level Versus **Multilevel Interrupt** Systems

Three Interrupts representing tasks of three different priority levels arrive for service in the reverse order of (heir respective priorities. Task 1with the lowest priority, arrives first. Shortly later.higher priority Task 2 arrives. And shortly later,

highest pnority Task 3 arrives. How would the computer control system respond under (a) a suvglcle ce! interrupt system and (b) a rnurt'ilevcl interrupt system?

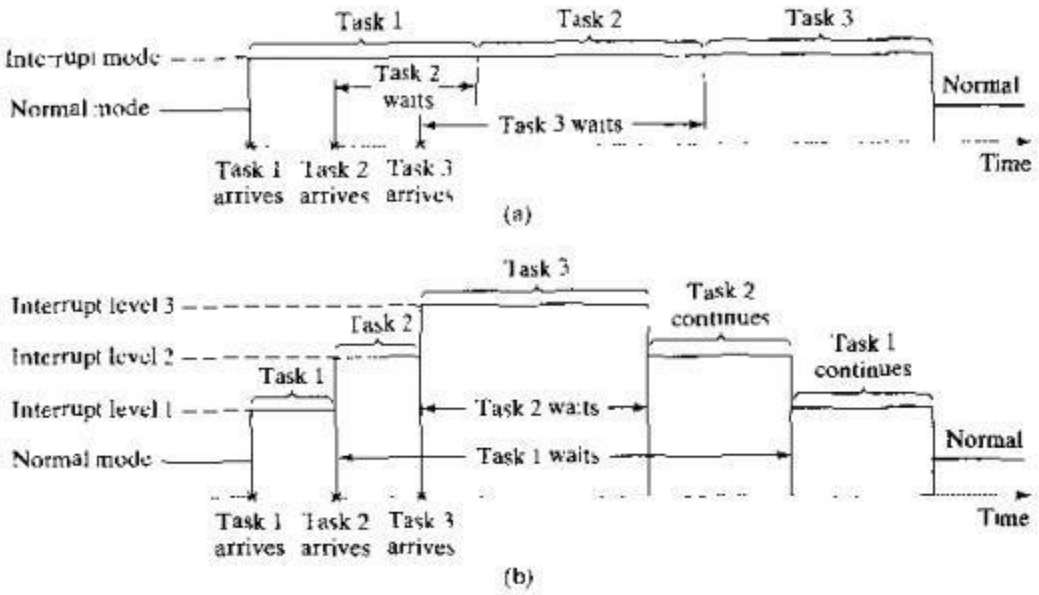


Figure 4.6 Response of the computer control system in Example 4.1 to three different priority interrupts for (a) a single-level interrupt system and (b) a multilevel interrupt system. Task 3 has the highest level priority. Task 1 has the lowest level. Tasks arrive for servicing in the order 1, then 2, then 3. In (a), Task 3 must wait until Tasks 1 and 2 have been completed. In (b), Task 3 interrupts execution of Task 2, whose priority level allowed it to interrupt Task 1.

Exception Handling. In process control, an *exception* is an even! that is outside the normal or desired operation of the process or control system. Dealing with the exception is an essential function in industrial process control and generally occupies a major portion of the control algorithm. The need for exception handling may be indicated through the normal polling procedure or by the interrupt system. Examples of events that may invoke exception handling routines include:

product quality problem
process variables operating outside their normal ranges
shortage of raw materials or supplies necessary to sustain the process
hazardous conditions such as a fire
controller malfunction

In effect, exception handling is a form of error detection and recovery, discussed in the context of advanced automation capabilities (Section 3.2.3).

Levels of Industrial Process Control

In general. industrial control systems possess a hierarchical structure consisting of multiple levels of functions, similar to our levels of automation described in the previous chap. ter [Table 4.2). *ANSIIISAS88.011995*^{J} [1] divides process control functions into three

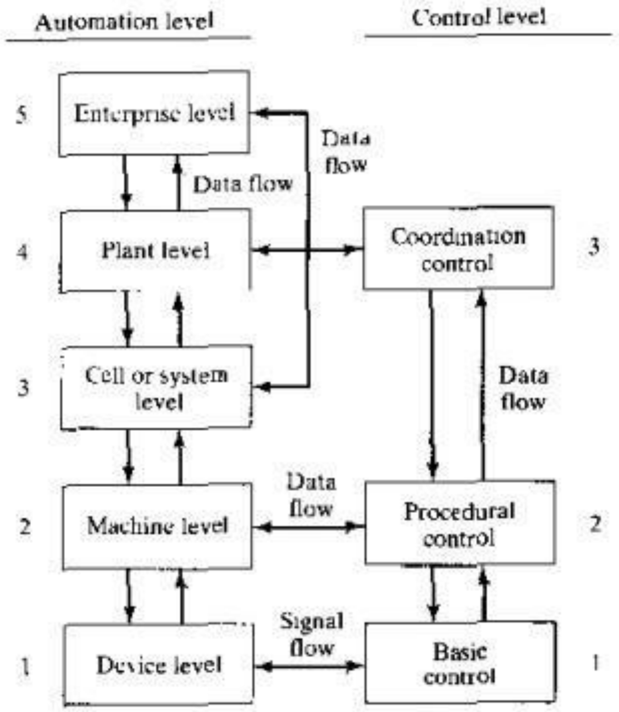


Figure 4.7 Mapping of *ANSI/ISA S88.01-1995* [1] control levels into the levels of automation in a factory.

levels: (1) basic control, (2) procedural control, and (3) coordination contro1.These control levels map into our automation hierarchy as shown in Figure 4.7, We now describe the three control levels, perhaps adapting the standard to fit our own models of continuous and discrete control (the reader is referred to the original standard [1], available from the Instrument Society of America)

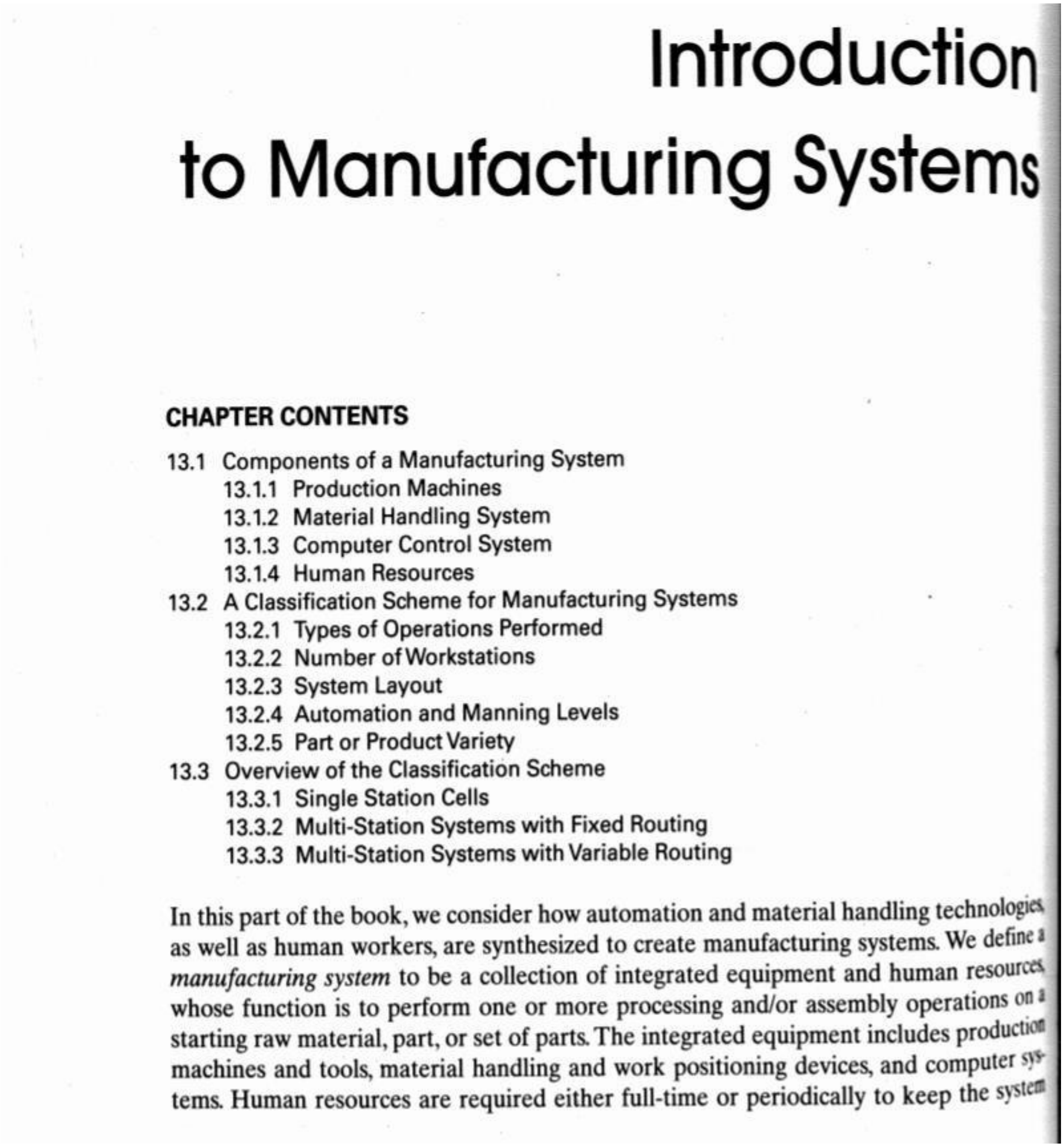
Basic Control. This is the lowest level of control defined in the standard, corresponding to the device level in our automation hierarchy. In the process industries, this level is concerned with feedback control in the basic control loops. In the discrete manufacturing industries, basic control is concerned with directing the servomotors and other actuators of the production machines. Basic control includes functions such as feedback control. polling, interlocking, interrupts. and certain exception handling actions. Basic control functions may be activated.deactivated, or modified by either of the higher control levcis (procedural or coordination control) or by operator commands.

Procedural Control. This intermediate level of control maps into regulatory control of unit operations in the process industries and into the machine level in discrete manufacturing automation (Table 4.2). In continuous control, procedural control functions include using data collected during polling to compute some process parameter value, changing serpoints and other process parameters in basic control, and changing controller gain constants, In discrete control, the functions are concerned with executing the work cycle program, that is.directing the machine to perform actions in an ordered sequence to accomplish sornc productive task. PI ocedural control may also involve executing error detection and recovery procedures and making decisions regarding safety hazards that occur during the process,

Coordination Control. This is the highest level in the control hierarchy in the A'JSI/ISA standard. It corresponds to the supervisor} level in the process industries and the cell or system level in discrete manufacturing. It is also likely to involve the plant and possibly the enterprise levels of automation. Coordination control initiates, directs, or alters the execution of programs at the procedural control level. Its actions and outcomes change over rime. as in procedural control. but its control algorithms are not stnleturoo for a specific process oriented task. It IS more reactive and adaptive. Functions of coordination control at the cell level include. coordinating the actions of groups of equipment or machines. coordinating material handling activities between machines in a cell or system, allocating production orders to machines in the cell, and selecting among alternative work cycle programs.

At the plant and enterprise levels. coordination control is concerned with manufacturing support functions, including production planning and scheduling; coordinating common resources. such as equipment used in more than one production cell; and supervising availability, utilization. and capacity of equipment. These control functions are accomplished through the company's integrated computer and information system.

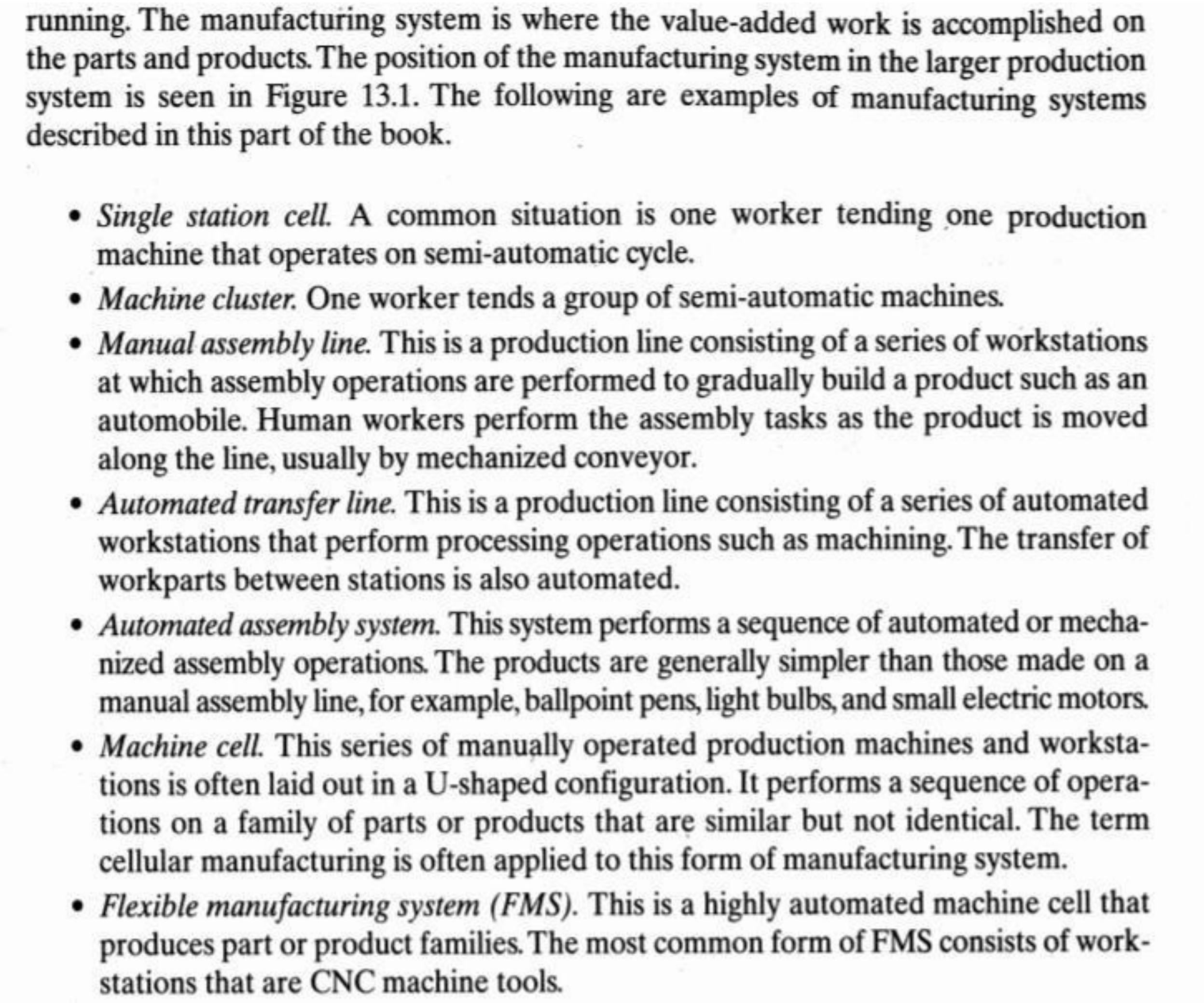
MODULE 3



Introduction to Manufacturing Systems

CHAPTER CONTENTS

In this part of the book, we consider how automation and material handling technologies, as well as human workers, are synthesized to create manufacturing systems. We define a *manufacturing system* to be a collection of integrated equipment and human resources, whose function is to perform one or more processing and/or assembly operations on a starting raw material, part, or set of parts. The integrated equipment includes production machines and tools, material handling and work positioning devices, and computer systems. Human resources are required either full-time or periodically to keep the system



running. The manufacturing system is where the value-added work is accomplished on the parts and products. The position of the manufacturing system in the larger production system is seen in Figure 13.1. The following are examples of manufacturing systems described in this part of the book.

- *Single station cell.* A common situation is one worker tending one production machine that operates on semi-automatic cycle.
- *Machine cluster.* One worker tends a group of semi-automatic machines.
- *Manual assembly line.* This is a production line consisting of a series of workstations at which assembly operations are performed to gradually build a product such as an automobile. Human workers perform the assembly tasks as the product is moved along the line, usually by mechanized conveyor.
- *Automated transfer line.* This is a production line consisting of a series of automated workstations that perform processing operations such as machining. The transfer of workparts between stations is also automated.
- *Automated assembly system.* This system performs a sequence of automated or mechanized assembly operations. The products are generally simpler than those made on a manual assembly line, for example, ballpoint pens, light bulbs, and small electric motors.
- *Machine cell.* This series of manually operated production machines and workstations is often laid out in a U-shaped configuration. It performs a sequence of operations on a family of parts or products that are similar but not identical. The term cellular manufacturing is often applied to this form of manufacturing system.
- *Flexible manufacturing system (FMS).* This is a highly automated machine cell that produces part or product families. The most common form of FMS consists of workstations that are CNC machine tools.

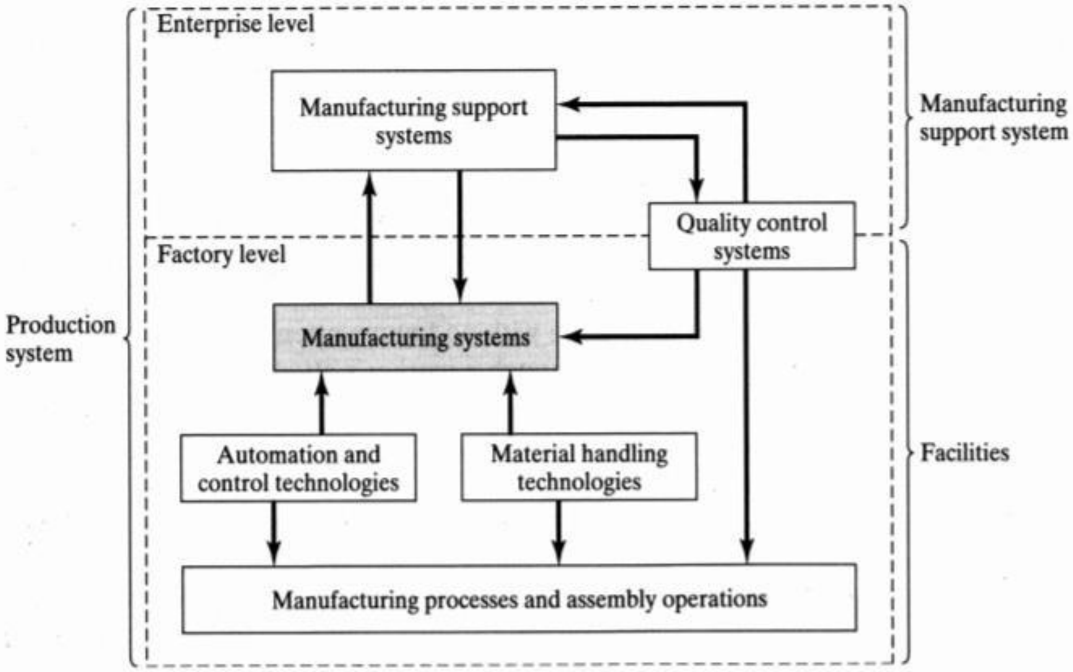
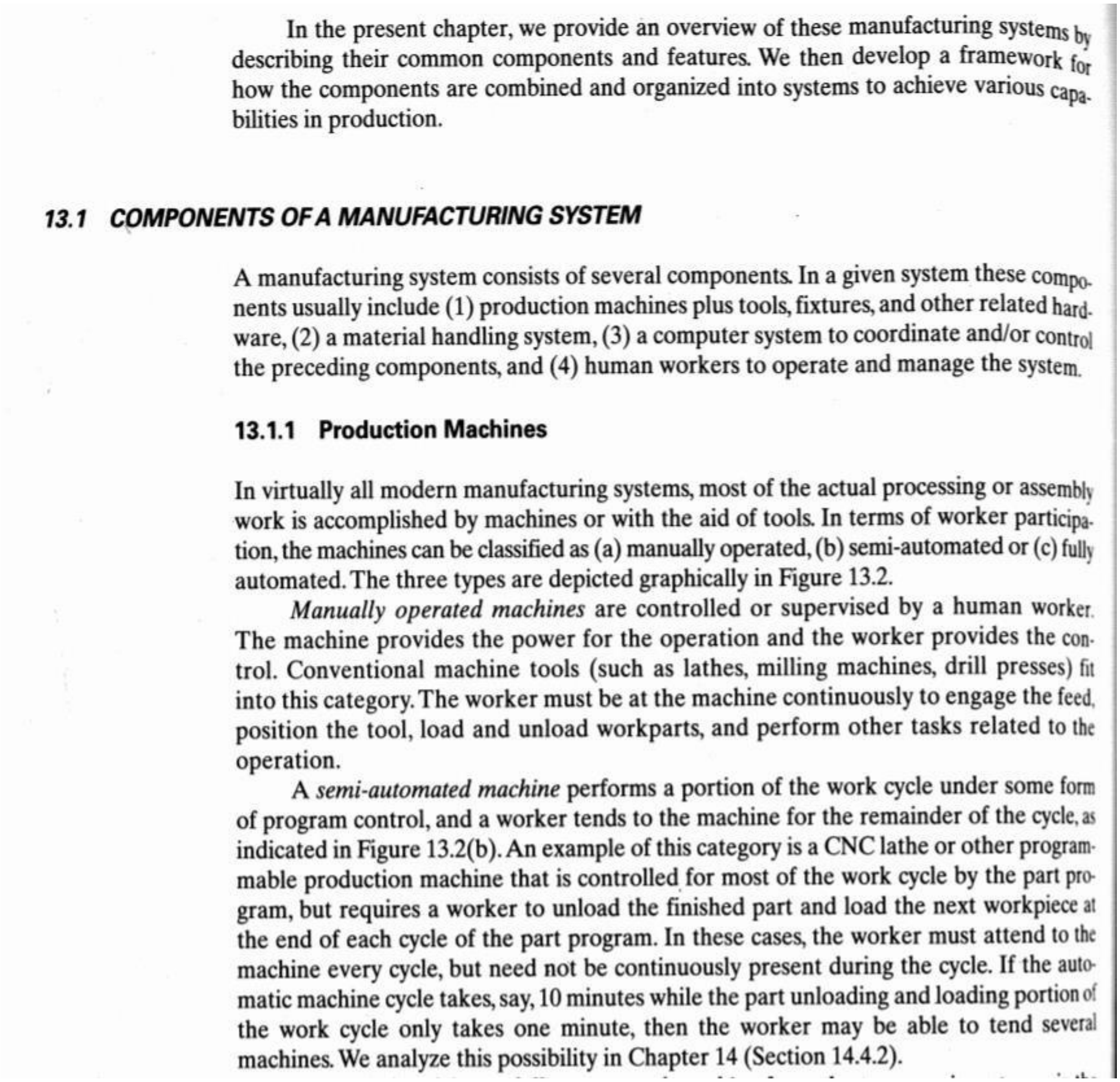


Figure 13.1 The position of the manufacturing system in the larger production system.



In the present chapter, we provide an overview of these manufacturing systems by describing their common components and features. We then develop a framework for how the components are combined and organized into systems to achieve various capabilities in production.

13.1 COMPONENTS OF A MANUFACTURING SYSTEM

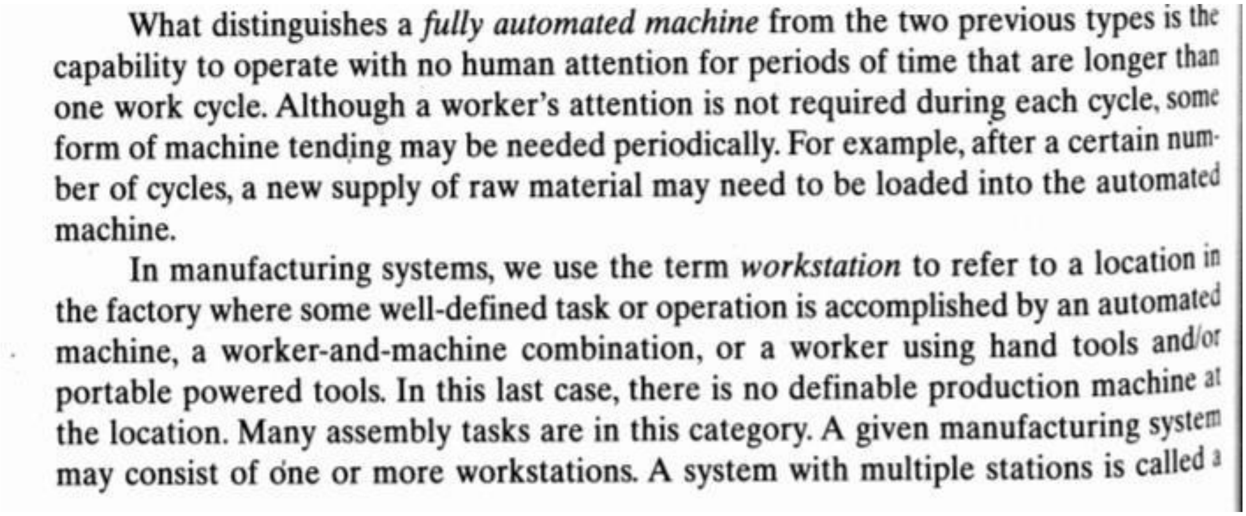
A manufacturing system consists of several components. In a given system these components usually include (1) production machines plus tools, fixtures, and other related hardware, (2) a material handling system, (3) a computer system to coordinate and/or control the preceding components, and (4) human workers to operate and manage the system.

13.1.1 Production Machines

In virtually all modern manufacturing systems, most of the actual processing or assembly work is accomplished by machines or with the aid of tools. In terms of worker participation, the machines can be classified as (a) manually operated, (b) semi-automated or (c) fully automated. The three types are depicted graphically in Figure 13.2.

Manually operated machines are controlled or supervised by a human worker. The machine provides the power for the operation and the worker provides the control. Conventional machine tools (such as lathes, milling machines, drill presses) fit into this category. The worker must be at the machine continuously to engage the feed, position the tool, load and unload workparts, and perform other tasks related to the operation.

A *semi-automated machine* performs a portion of the work cycle under some form of program control, and a worker tends to the machine for the remainder of the cycle, as indicated in Figure 13.2(b). An example of this category is a CNC lathe or other programmable production machine that is controlled for most of the work cycle by the part program, but requires a worker to unload the finished part and load the next workpiece at the end of each cycle of the part program. In these cases, the worker must attend to the machine every cycle, but need not be continuously present during the cycle. If the automatic machine cycle takes, say, 10 minutes while the part unloading and loading portion of the work cycle only takes one minute, then the worker may be able to tend several machines. We analyze this possibility in Chapter 14 (Section 14.4.2).



What distinguishes a *fully automated machine* from the two previous types is the capability to operate with no human attention for periods of time that are longer than one work cycle. Although a worker's attention is not required during each cycle, some form of machine tending may be needed periodically. For example, after a certain number of cycles, a new supply of raw material may need to be loaded into the automated machine.

In manufacturing systems, we use the term *workstation* to refer to a location in the factory where some well-defined task or operation is accomplished by an automated machine, a worker-and-machine combination, or a worker using hand tools and/or portable powered tools. In this last case, there is no definable production machine at the location. Many assembly tasks are in this category. A given manufacturing system may consist of one or more workstations. A system with multiple stations is called a

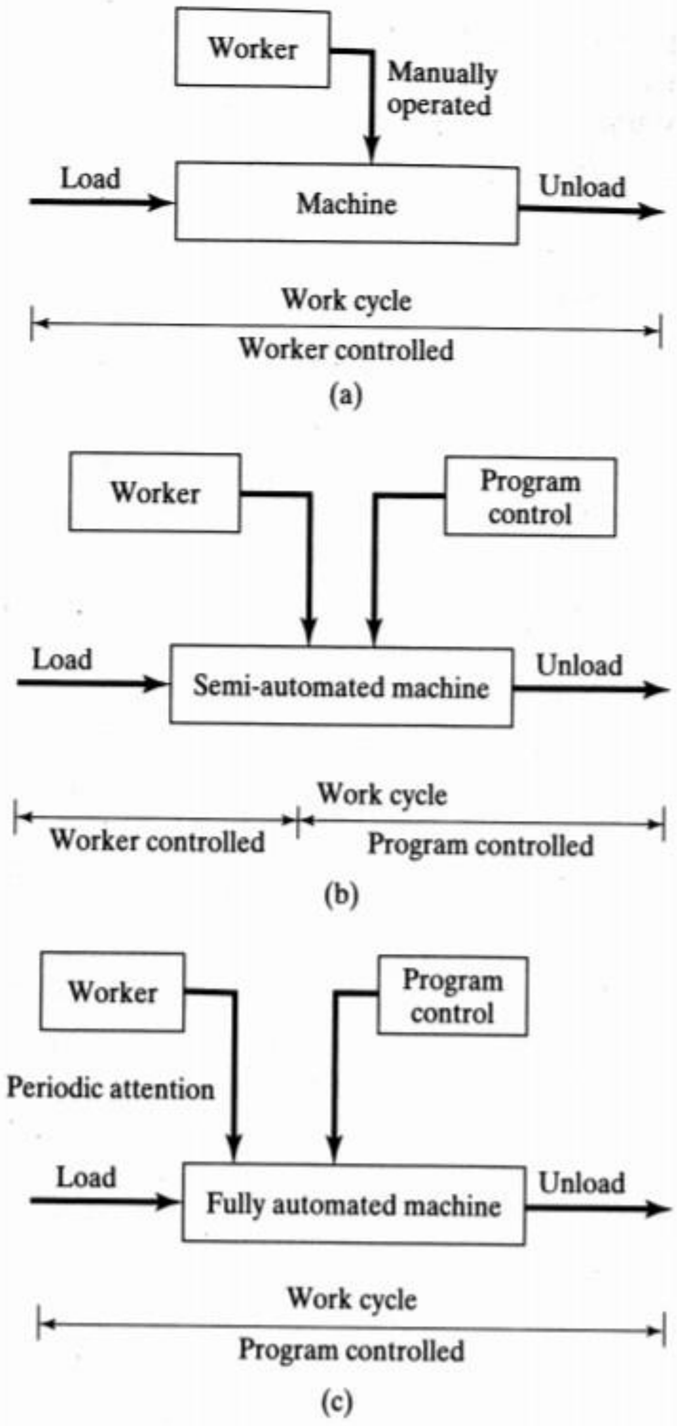
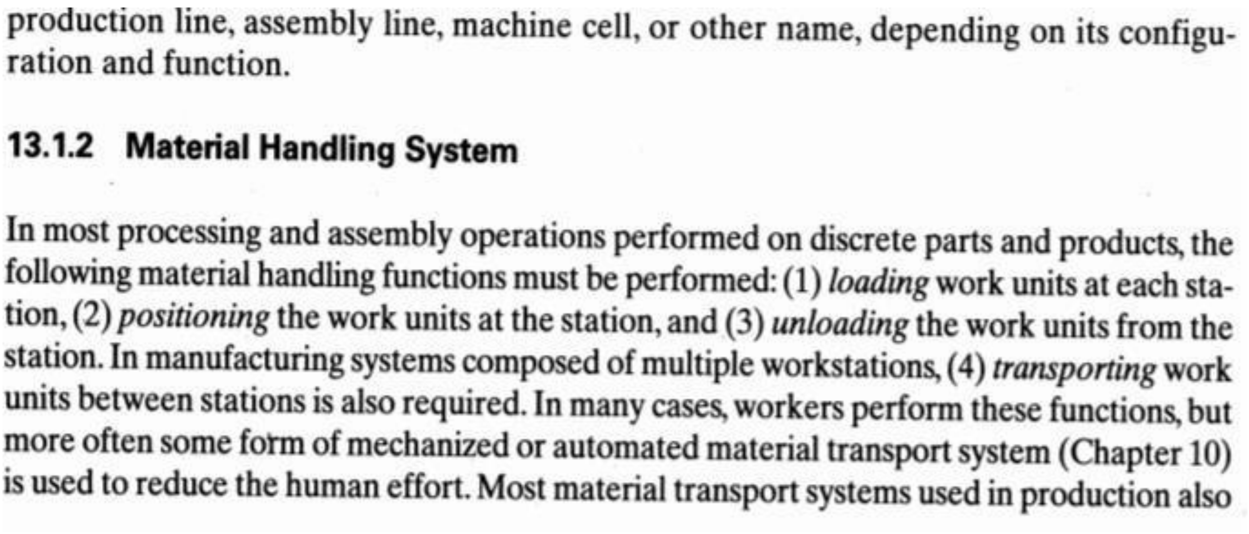


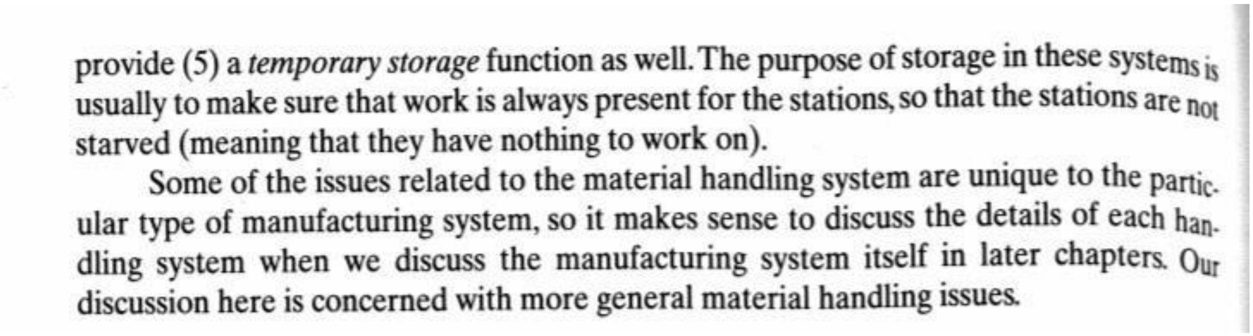
Figure 13.2 Three types of production machines are (a) manually operated, (b) semi-automated, and (c) fully automated.



production line, assembly line, machine cell, or other name, depending on its configuration and function.

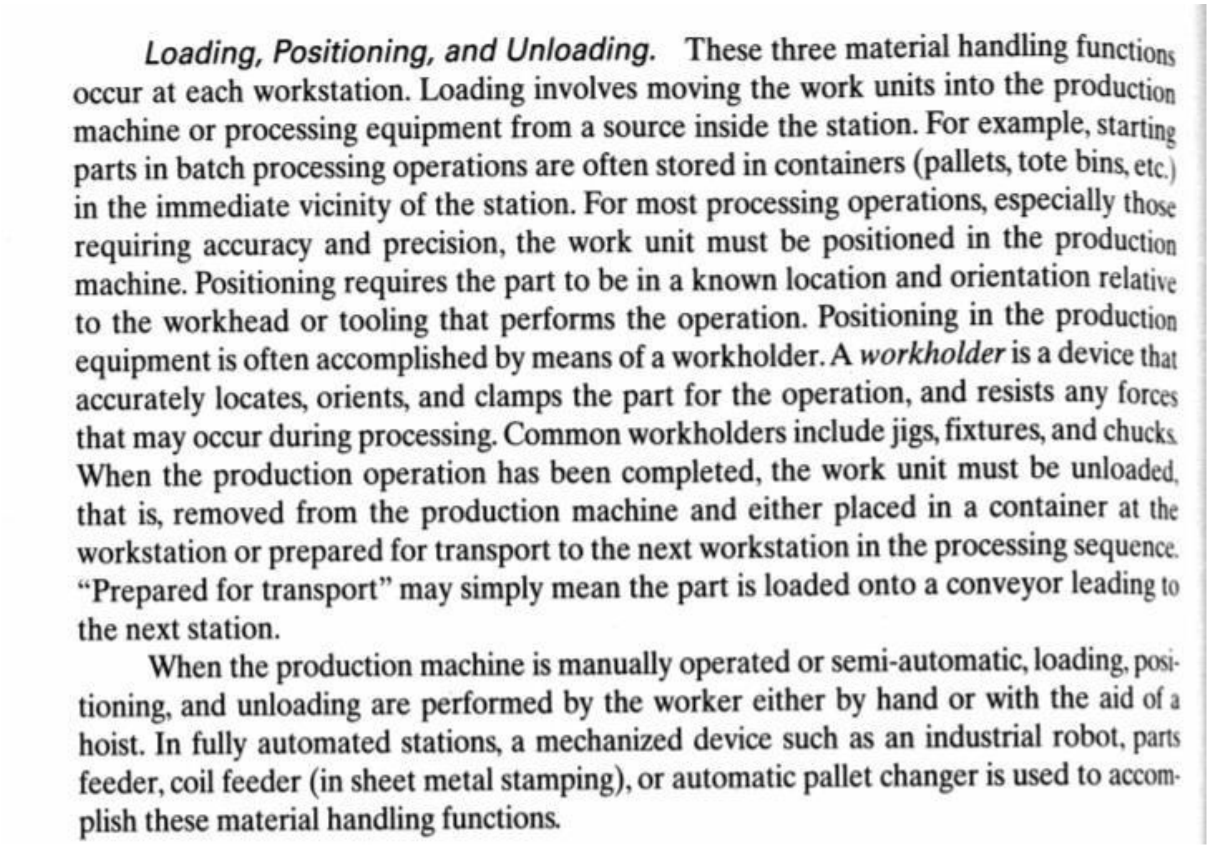
13.1.2 Material Handling System

In most processing and assembly operations performed on discrete parts and products, the following material handling functions must be performed: (1) *loading* work units at each station, (2) *positioning* the work units at the station, and (3) *unloading* the work units from the station. In manufacturing systems composed of multiple workstations, (4) *transporting* work units between stations is also required. In many cases, workers perform these functions, but more often some form of mechanized or automated material transport system (Chapter 10) is used to reduce the human effort. Most material transport systems used in production also



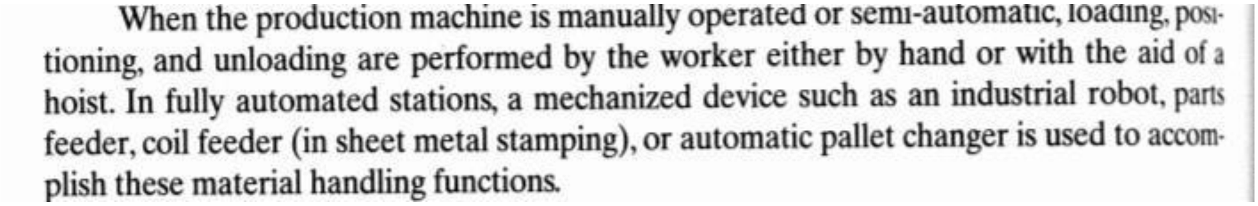
provide (5) a *temporary storage* function as well. The purpose of storage in these systems is usually to make sure that work is always present for the stations, so that the stations are not starved (meaning that they have nothing to work on).

Some of the issues related to the material handling system are unique to the particular type of manufacturing system, so it makes sense to discuss the details of each handling system when we discuss the manufacturing system itself in later chapters. Our discussion here is concerned with more general material handling issues.

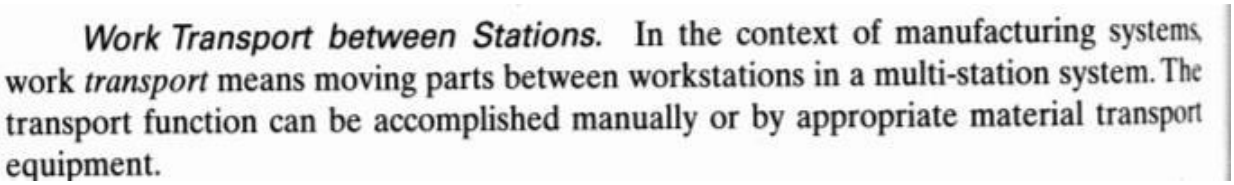


Loading, Positioning, and Unloading. These three material handling functions occur at each workstation. Loading involves moving the work units into the production machine or processing equipment from a source inside the station. For example, starting parts in batch processing operations are often stored in containers (pallets, tote bins, etc.) in the immediate vicinity of the station. For most processing operations, especially those requiring accuracy and precision, the work unit must be positioned in the production machine. Positioning requires the part to be in a known location and orientation relative to the workhead or tooling that performs the operation. Positioning in the production equipment is often accomplished by means of a workholder. A *workholder* is a device that accurately locates, orients, and clamps the part for the operation, and resists any forces that may occur during processing. Common workholders include jigs, fixtures, and chucks. When the production operation has been completed, the work unit must be unloaded, that is, removed from the production machine and either placed in a container at the workstation or prepared for transport to the next workstation in the processing sequence. "Prepared for transport" may simply mean the part is loaded onto a conveyor leading to the next station.

When the production machine is manually operated or semi-automatic, loading, positioning, and unloading are performed by the worker either by hand or with the aid of a hoist. In fully automated stations, a mechanized device such as an industrial robot, parts feeder, coil feeder (in sheet metal stamping), or automatic pallet changer is used to accomplish these material handling functions.



When the production machine is manually operated or semi-automatic, loading, positioning, and unloading are performed by the worker either by hand or with the aid of a hoist. In fully automated stations, a mechanized device such as an industrial robot, parts feeder, coil feeder (in sheet metal stamping), or automatic pallet changer is used to accomplish these material handling functions.



Work Transport between Stations. In the context of manufacturing systems, work *transport* means moving parts between workstations in a multi-station system. The transport function can be accomplished manually or by appropriate material transport equipment.

In some manufacturing systems, work units are passed from station to station by hand, either one at a time or in batches. Moving parts in batches is generally more efficient according to the Unit Load Principle (Section 10.1.2). Manual work transport is limited to cases in which the parts are small and light, so that the manual labor is ergonomically acceptable. When the load to be moved exceeds certain weight standards, powered hoists (Section 10.2.5) and similar lift equipment are used. Manufacturing systems that utilize manual work transport include manual assembly lines and group technology machine cells.

Various types of mechanized and automated material handling equipment are widely used to transport work units in manufacturing systems. We distinguish two general categories of work transport, according to the type of routing between stations: (1) fixed routing and (2) variable routing. In *fixed routing*, the work units always flow through the same sequence of workstations. This means that the work units are identical, or similar enough that the processing sequence is identical. Fixed routing transport is commonly used on production lines. In *variable routing*, work units are transported

through a variety of different station sequences. This means that the manufacturing system processes or assembles different types of work units. Variable routing transport is associated with job shop production and many batch production operations. Manufacturing systems that use variable routing include machine cells and flexible manufacturing systems. The difference between fixed and variable routing is portrayed in Figure 13.3. Table 13.1 lists some of the typical material transport equipment used for the two types of part routing.

Pallet Fixtures and Work Carriers in Transport Systems. Depending on the geometry of the work units and the nature of the processing and/or assembly operations performed, the transport system may be designed to accommodate some form of pallet fixture. A *pallet fixture* is a workholder that is designed to be transported by the material handling system. The part is accurately attached to the fixture on the upper face of the pallet, and the under portion of the pallet is designed to be moved, located, and clamped in position at each workstation in the system. Since the part is accurately located in the fixture, and the pallet is accurately clamped at the station, the part is accurately located at each station for processing or assembly. Use of pallet fixtures is common in automated manufacturing systems, such as single machine cells with automatic pallet changers, transfer lines, and automated assembly systems.

The fixtures can be designed with modular features that allow them to be used for different workpart geometries. With different components and a few adjustments, the fixture can accommodate variations in part sizes and shapes. These *modular pallet fixtures* are ideal for use in flexible manufacturing systems.

Alternative methods of workpart transport avoid the use of pallet fixtures. Instead, parts are moved by the handling system either with or without work carriers. A *work*

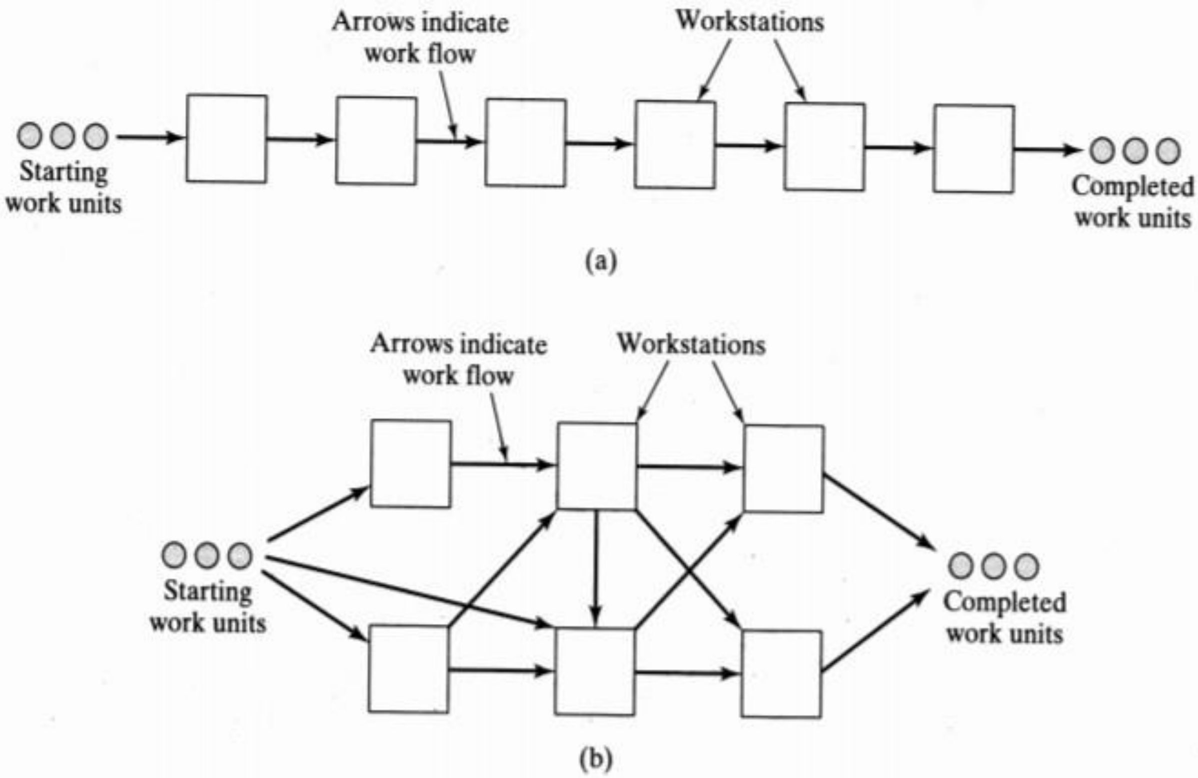


Figure 13.3 Two types of routing in multi-station manufacturing systems are (a) fixed routing and (b) variable routing.

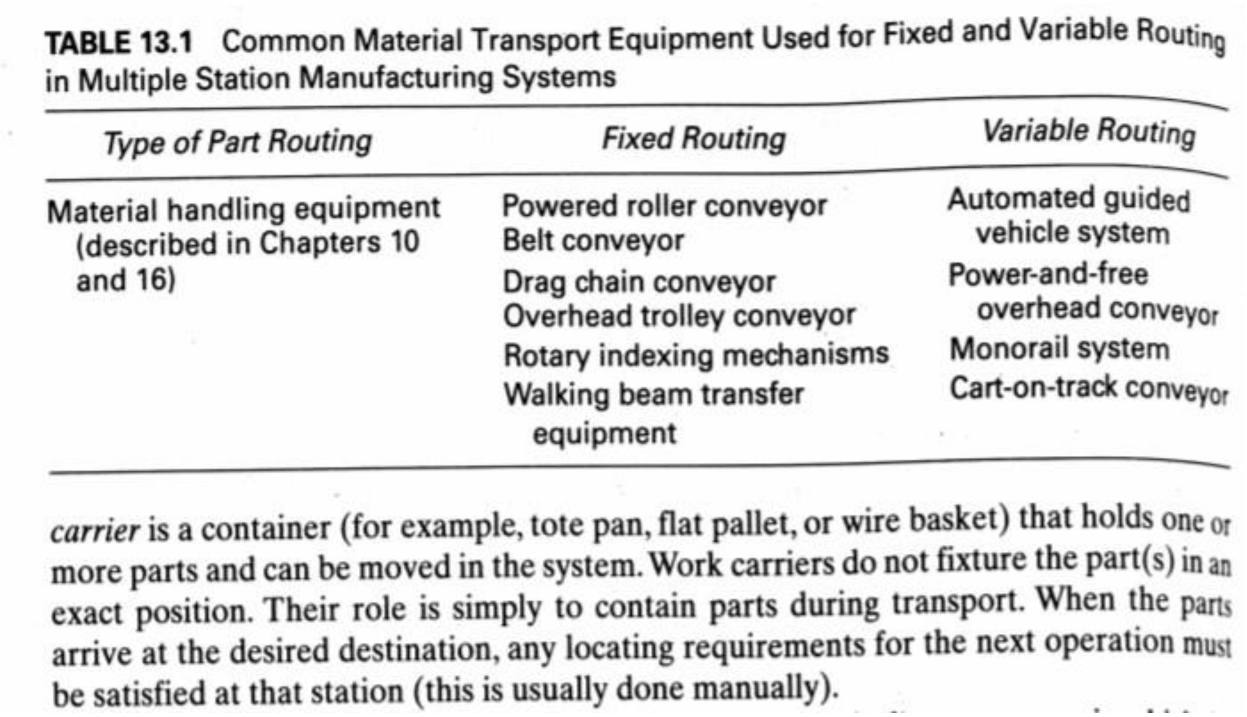
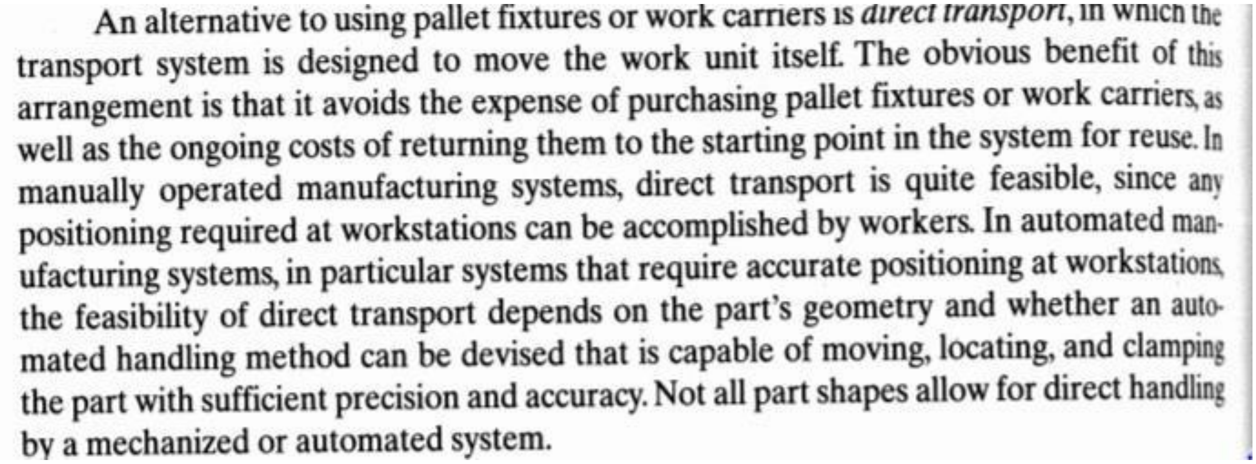


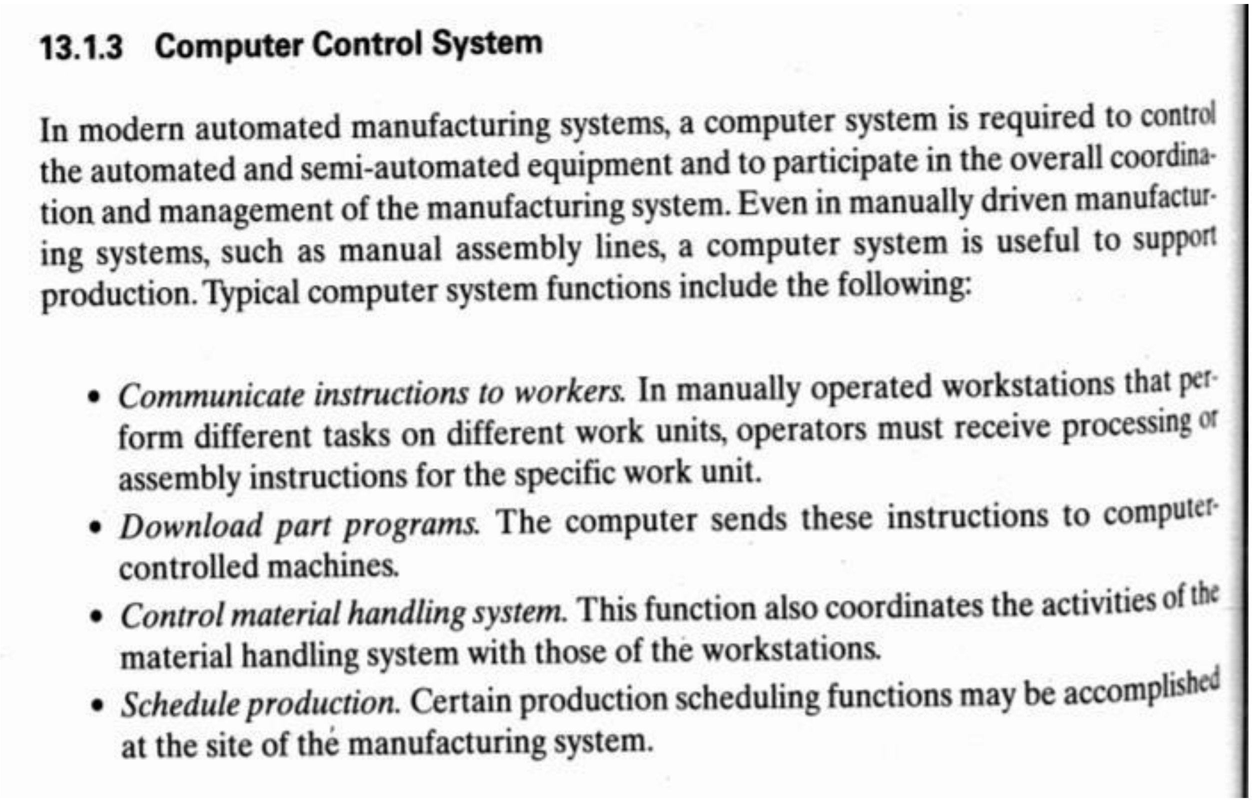
TABLE 13.1 Common Material Transport Equipment Used for Fixed and Variable Routing in Multiple Station Manufacturing Systems

Type of Part Routing	*Fixed Routing*	*Variable Routing*
Material handling equipment (described in Chapters 10 and 16)	Powered roller conveyor Belt conveyor Drag chain conveyor Overhead trolley conveyor Rotary indexing mechanisms Walking beam transfer equipment	Automated guided vehicle system Power-and-free overhead conveyor Monorail system Cart-on-track conveyor

carrier is a container (for example, tote pan, flat pallet, or wire basket) that holds one or more parts and can be moved in the system. Work carriers do not fixture the part(s) in an exact position. Their role is simply to contain parts during transport. When the parts arrive at the desired destination, any locating requirements for the next operation must be satisfied at that station (this is usually done manually).



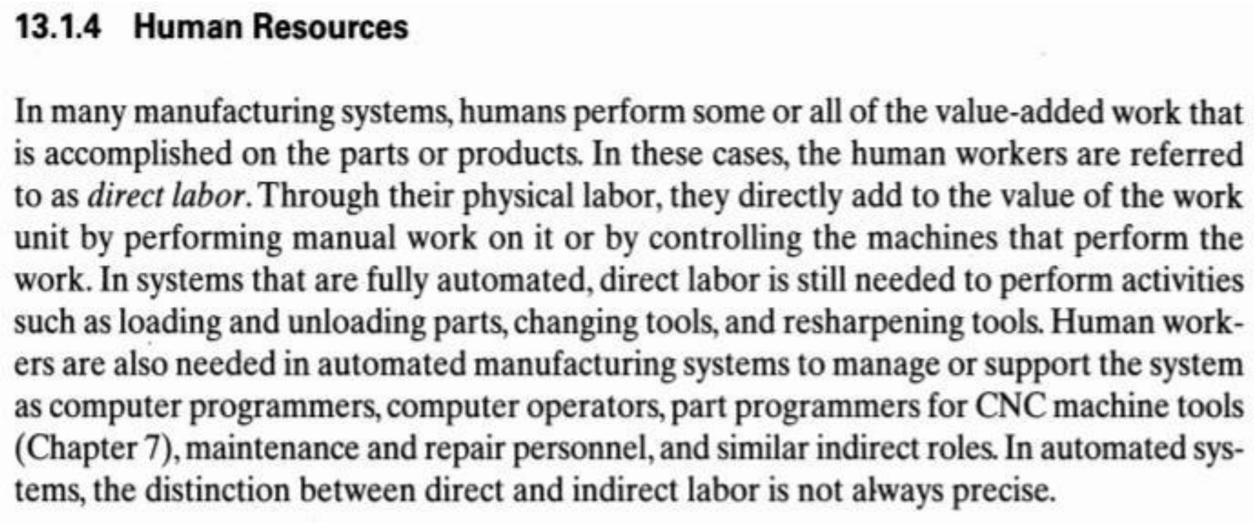
An alternative to using pallet fixtures or work carriers is *direct transport*, in which the transport system is designed to move the work unit itself. The obvious benefit of this arrangement is that it avoids the expense of purchasing pallet fixtures or work carriers, as well as the ongoing costs of returning them to the starting point in the system for reuse. In manually operated manufacturing systems, direct transport is quite feasible, since any positioning required at workstations can be accomplished by workers. In automated manufacturing systems, in particular systems that require accurate positioning at workstations, the feasibility of direct transport depends on the part's geometry and whether an automated handling method can be devised that is capable of moving, locating, and clamping the part with sufficient precision and accuracy. Not all part shapes allow for direct handling by a mechanized or automated system.



13.1.3 Computer Control System

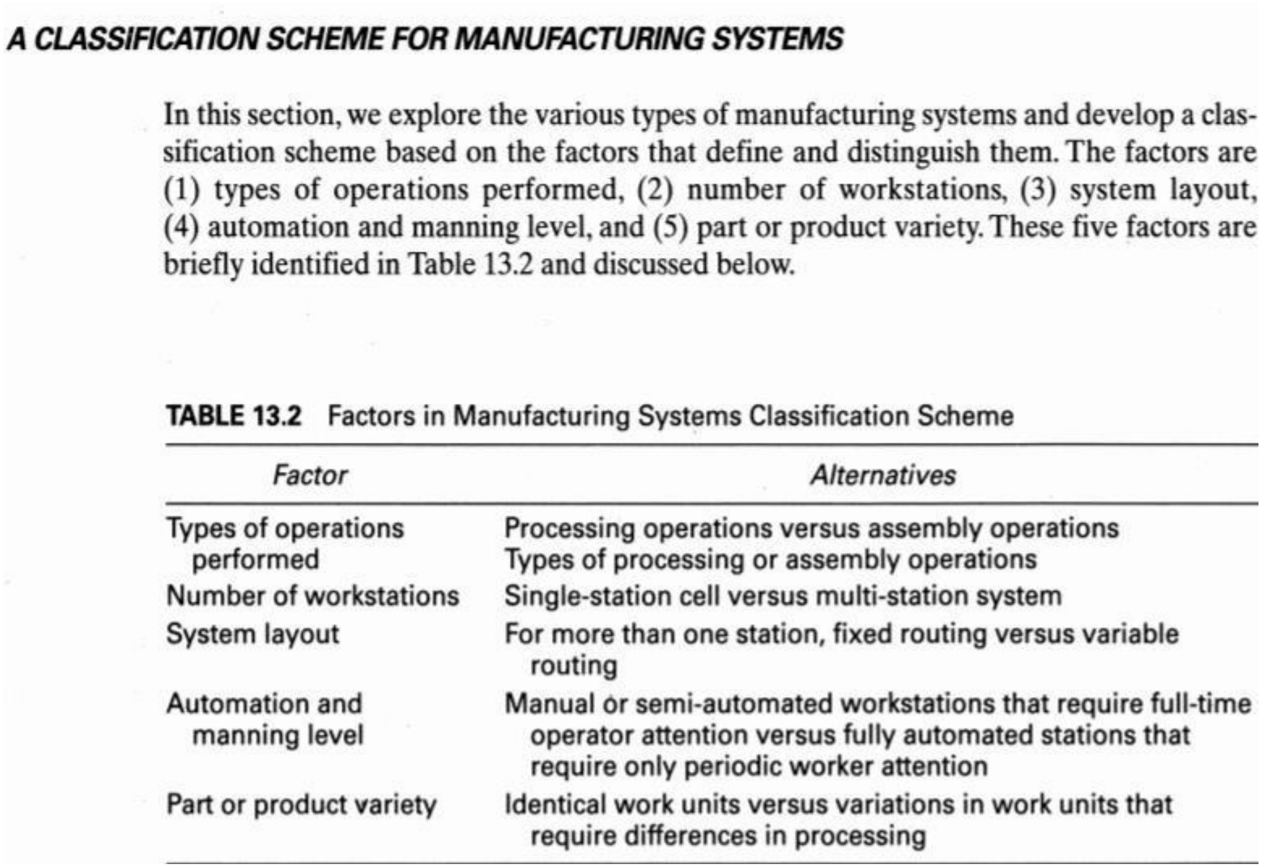
In modern automated manufacturing systems, a computer system is required to control the automated and semi-automated equipment and to participate in the overall coordination and management of the manufacturing system. Even in manually driven manufacturing systems, such as manual assembly lines, a computer system is useful to support production. Typical computer system functions include the following:

- *Communicate instructions to workers.* In manually operated workstations that perform different tasks on different work units, operators must receive processing or assembly instructions for the specific work unit.
- *Download part programs.* The computer sends these instructions to computer-controlled machines.
- *Control material handling system.* This function also coordinates the activities of the material handling system with those of the workstations.
- *Schedule production.* Certain production scheduling functions may be accomplished at the site of the manufacturing system.



13.1.4 Human Resources

In many manufacturing systems, humans perform some or all of the value-added work that is accomplished on the parts or products. In these cases, the human workers are referred to as *direct labor*. Through their physical labor, they directly add to the value of the work unit by performing manual work on it or by controlling the machines that perform the work. In systems that are fully automated, direct labor is still needed to perform activities such as loading and unloading parts, changing tools, and resharpening tools. Human workers are also needed in automated manufacturing systems to manage or support the system as computer programmers, computer operators, part programmers for CNC machine tools (Chapter 7), maintenance and repair personnel, and similar indirect roles. In automated systems, the distinction between direct and indirect labor is not always precise.

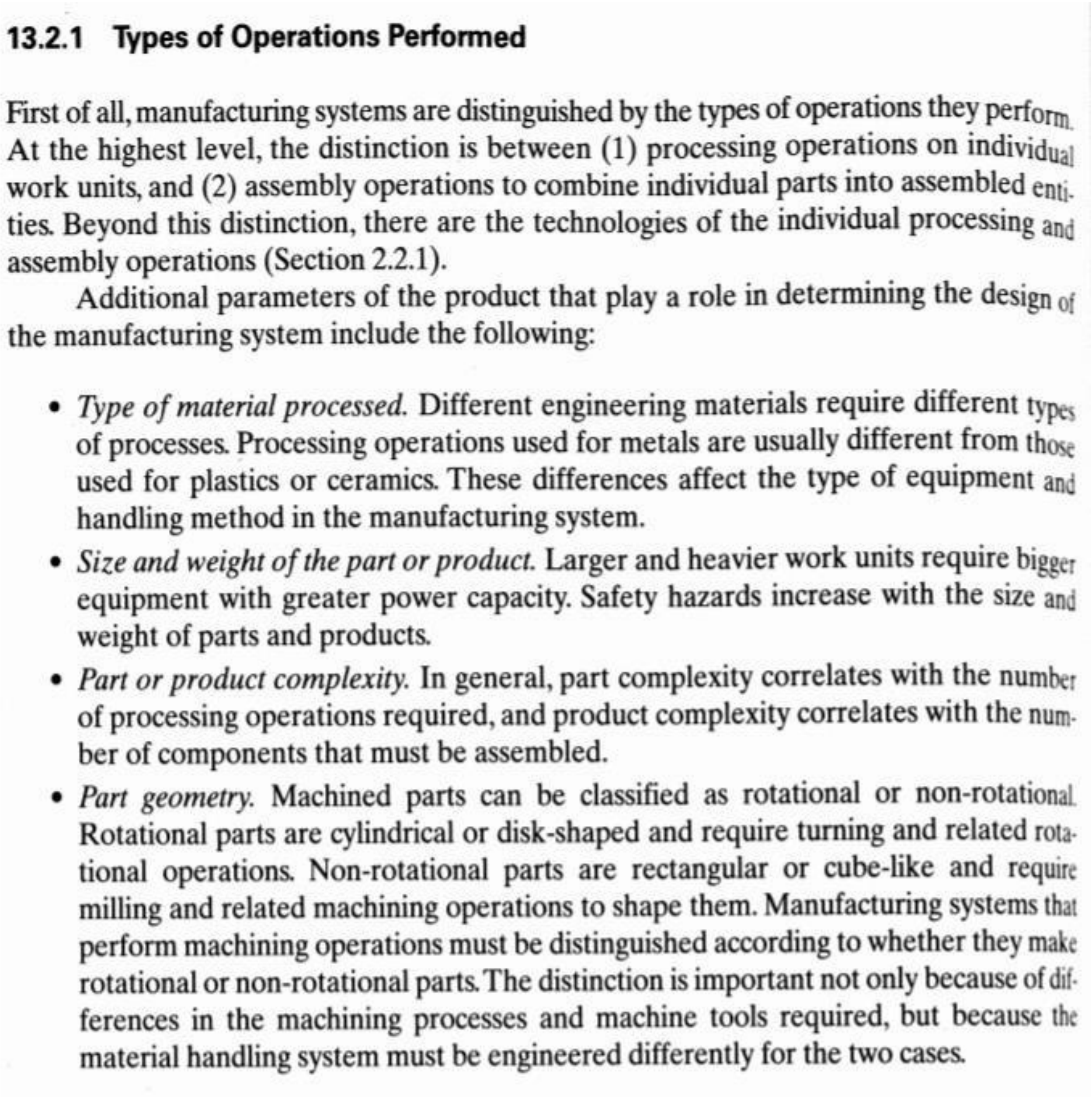


A CLASSIFICATION SCHEME FOR MANUFACTURING SYSTEMS

In this section, we explore the various types of manufacturing systems and develop a classification scheme based on the factors that define and distinguish them. The factors are (1) types of operations performed, (2) number of workstations, (3) system layout, (4) automation and manning level, and (5) part or product variety. These five factors are briefly identified in Table 13.2 and discussed below.

TABLE 13.2 Factors in Manufacturing Systems Classification Scheme

Factor	*Alternatives*
Types of operations performed	Processing operations versus assembly operations Types of processing or assembly operations
Number of workstations	Single-station cell versus multi-station system
System layout	For more than one station, fixed routing versus variable routing
Automation and manning level	Manual or semi-automated workstations that require full-time operator attention versus fully automated stations that require only periodic worker attention
Part or product variety	Identical work units versus variations in work units that require differences in processing



13.2.1 Types of Operations Performed

First of all, manufacturing systems are distinguished by the types of operations they perform. At the highest level, the distinction is between (1) processing operations on individual work units, and (2) assembly operations to combine individual parts into assembled entities. Beyond this distinction, there are the technologies of the individual processing and assembly operations (Section 2.2.1).

Additional parameters of the product that play a role in determining the design of the manufacturing system include the following:

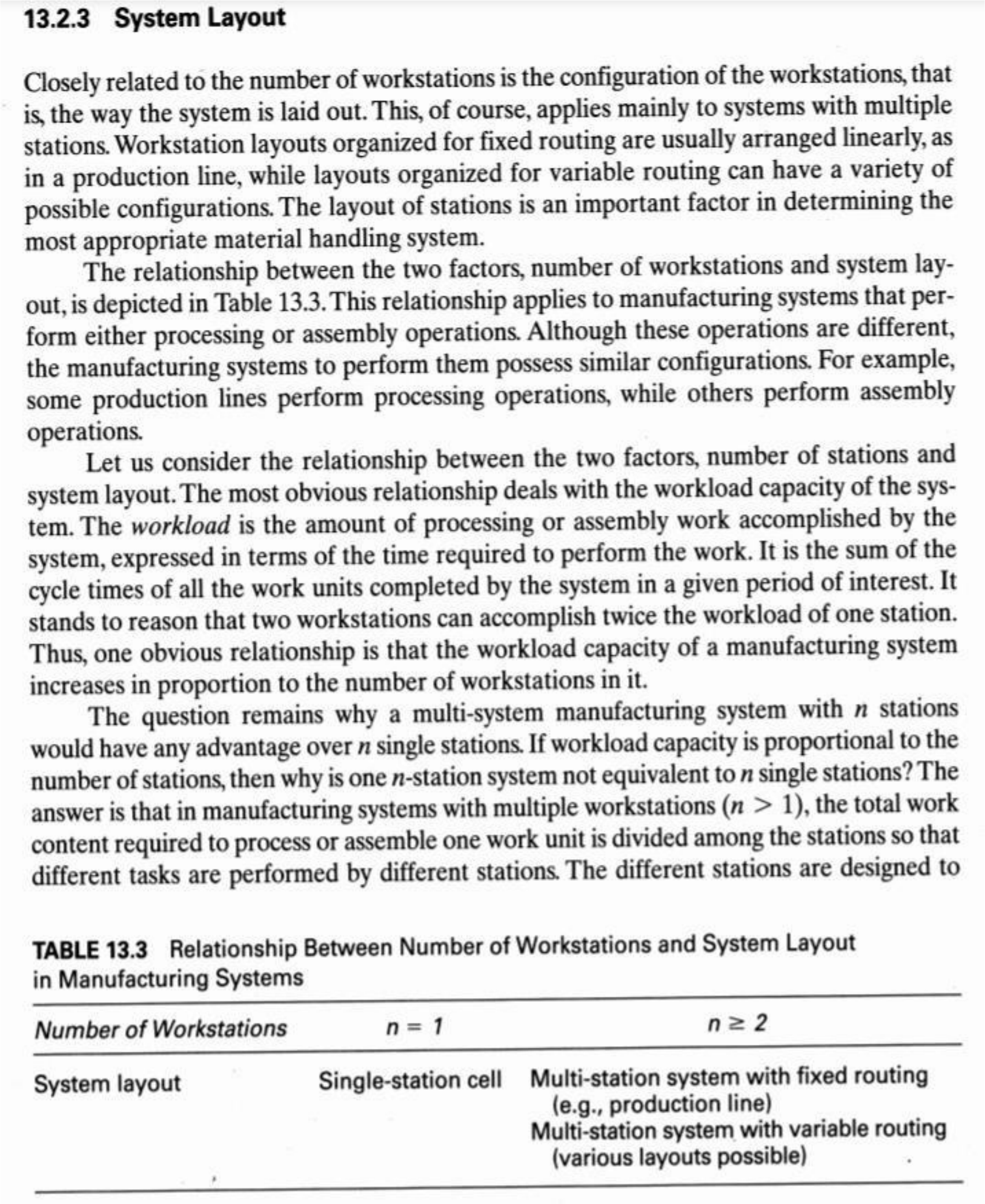
- *Type of material processed.* Different engineering materials require different types of processes. Processing operations used for metals are usually different from those used for plastics or ceramics. These differences affect the type of equipment and handling method in the manufacturing system.
- *Size and weight of the part or product.* Larger and heavier work units require bigger equipment with greater power capacity. Safety hazards increase with the size and weight of parts and products.
- *Part or product complexity.* In general, part complexity correlates with the number of processing operations required, and product complexity correlates with the number of components that must be assembled.
- *Part geometry.* Machined parts can be classified as rotational or non-rotational. Rotational parts are cylindrical or disk-shaped and require turning and related rotational operations. Non-rotational parts are rectangular or cube-like and require milling and related machining operations to shape them. Manufacturing systems that perform machining operations must be distinguished according to whether they make rotational or non-rotational parts. The distinction is important not only because of differences in the machining processes and machine tools required, but because the material handling system must be engineered differently for the two cases.

13.2.2 Number of Workstations

The number of workstations is a key factor in our manufacturing systems classification scheme. It exerts a strong influence on the performance of the manufacturing system in terms of performance factors such as workload capacity, production rate, and reliability. Let us denote the number of workstations in the system by the symbol n. The individual stations in a manufacturing system can be identified by the subscript i, where $i = 1, 2, \ldots, n$. This might be useful in identifying parameters of the individual workstations, such as operation time or number of workers at a station. In our classification scheme, we distinguish between single-station cells ($n = 1$) and multi-station systems ($n > 1$).

The number of workstations in the manufacturing system is a convenient measure of its size. As the number of stations increases, the amount of work that can be accomplished by the system increases. This may translate into a higher production rate, certainly compared to the output of a single station, but also compared to the same number of single stations working independently. There must be a synergistic benefit obtained from multiple stations working together rather than independently; otherwise, it makes more sense for the stations to work as independent entities. The synergistic benefit is usually derived from the fact that the total amount of work performed on the part or product is too complex to accomplish at a single workstation. There are too many tasks to perform at one station. When separate tasks are assigned to individual stations, the task performed at each station is simplified. We build on this notion in Section 13.2.3.

More stations also mean that the system is more complex, and therefore more difficult to manage and maintain. The system consists of more workers, more machines, and more parts being handled. The material handling system is more complex in a multi-station system. It becomes increasingly complex as n increases. The logistics and coordination of the system is more involved. Reliability and maintenance problems occur more frequently.



13.2.3 System Layout

Closely related to the number of workstations is the configuration of the workstations, that is, the way the system is laid out. This, of course, applies mainly to systems with multiple stations. Workstation layouts organized for fixed routing are usually arranged linearly, as in a production line, while layouts organized for variable routing can have a variety of possible configurations. The layout of stations is an important factor in determining the most appropriate material handling system.

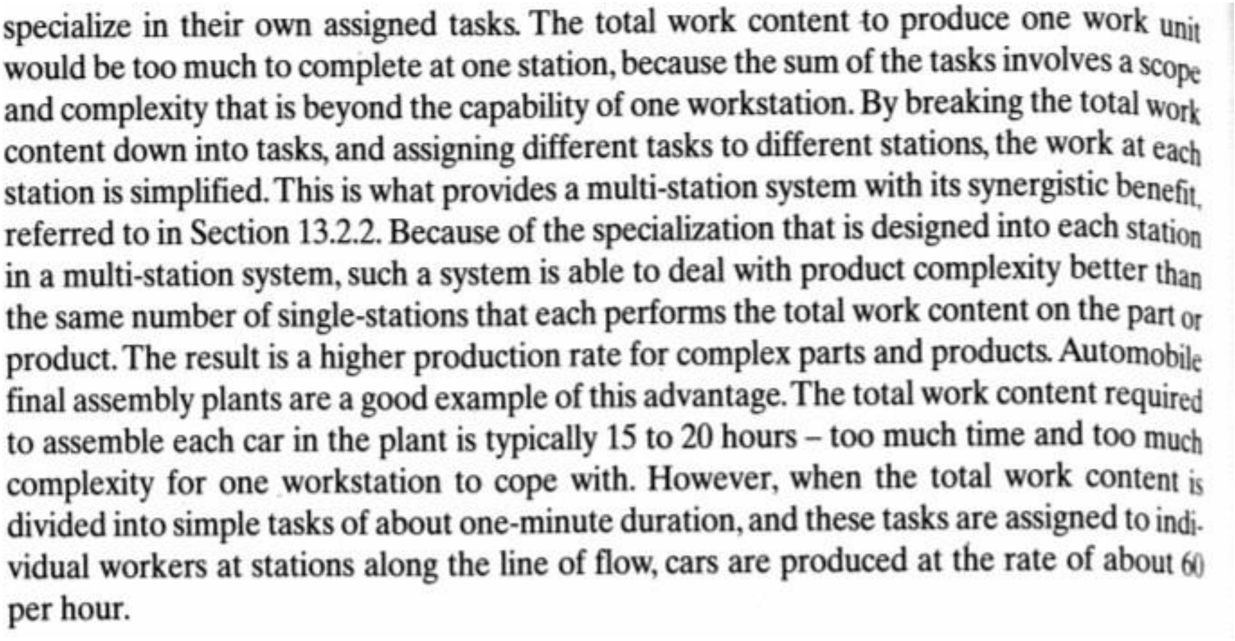
The relationship between the two factors, number of workstations and system layout, is depicted in Table 13.3. This relationship applies to manufacturing systems that perform either processing or assembly operations. Although these operations are different, the manufacturing systems to perform them possess similar configurations. For example, some production lines perform processing operations, while others perform assembly operations.

Let us consider the relationship between the two factors, number of stations and system layout. The most obvious relationship deals with the workload capacity of the system. The *workload* is the amount of processing or assembly work accomplished by the system, expressed in terms of the time required to perform the work. It is the sum of the cycle times of all the work units completed by the system in a given period of interest. It stands to reason that two workstations can accomplish twice the workload of one station. Thus, one obvious relationship is that the workload capacity of a manufacturing system increases in proportion to the number of workstations in it.

The question remains why a multi-system manufacturing system with n stations would have any advantage over n single stations. If workload capacity is proportional to the number of stations, then why is one n-station system not equivalent to n single stations? The answer is that in manufacturing systems with multiple workstations ($n > 1$), the total work content required to process or assemble one work unit is divided among the stations so that different tasks are performed by different stations. The different stations are designed to

TABLE 13.3 Relationship Between Number of Workstations and System Layout in Manufacturing Systems

Number of Workstations	$n = 1$	$n \geq 2$
System layout	Single-station cell	Multi-station system with fixed routing (e.g., production line) Multi-station system with variable routing (various layouts possible)



specialize in their own assigned tasks. The total work content to produce one work unit would be too much to complete at one station, because the sum of the tasks involves a scope and complexity that is beyond the capability of one workstation. By breaking the total work content down into tasks, and assigning different tasks to different stations, the work at each station is simplified. This is what provides a multi-station system with its synergistic benefit, referred to in Section 13.2.2. Because of the specialization that is designed into each station in a multi-station system, such a system is able to deal with product complexity better than the same number of single-stations that each performs the total work content on the part or product. The result is a higher production rate for complex parts and products. Automobile final assembly plants are a good example of this advantage. The total work content required to assemble each car in the plant is typically 15 to 20 hours – too much time and too much complexity for one workstation to cope with. However, when the total work content is divided into simple tasks of about one-minute duration, and these tasks are assigned to individual workers at stations along the line of flow, cars are produced at the rate of about 60 per hour.

13.2.4 Automation and Manning Levels

The level of automation is another factor that characterizes the manufacturing system. As defined above, the workstation machines in a manufacturing system can be manually operated, semi-automated, or automated. Inversely correlated with the level of automation is the proportion of time that a worker must be in attendance at each station. The *manning level* of a workstation, symbolized M_i, is the proportion of time that a worker is at the station. If $M_i = 1$ for station i, it means that one worker must be at the station continuously. If one worker tends four automatic machines, then $M_i = 0.25$ for each of the four machines, assuming each machine requires the same amount of attention. On sections of an automobile final assembly line, there are stations each tended by multiple workers, in which case $M_i = 2$ or 3 or more. In general, high values of M_i ($M_i \geq 1$) indicate manual operations at the workstation, while low values ($M_i < 1$) denote some form of automation.

The average manning level of a multi-station manufacturing system is a useful indicator of the direct labor content of the system. Let us define it as

$$M = \frac{w_u + \sum_{i=1}^{n} w_i}{n} = \frac{w}{n} \tag{13.1}$$

where M = average manning level for the system; w_u = number of utility workers assigned to the system; w_i = number of workers assigned specifically to station i, for $i = 1, 2, \ldots, n$; and w = total number of workers assigned to the system. *Utility workers* are workers who are not specifically assigned to individual processing or assembly stations; instead they perform functions such as (1) relieving workers at stations for personal breaks, (2) maintenance and repair of the system, (3) material handling, and (4) tool changing. Even a fully automated multi-station manufacturing system is likely to have one or more utility workers who are responsible for keeping it running.

Including automation and manning level in our classification scheme, we have two possible levels for single stations and three possible levels for multi-station systems. The two levels for single stations are manned and fully automated. The manned station is identified by the fact that one or more workers must be at the station every cycle. This means that any machine at the station is manually operated or semi-automatic and that manning is equal to or greater than one ($M \geq 1$). However, in some cases, one worker may be able to attend more than one machine (e.g., a machine cluster) if the semi-automatic cycle is long relative to the service required each cycle of the worker (thus, $M < 1$). We discuss machine clusters in Section 14.4.2. A fully automated station requires less than full-time attention of a worker ($M < 1$). For multi-station systems, the same two levels are applicable (manned and fully automated), but a third level is also possible for the system. This is of a hybrid system, in which some stations are manned while others are fully automated. Expanding the information portrayed in previous Table 13.3 to include automation and manning level, we have Table 13.4.

13.2.5 Part or Product Variety

A fifth factor that characterizes a manufacturing system is the degree to which it is capable of dealing with variations in the parts or products it produces. Examples of possible variations that a manufacturing system may have to cope with include

- Variations in type and/or color of plastic of molded parts in injection molding
- Variations in electronic components placed on a standard size printed circuit board
- Variations in the size of printed circuit boards handled by a component placement machine
- Variations in geometry of machined parts
- Variations in parts and options in an assembled product.

In this section, we identify three types of manufacturing systems, distinguished by their capability to cope with part or product variety. We then discuss two ways in which manufacturing systems can be endowed with this capability.

Part or Product Variety: Three Cases. Borrowing from the terminology used in manual assembly line technology (Section 15.1.4), the three cases of part or product variety in manufacturing systems are (1) single model, (2) batch model, and (3) mixed model.

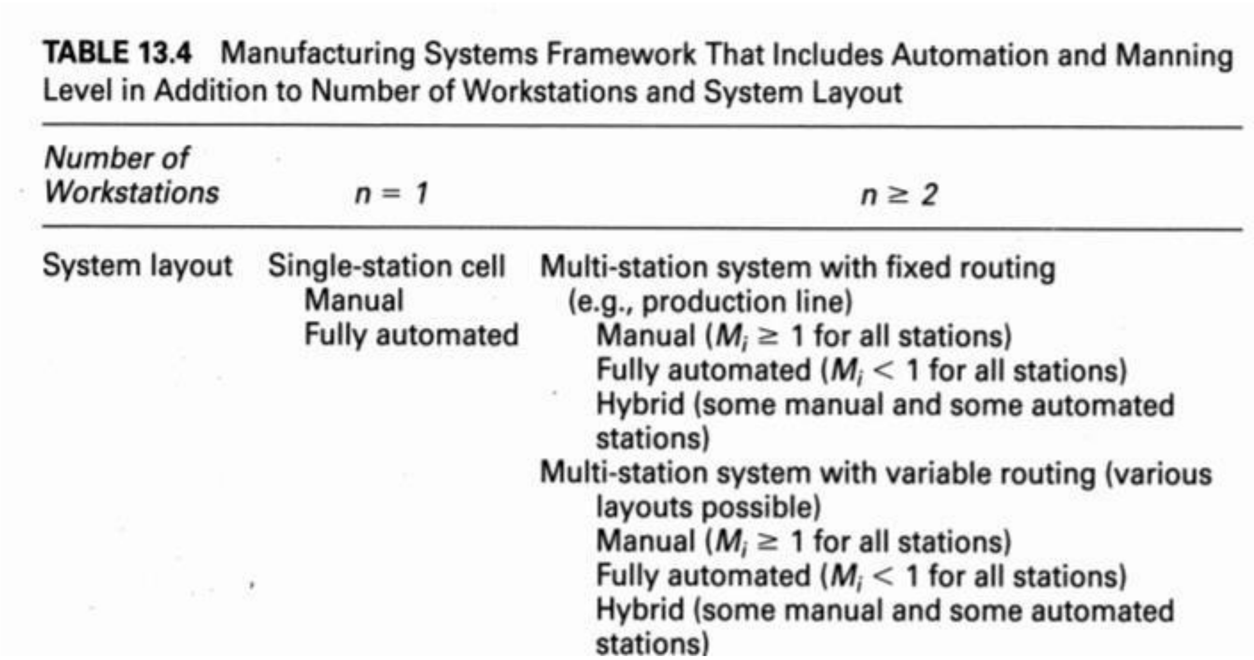
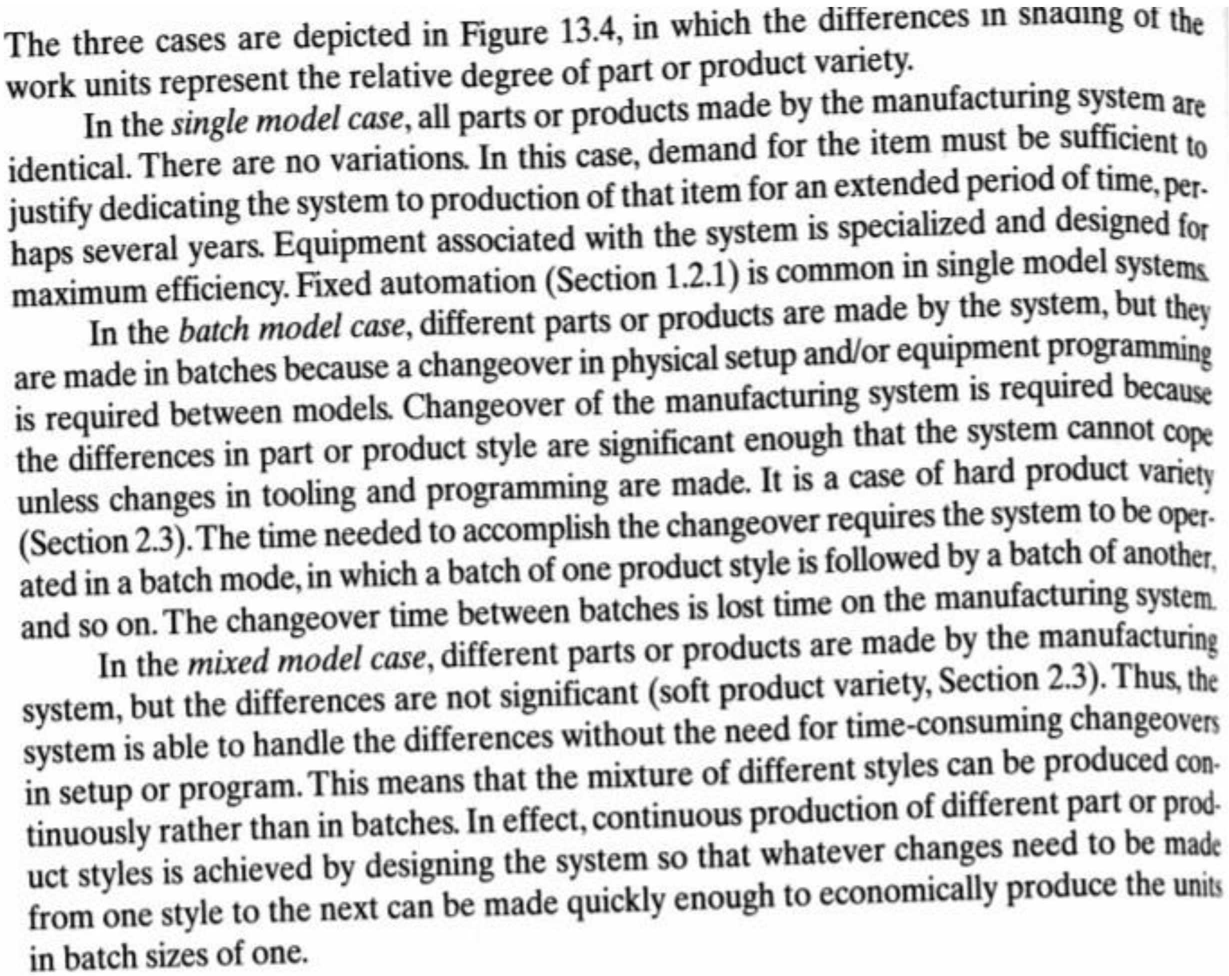


TABLE 13.4 Manufacturing Systems Framework That Includes Automation and Manning Level in Addition to Number of Workstations and System Layout

Number of Workstations	$n = 1$	$n \geq 2$
System layout	Single-station cell Manual Fully automated	Multi-station system with fixed routing (e.g., production line) Manual ($M_i \geq 1$ for all stations) Fully automated ($M_i < 1$ for all stations) Hybrid (some manual and some automated stations) Multi-station system with variable routing (various layouts possible) Manual ($M_i \geq 1$ for all stations) Fully automated ($M_i < 1$ for all stations) Hybrid (some manual and some automated stations)



The three cases are depicted in Figure 13.4, in which the differences in shading of the work units represent the relative degree of part or product variety.

In the *single model case*, all parts or products made by the manufacturing system are identical. There are no variations. In this case, demand for the item must be sufficient to justify dedicating the system to production of that item for an extended period of time, perhaps several years. Equipment associated with the system is specialized and designed for maximum efficiency. Fixed automation (Section 1.2.1) is common in single model systems.

In the *batch model case*, different parts or products are made by the system, but they are made in batches because a changeover in physical setup and/or equipment programming is required between models. Changeover of the manufacturing system is required because the differences in part or product style are significant enough that the system cannot cope unless changes in tooling and programming are made. It is a case of hard product variety (Section 2.3). The time needed to accomplish the changeover requires the system to be operated in a batch mode, in which a batch of one product style is followed by a batch of another, and so on. The changeover time between batches is lost time on the manufacturing system.

In the *mixed model case*, different parts or products are made by the manufacturing system, but the differences are not significant (soft product variety, Section 2.3). Thus, the system is able to handle the differences without the need for time-consuming changeovers in setup or program. This means that the mixture of different styles can be produced continuously rather than in batches. In effect, continuous production of different part or product styles is achieved by designing the system so that whatever changes need to be made from one style to the next can be made quickly enough to economically produce the units in batch sizes of one.

Flexibility in Mixed Model Manufacturing Systems. Flexibility allows a mixed model manufacturing system to cope with a certain level of variation in part or product style without interruptions in production for changeovers between models. Flexibility is

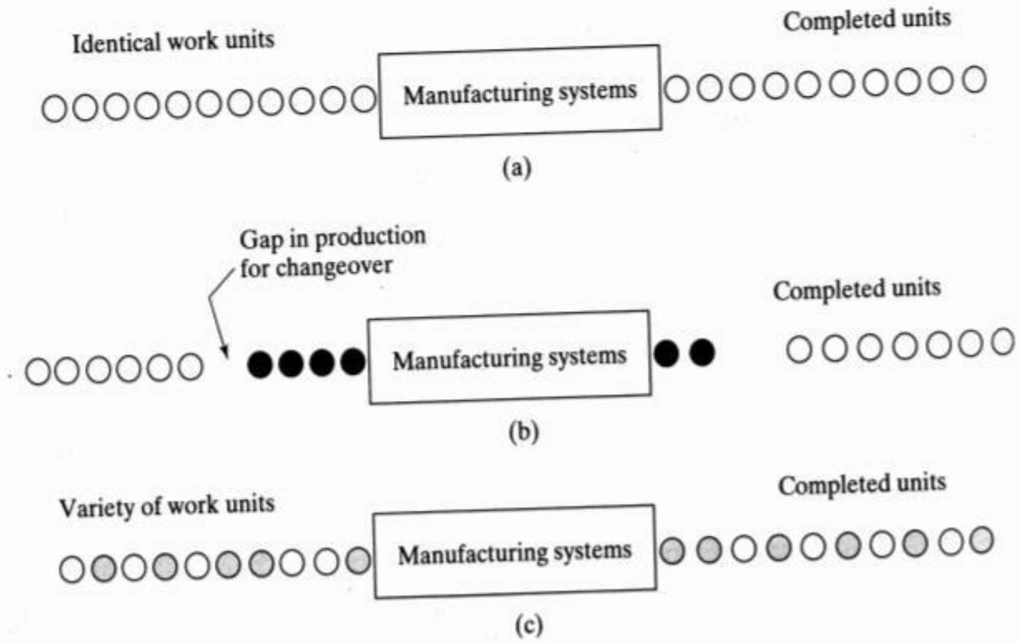
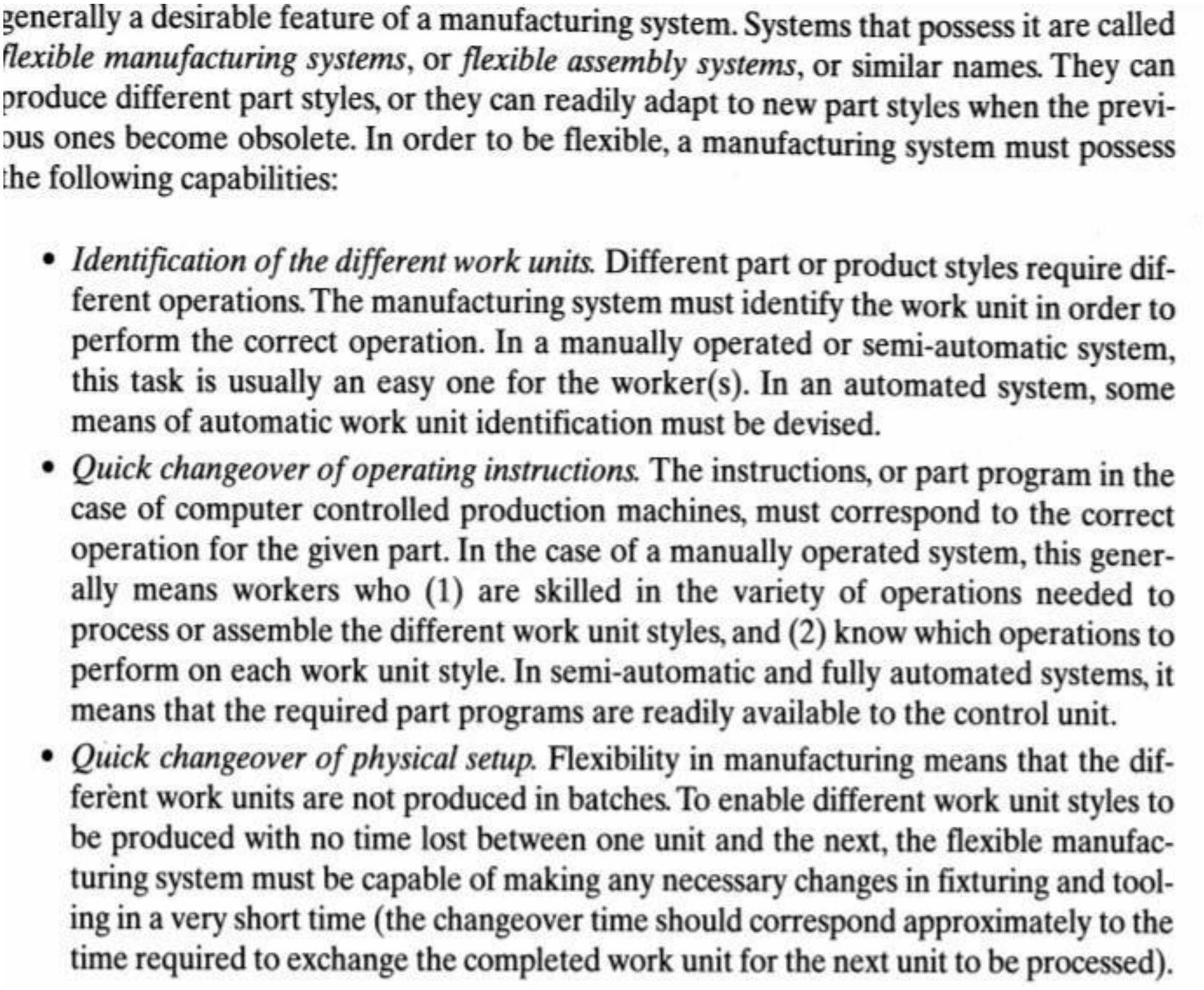


Figure 13.4 Three cases of part or product variety in manufacturing systems: (a) single model case, (b) batch model case, and (c) mixed model case.



generally a desirable feature of a manufacturing system. Systems that possess it are called *flexible manufacturing systems*, or *flexible assembly systems*, or similar names. They can produce different part styles, or they can readily adapt to new part styles when the previous ones become obsolete. In order to be flexible, a manufacturing system must possess the following capabilities:

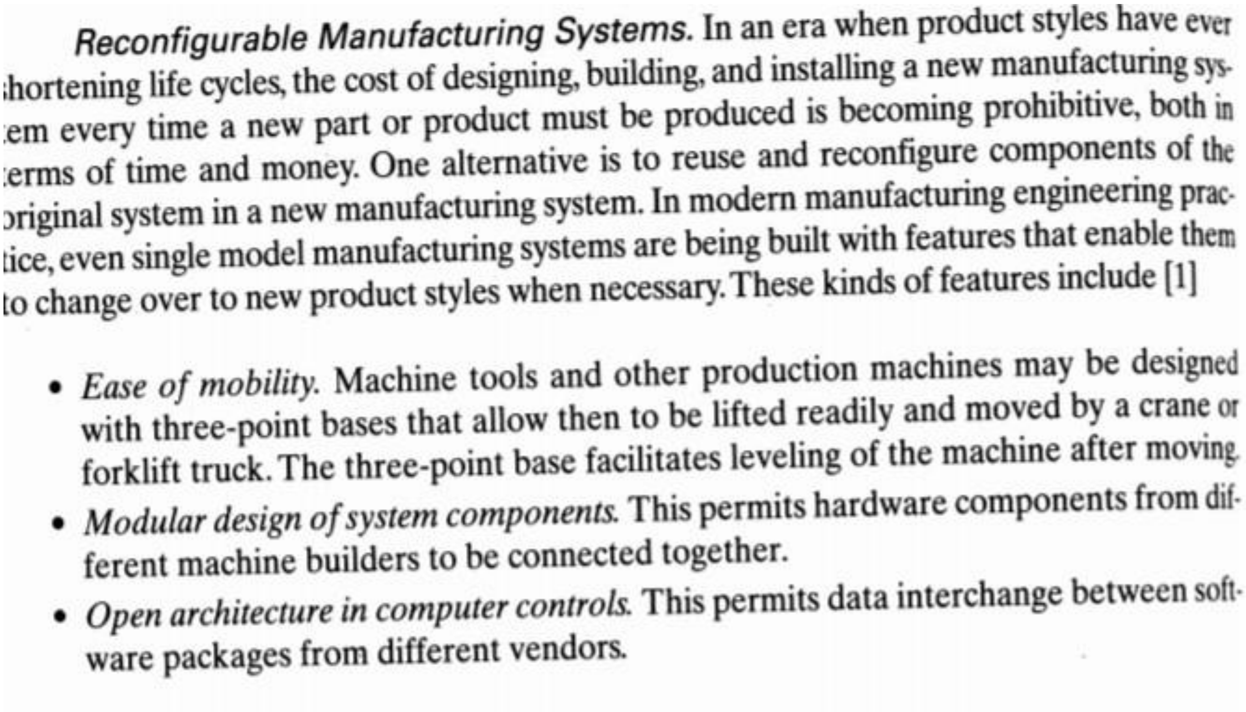
- *Identification of the different work units.* Different part or product styles require different operations. The manufacturing system must identify the work unit in order to perform the correct operation. In a manually operated or semi-automatic system, this task is usually an easy one for the worker(s). In an automated system, some means of automatic work unit identification must be devised.
- *Quick changeover of operating instructions.* The instructions, or part program in the case of computer controlled production machines, must correspond to the correct operation for the given part. In the case of a manually operated system, this generally means workers who (1) are skilled in the variety of operations needed to process or assemble the different work unit styles, and (2) know which operations to perform on each work unit style. In semi-automatic and fully automated systems, it means that the required part programs are readily available to the control unit.
- *Quick changeover of physical setup.* Flexibility in manufacturing means that the different work units are not produced in batches. To enable different work unit styles to be produced with no time lost between one unit and the next, the flexible manufacturing system must be capable of making any necessary changes in fixturing and tooling in a very short time (the changeover time should correspond approximately to the time required to exchange the completed work unit for the next unit to be processed).

These capabilities are often difficult to engineer. In manually operated manufacturing systems, human errors can cause problems—operators not performing the correct operations on the different work unit styles. In automated systems, sensor systems must be designed to enable work unit identification. Part program changeover is accomplished with relative ease using today's computer technology. Changing the physical setup is often the most challenging problem, and it becomes more difficult as part or product variety increases. Endowing a manufacturing system with flexibility increases its complexity. The material handling system and/or pallet fixtures must be designed to hold a variety of part shapes. The required number of different tools increases. Inspection becomes more complicated because of part variety. The logistics of supplying the system with the correct quantities of different starting workparts is more involved. Scheduling and coordinating the system become more difficult.

Single-station manned cells inherently possess the greatest flexibility. Human workers are dexterous and can adapt to a great variety of tasks requiring a range of skills. Given the proper tools, a worker can change over his or her workstation to accommodate a significant diversity of jobs and work units. However, single stations are limited in terms of the part or product complexity they can cope with. If the work unit is simple, requiring only one or a limited number of processing or assembly operations, then a single-station cell can be justified for high as well as low annual production quantities. Higher quantities make automated cells more attractive.

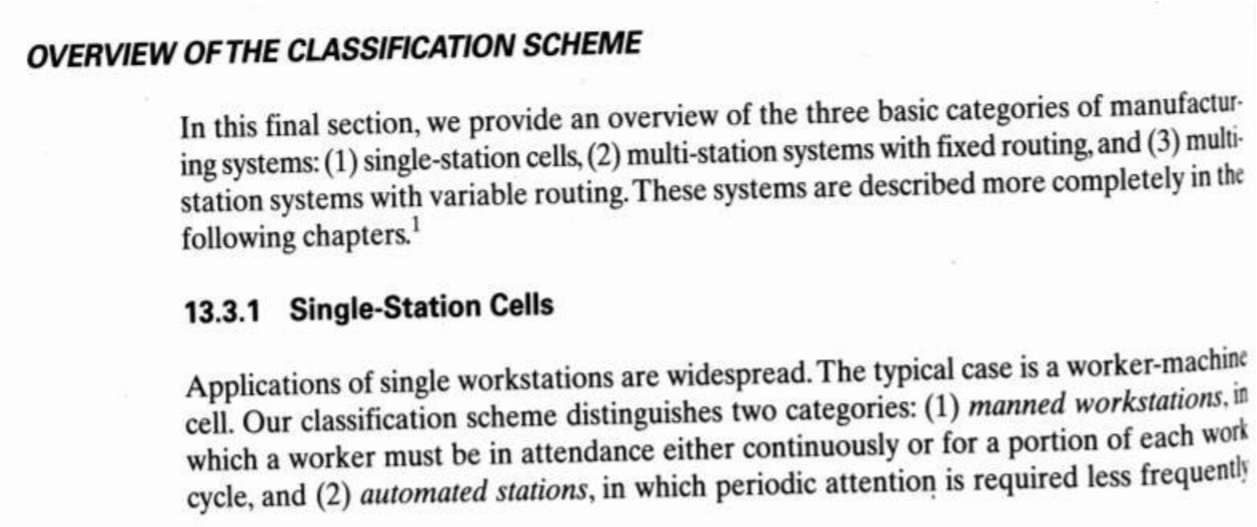
As the complexity of the work unit increases, the advantage shifts toward multi-station systems. The larger number of tasks and additional tooling required for more complex parts or products begins to overwhelm a single station. Dividing the work among multiple stations is a way to reduce complexity at each station. If there is no product variety or soft product variety, and the product is made in high quantities, then a multi-station system with fixed routing is appropriate. As product variety increases for production quantities in the medium range, a multi-station system with variable routing becomes more appropriate. Variable routing allows different work units to follow their own individual sequence of stations and operations in the system. Finally, in cases of significant product variety and low production quantities, the greatest flexibility is achieved by using a collection of single-station cells, each organized to perform a limited set of tasks but integrated to complete the total work content on each work unit. Of course, what we are describing is a job shop, the most flexible but least efficient of the factory organizations. Much of the discussion in the preceding sections is summarized in the Figure 13.5(a) and (b).

Flexibility itself is a complex issue, certainly more complex than it appears in this introductory treatment of it. It is recognized as an important attribute for a system to possess. We provide a more in-depth discussion of the issue in Chapter 19.



Reconfigurable Manufacturing Systems. In an era when product styles have ever shortening life cycles, the cost of designing, building, and installing a new manufacturing system every time a new part or product must be produced is becoming prohibitive, both in terms of time and money. One alternative is to reuse and reconfigure components of the original system in a new manufacturing system. In modern manufacturing engineering practice, even single model manufacturing systems are being built with features that enable them to change over to new product styles when necessary. These kinds of features include [1]

- *Ease of mobility.* Machine tools and other production machines may be designed with three-point bases that allow then to be lifted readily and moved by a crane or forklift truck. The three-point base facilitates leveling of the machine after moving.
- *Modular design of system components.* This permits hardware components from different machine builders to be connected together.
- *Open architecture in computer controls.* This permits data interchange between software packages from different vendors.

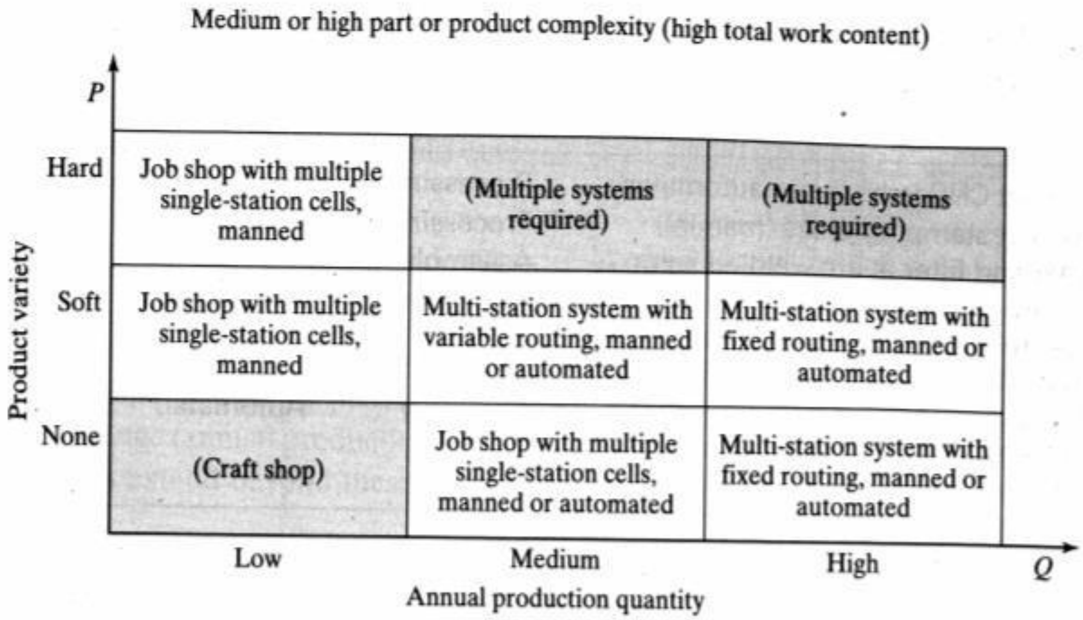


OVERVIEW OF THE CLASSIFICATION SCHEME

In this final section, we provide an overview of the three basic categories of manufacturing systems: (1) single-station cells, (2) multi-station systems with fixed routing, and (3) multistation systems with variable routing. These systems are described more completely in the following chapters.[1]

13.3.1 Single-Station Cells

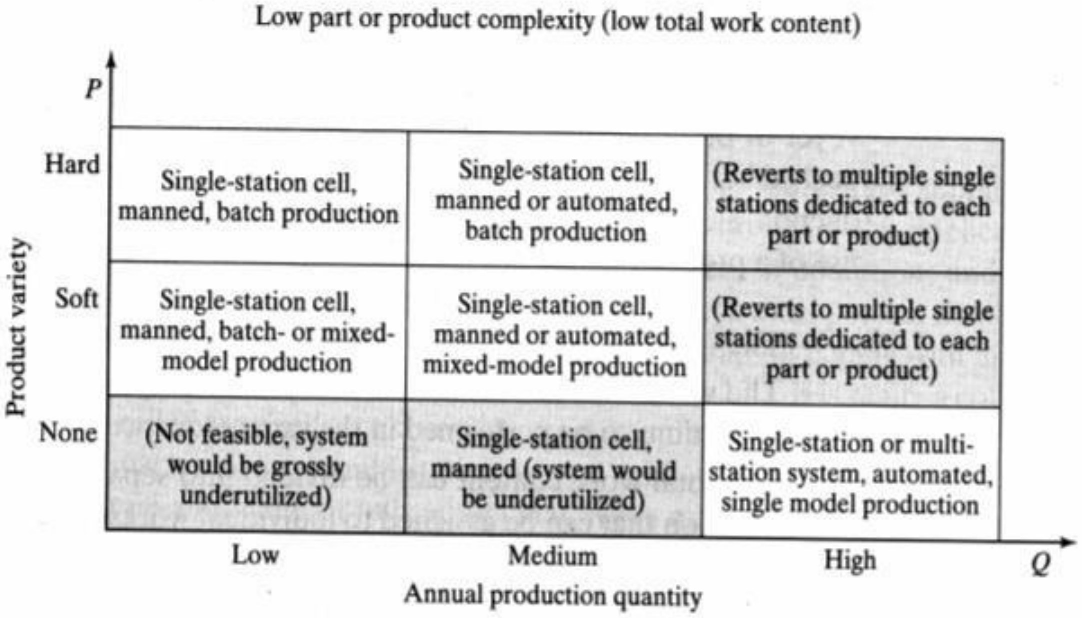
Applications of single workstations are widespread. The typical case is a worker-machine cell. Our classification scheme distinguishes two categories: (1) *manned workstations*, in which a worker must be in attendance either continuously or for a portion of each work cycle, and (2) *automated stations*, in which periodic attention is required less frequently



Medium or high part or product complexity (high total work content)

Product variety	Low	Medium	High
Hard	Job shop with multiple single-station cells, manned	(Multiple systems required)	(Multiple systems required)
Soft	Job shop with multiple single-station cells, manned	Multi-station system with variable routing, manned or automated	Multi-station system with fixed routing, manned or automated
None	(Craft shop)	Job shop with multiple single-station cells, manned or automated	Multi-station system with fixed routing, manned or automated

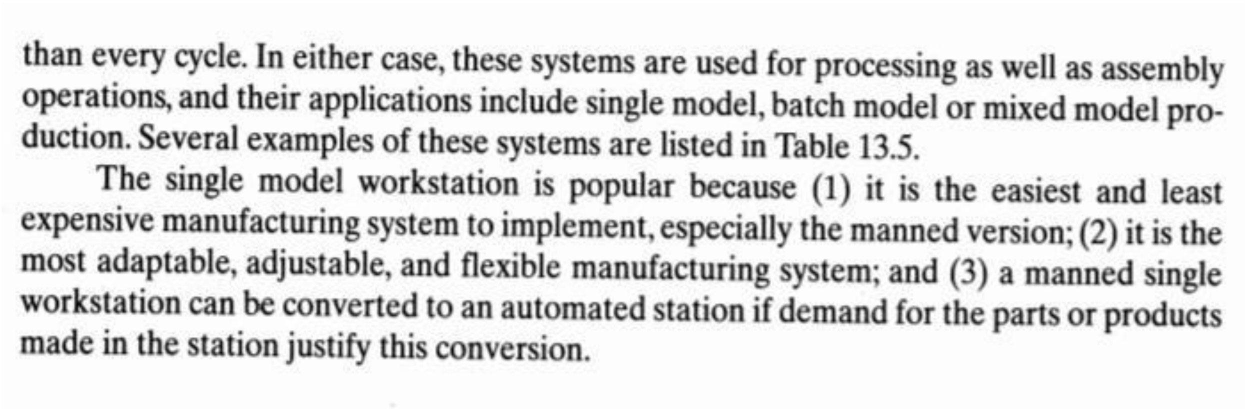
(a)



Low part or product complexity (low total work content)

Product variety	Low	Medium	High
Hard	Single-station cell, manned, batch production	Single-station cell, manned or automated, batch production	(Reverts to multiple single stations dedicated to each part or product)
Soft	Single-station cell, manned, batch- or mixed-model production	Single-station cell, manned or automated, mixed-model production	(Reverts to multiple single stations dedicated to each part or product)
None	(Not feasible, system would be grossly underutilized)	Single-station cell, manned (system would be underutilized)	Single-station or multi-station system, automated, single model production

(b)



than every cycle. In either case, these systems are used for processing as well as assembly operations, and their applications include single model, batch model or mixed model production. Several examples of these systems are listed in Table 13.5.

The single model workstation is popular because (1) it is the easiest and least expensive manufacturing system to implement, especially the manned version; (2) it is the most adaptable, adjustable, and flexible manufacturing system; and (3) a manned single workstation can be converted to an automated station if demand for the parts or products made in the station justify this conversion.

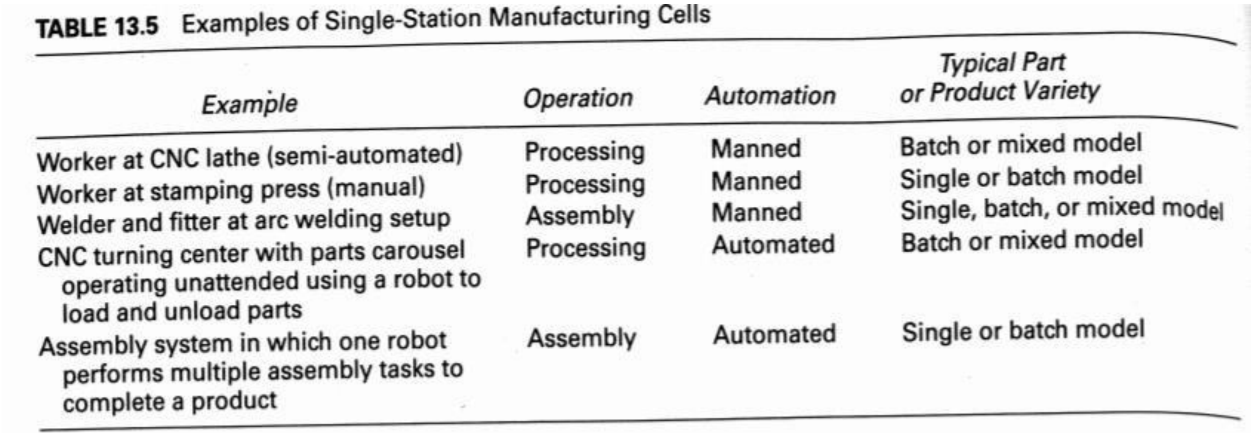


TABLE 13.5 Examples of Single-Station Manufacturing Cells

Example	*Operation*	*Automation*	*Typical Part or Product Variety*
Worker at CNC lathe (semi-automated)	Processing	Manned	Batch or mixed model
Worker at stamping press (manual)	Processing	Manned	Single or batch model
Welder and fitter at arc welding setup	Assembly	Manned	Single, batch, or mixed model
CNC turning center with parts carousel operating unattended using a robot to load and unload parts	Processing	Automated	Batch or mixed model
Assembly system in which one robot performs multiple assembly tasks to complete a product	Assembly	Automated	Single or batch model

13.3.2 Multi-Station Systems with Fixed Routing

A multi-station manufacturing system with fixed routing is a production line. A *production line* consists of a series of workstations laid out so that the part or product moves from one station to the next, and a portion of the total work content is performed on it at each station. Transfer of work units from one station to the next is usually accomplished by a conveyor or other mechanical transport system. However, in some cases the work is simply pushed between stations by hand. Production lines are generally associated with mass production, although they can also be applied in batch production. Conditions that favor the use of a production line are the following:

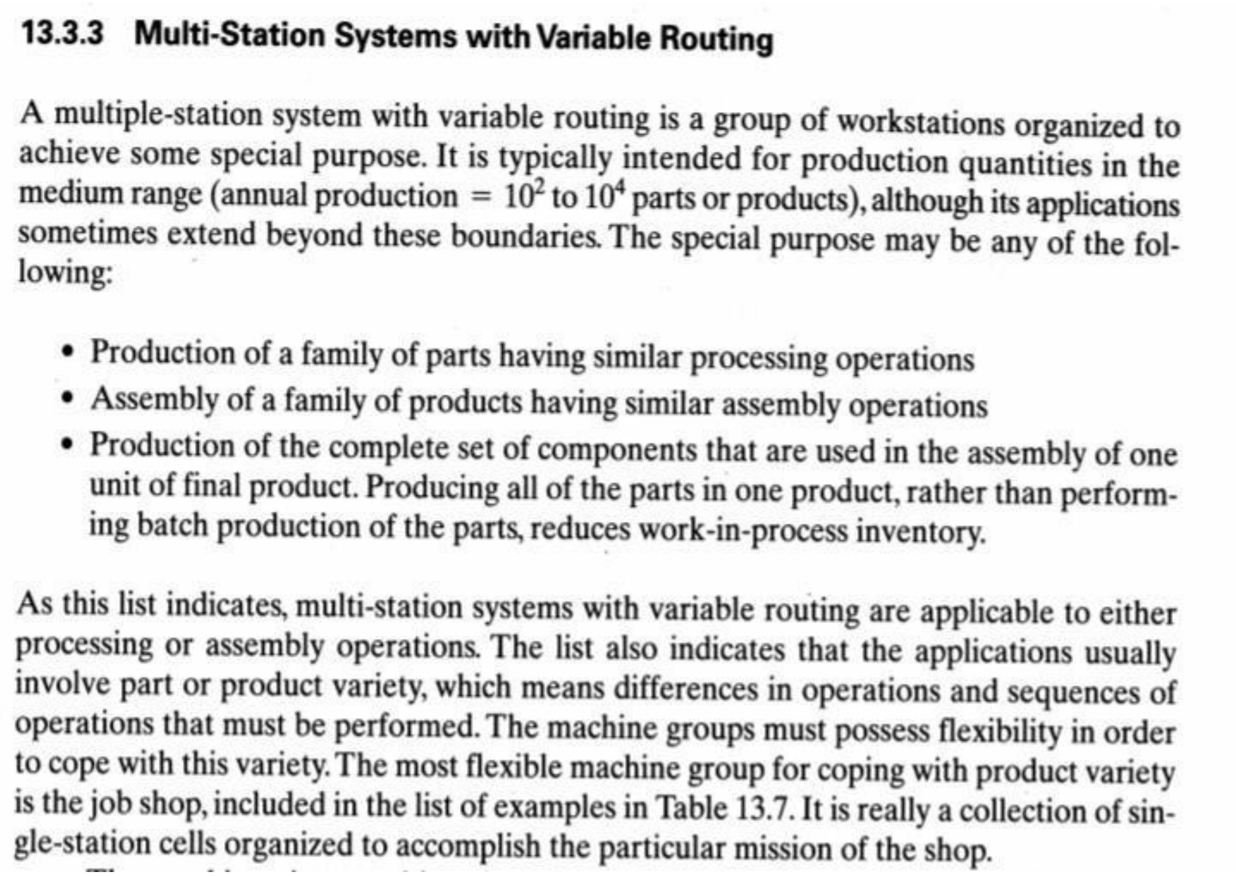
- The quantity of parts or products to be made is very high (up to millions of units)
- The work units are identical or very similar (thus, they require the same or similar operations to be performed in the same sequence)
- The total work content can be divided into separate tasks of approximately equal duration that can be assigned to individual workstations.

Table 13.6 lists some examples of multi-station manufacturing systems with fixed routing, most of which would be called production lines. Production lines are used for either processing or assembly operations, and they can be either manually operated or automated.

TABLE 13.6 Examples of Multi-Station Manufacturing Systems with Fixed Routing

Example	*Operation*	*Automation*	*Typical Part or Product Variety*
Manual assembly line that produces small power tools	Assembly	Manned	Single, batch, or mixed model
Machining transfer line	Processing	Automated	Single model
Automated assembly machine with a carousel system for work transport	Assembly	Automated	Single model
Automobile final assembly plant, in which many of the spot welding and spray painting operations are automated while general assembly is manual	Assembly and processing	Hybrid	Mixed model

Manual production lines usually perform assembly operations, and we discuss manual assembly lines in Chapter 15. Automated lines perform either processing or assembly operations, and we discuss these two system types in Chapters 16 and 17. There are also hybrid systems, in which both manual and automated stations exist in the same line. This case is analyzed in Section 17.2.4.

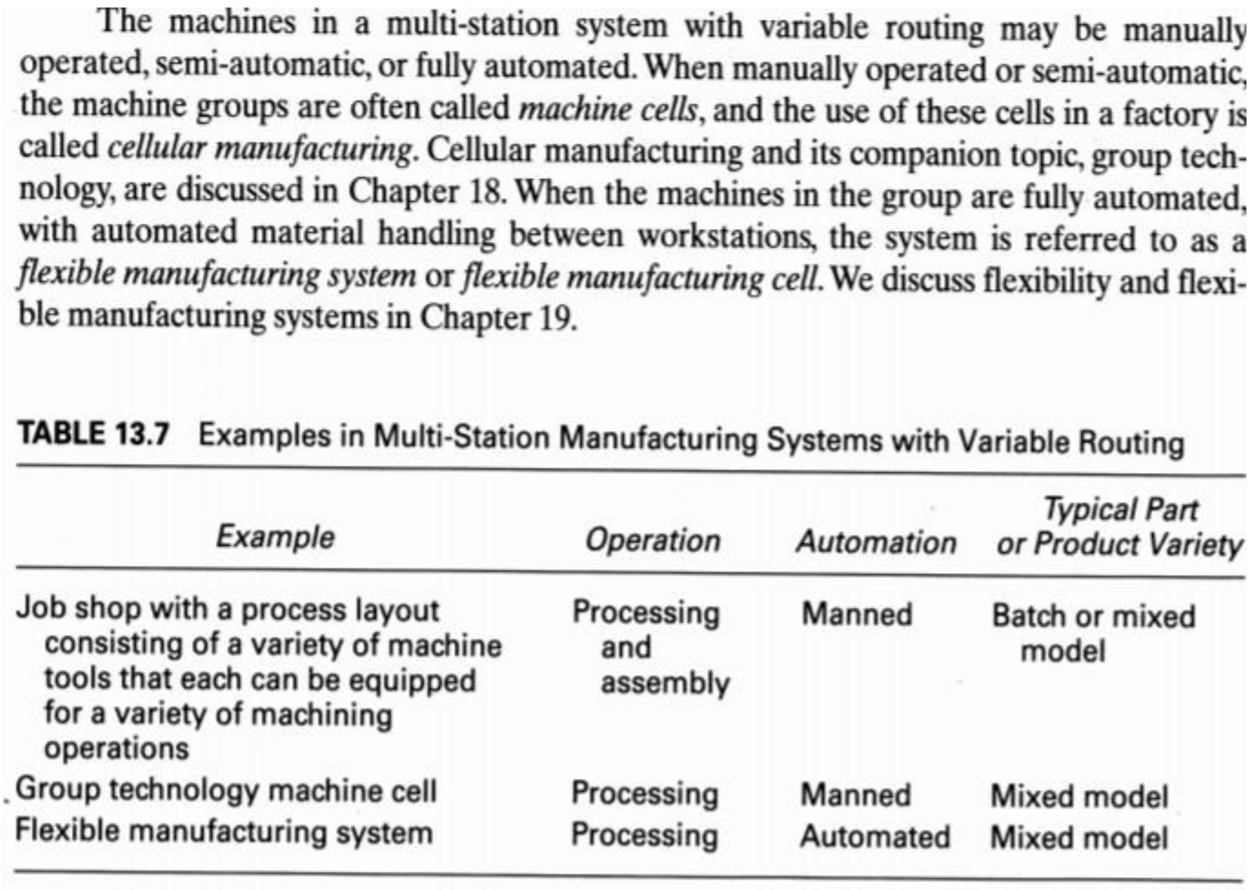


13.3.3 Multi-Station Systems with Variable Routing

A multiple-station system with variable routing is a group of workstations organized to achieve some special purpose. It is typically intended for production quantities in the medium range (annual production = 10^2 to 10^4 parts or products), although its applications sometimes extend beyond these boundaries. The special purpose may be any of the following:

- Production of a family of parts having similar processing operations
- Assembly of a family of products having similar assembly operations
- Production of the complete set of components that are used in the assembly of one unit of final product. Producing all of the parts in one product, rather than performing batch production of the parts, reduces work-in-process inventory.

As this list indicates, multi-station systems with variable routing are applicable to either processing or assembly operations. The list also indicates that the applications usually involve part or product variety, which means differences in operations and sequences of operations that must be performed. The machine groups must possess flexibility in order to cope with this variety. The most flexible machine group for coping with product variety is the job shop, included in the list of examples in Table 13.7. It is really a collection of single-station cells organized to accomplish the particular mission of the shop.



The machines in a multi-station system with variable routing may be manually operated, semi-automatic, or fully automated. When manually operated or semi-automatic, the machine groups are often called *machine cells*, and the use of these cells in a factory is called *cellular manufacturing*. Cellular manufacturing and its companion topic, group technology, are discussed in Chapter 18. When the machines in the group are fully automated, with automated material handling between workstations, the system is referred to as a *flexible manufacturing system* or *flexible manufacturing cell*. We discuss flexibility and flexible manufacturing systems in Chapter 19.

TABLE 13.7 Examples in Multi-Station Manufacturing Systems with Variable Routing

Example	*Operation*	*Automation*	*Typical Part or Product Variety*
Job shop with a process layout consisting of a variety of machine tools that each can be equipped for a variety of machining operations	Processing and assembly	Manned	Batch or mixed model
Group technology machine cell	Processing	Manned	Mixed model
Flexible manufacturing system	Processing	Automated	Mixed model

MODULE 4

PART FAMILIES

Apart family is a collection of parts that are similar either because of geometric shape and size or because similar processing steps are required in theirmanufacture. The parts within a family are different, but their similarities are close enough to merit their inclusion as members of the part family. Figures 15.1 and 15.2 show two different part families. The two parts in Figure 15.1 are very similar in terms of geometric design, but quite different in terms of manufacturing because of differences in tolerances, production quantities, and material. The ten parts shown in Figure 15.2 constitute fl. part family in manufacturing, but their different geometries make them appear quite different from a design viewpoint.

One of the important manufacturing advantages of grouping workparts into families can be explained with reference to Figures 15.3 and 15.4. Figure 15.3 shows a process

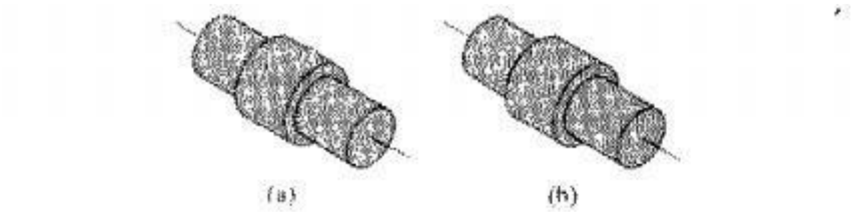


Figure 15.1 Two parts of identical shape and size but different manufacturing requirements: (a) 1,000,000 pc/yr, tolerance = ±0.010 in, material = 1015 CR steel, nickel plate; and (b) 100 pc/yr, tolerance = ±0.001 in, material = 18 − 8 stainless steel.

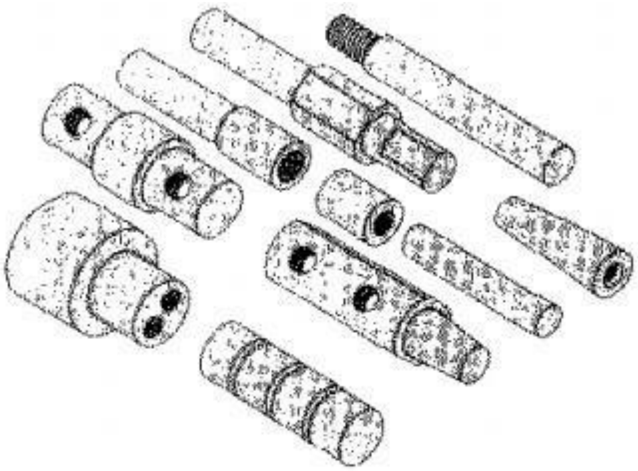


Figure 15.2 A family of parts with similar manufacturing process requirements but different design attributes. All parts are machined from cylindrical stock by turning; some parts require drilling and/or milling.

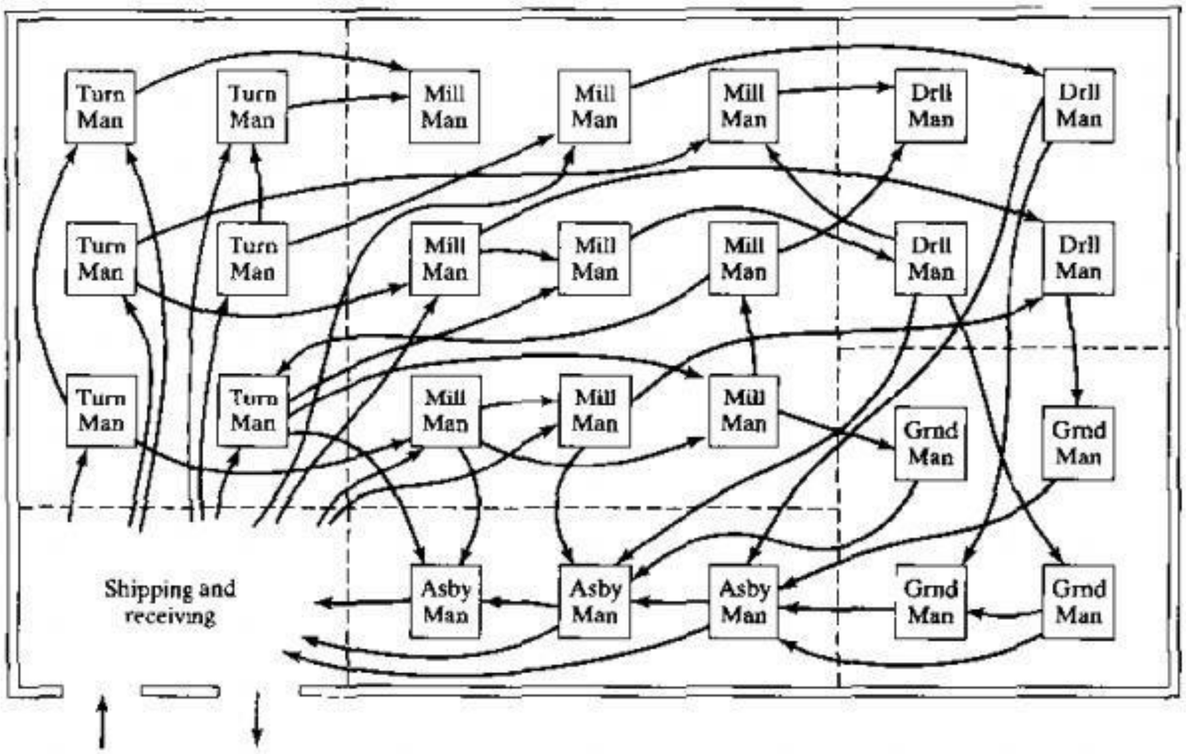


Figure 15.3 Process type plant layout. (Key: "Turn" = turning, "Mill" = milling, "Drll" = drilling, "Grnd" = grinding, "Asby" = assembly, "Man" = manual operation; arrows indicate work flow through plant, dashed lines indicate separation of machines into departments.)

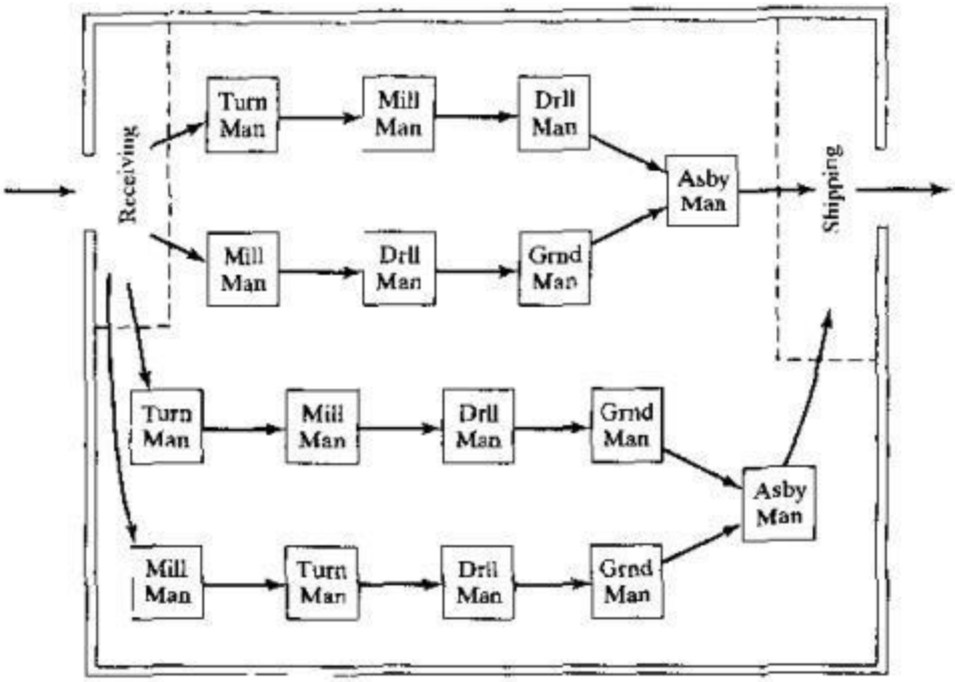


Figure 15.4 Group technology layout. (Key: "Turn" = turning, "Mill" = milling, "Drll" = drilling, "Grnd" = grinding, "Asby" = assembly, "Man" = manual operation; arrows indicate work flow in machine cells.)

type plant layout for batch production in a machine shop. The various machine tools are arranged by function. There is a lathe department, milling machine department, drill press department, and so all. To machine a given part, the workpiece must be transported between departments, with perhaps the same department being visited several times. This results in a significant amount of material handling, large in-process inventory, many machine setups, long manufacturing lead times, and high cost. Figure 15.4 shows a production shop of equivalent capacity, but the machines are arranged into cells. Each cell is organized to specialize in the production of a particular part family. Advantages of reduced work-piece handling yield lower setup times, fewer setups (in some cases,no setup changes are necessary), less in-process inventory, and shorter lead times.

The biggest single obstacle in changing over to group technology from a conventional production shop is the problem of grouping the parts into families. There are three general methods for solving this problem. All three are time consuming and involve the analysis of much data by properly trained personnel. The three methods are; (1) visual inspection, (2) parts classification and coding, and (3) production flow analysis. Let us provide a brief description of the visual inspection method and then examine the second and third methods in more detail.

The *visual inspection* method is the least sophisticated and least expensive method. It involves the classification of parts into families by looking at either the physical parts or their photographs and arranging them into groups having similar features. Although this method is generally considered to be the least accurate of the three. one of the first major-success stories of GT in the United States made the changeover using the visual inspection method. This was the Langston Division of Harris Intertype in Cherry Hill, New Jersey

PARTS CLASSIFICATION AND CODING

This is the most time consuming of the three methods. In *parts classification and coding*, similarities among parts are identified, and these similarities are related in a coding system. Two categories of part similarities can be distinguished:
(1) *design attributes*, which arc concerned with part characteristics such as geometry, size, and material; and (2) *manufacturing attributes*, which consider the sequence of processing steps required to make a part. While the design and manufacturing attributes of a part are usually correlated, the correlation is less than perfect. Accordingly, classification and coding systems are devised to include both a part's design attributes and its manufacturing attributes. Reasons for using a coding scheme include:

Design retrieval. A designer faced with the task of developing a new part can use a design retrieval system to determine if a similar part already exists. A simple change in an existing part would take much less time than designing a whole new part from scratch.

Automated process planning. The part code for a new part can be used to search for process plans for existing parts with identical or similar codes

Machine cell design. The part codes can be used to design machine cells capable of producing all members of a particular part family, using the composite part concept (Section 15.4.1).

To accomplish parts classification and coding requires examination and analysis of the design and/or manufacturing attributes of each part. The examination is sometimes done

by looking in tables to match the subject part against the features described and diagrammed in the tables. An alternative and more-productive approach involves interaction with a computerized classification and coding system, in which the user responds to questions asked by the computer. On the basis of the responses, the computer assigns the code number to the part. Whichever method is used, the classification results in a code number that uniquely identifies the part's attributes.

The classification and coding procedure may be carried out on the entire list of active parts produced by the firm, or some sort of sampling procedure may be used to establish part families. For example, parts produced in the shop during a certain time period could be examined to identify part family categories. The trouble with any sampling procedure is the risk that the sample may be unrepresentative of the population.

A number of classification and coding systems are described in the literature [13], [16], [31], and there are a number of commercially available coding packages. However, none of the systems has been universally adopted. One of the reasons for this is that a classification and coding system should be customized for it given company or industry. A system that is best for one company may not be best for another company.

Features of Parts Classification and Coding Systems

The principal functional areas that utilize a parts classification and coding system are design and manufacturing. Accordingly. parts classification systems fall into one of three categories;

systems based on part *design attributes*

systems based on part *manufacturing attributes*

systems based on *both design and manufacturing attributes*

Table 15.1 presents a list of the common design and manufacturing attributes typically included in classification schemes. A certain amount of overlap exists between design and manufacturing attributes, since a part's geometry is largely determined by the sequence of manufacturing processes performed on it.

In terms of the meaning of the symbols in the code, there are three structures used in classification and coding schemes:

hierarchical structure, also known as a *monocode,* in which the interpretation of each successive symbol depends on the value of the preceding symbols

Chain-type structure, also known as a *polycode,* in which the interpretation ofeach symbol in the sequence is always the same; it does not depend on the value of preceding symbols *mixed-mode structure.* which is a hybrid of the two previous codes

To distinguish the hierarchical and chain-type structures, consider a two-digit code number for a part, such as 15 or 25. Suppose the first digit stands for the general shape of the part: 1 means the part is cylindrical (rotational), and 2 means the geometry is rectangular.

In a hierarchical structure, the interpretation of the second digit depends on the value of the first digit. If preceded by 1, the 5 might indicate a length to diameter ratio; and if preceded by 2, the 5 indicates an aspect ratio between the length and width dimensions of the part. In the chain-type structure, the symbol 5 would have the same meaning whether preceded by 1 or 2. For example, it might indicate the overall length of the part. The advantage of the hierarchical structure is that in general. more information can he included in a code of a given number of digits.

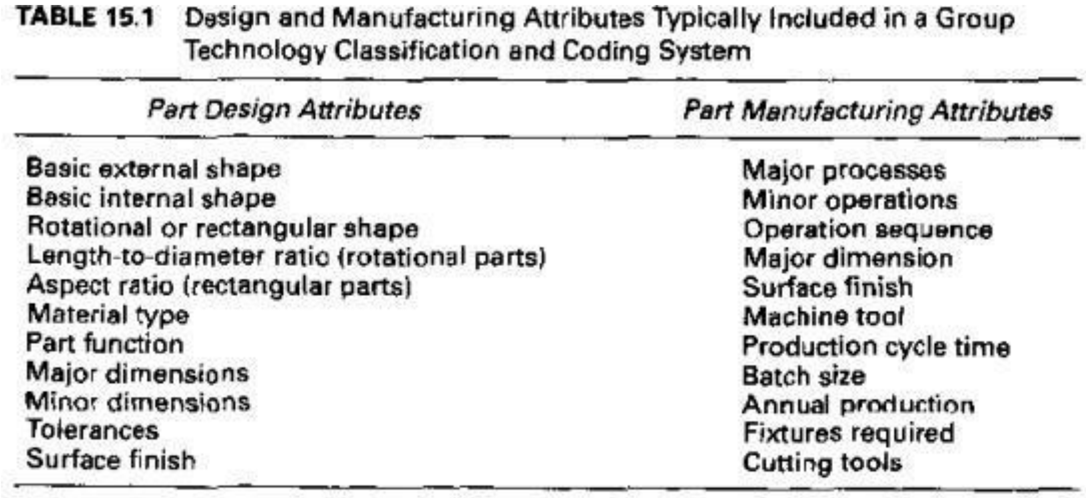


TABLE 15.1 Design and Manufacturing Attributes Typically Included in a Group Technology Classification and Coding System

Part Design Attributes	*Part Manufacturing Attributes*
Basic external shape	Major processes
Basic internal shape	Minor operations
Rotational or rectangular shape	Operation sequence
Length-to-diameter ratio (rotational parts)	Major dimension
Aspect ratio (rectangular parts)	Surface finish
Material type	Machine tool
Part function	Production cycle time
Major dimensions	Batch size
Minor dimensions	Annual production
Tolerances	Fixtures required
Surface finish	Cutting tools

The number of digits in the code can range from 6 to 30. Coding schemes that contain only design data require fewer digits. perhaps 12 or fewer. Most modem classification and coding systems include both design and manufacturing data, and this usually requires 2030 digits. This might seem like too many digits fur a human reader to easily comprehend, but it must be remembered that most of the data processing of the codes is accomplished by computer. for which a large number of digits is of minor concern

Examples of Parts Classification and Coding Systems

Some of the important systems (with emphasis on those in the United States) include: the Opitz classification system, which is nonproprietary; the Brisch System (Brisch-Birn, Inc.); CODE (Manufacturing Data Systems. lnc.]: CUTPLAN (Metcut Associates); DCLASS (Brigham Young University): Multi- Class (OIR: Organization for Industrial Research);and Part Analog System (Lovelace. Lawrence & Co., Inc.). Reviews of these systems and others can be found in [161 and [23].

In the following. we discuss two classification and coding systems: the Opitz System and Multi-Class. The Opitz system is 0' interest because it was one of the first published classification and coding schemes for mechanical parts [31] (Historical Note 15.1) and is still widely used. Multi Class is a commercial product offered by the Organization for Industrial Research (OIR)

Opitz Classification System. This system was developed by H. Opitz of the University of Aachen in Germany. It represents one of the pioneering efforts in group technology and is probably the best known, if not the most frequently used, of the parts classification and coding systems. It is intended for machined parts. The Opitz coding scheme uses thc following digit sequence:

12345 6789 ABCD

The basic code consists of nine digits, which can be extended by adding four more digits. The first nine arc intended to convey both design and manufacturing data. The interpretation of the first nine digits is defined in Figure 15.5. The first five digits, 12345, are called *the form code*. It describes the primary design attributes of the part, such as external shape (e.g., rotational vs. rectangular) and machined features (e.g., holes, threads, gear teeth, etc.]. The next four digits, 6789, constitute the *supplementary code*, which indicates some of the attributes that would be of use in manufacturing (e.g., dimensions, work material, starting shape, and accuracy). The extra four digits, ABCD, are referred to as the *secondary code* and are intended to identify the production operation type and sequence. The secondarycode can be designed by the user firm to serve its own particular needs.

The complete coding system is too complex to provide a comprehensive description here. Opitz wrote an entire book on his system [31]. However, toobtain a general idea of how it works, let us examine the form code consisting of the first five digits. defined generally in Figure 15.5. The first digit identifies whether the part is rotational or nonrotational.1t also describes the general shape and proportions of the part. We limit our survey here to rotational parts possessing no unusual features, those with first digit values of O, 1,

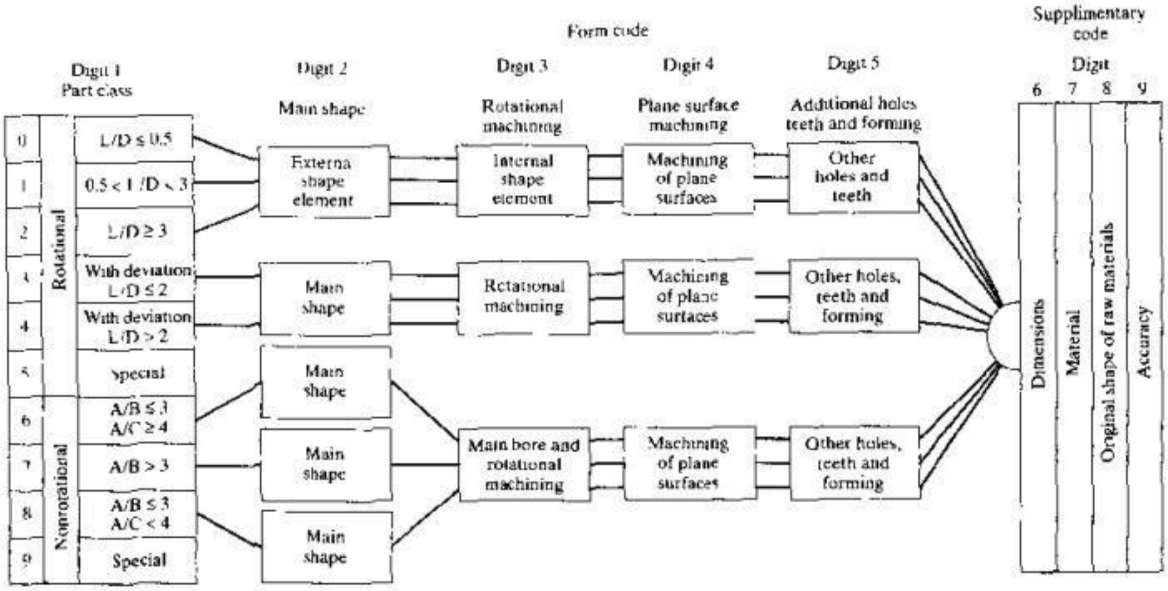


Figure 15.5 Basic structure of the Opitz system of parts classification and coding.

Or 2. For this etas, of work parts, the coding of the first five digits is defined in Figure 15,6. Consider the following example to demonstrate the coding of a given part.

EXAMPLE 15.1 Opitz Part Coding System

Given the rotational part design in Figure 15.7, determine the form code in the Opitz parts classification and coding system

Solution: With reference to Figure 15.6, the five digit code is developed as follows:

Length to diameter ratio, LID = 1.5 Digit 1 = 1

External shape: stepped on both ends with screw thread on one end Digit 2 = 5

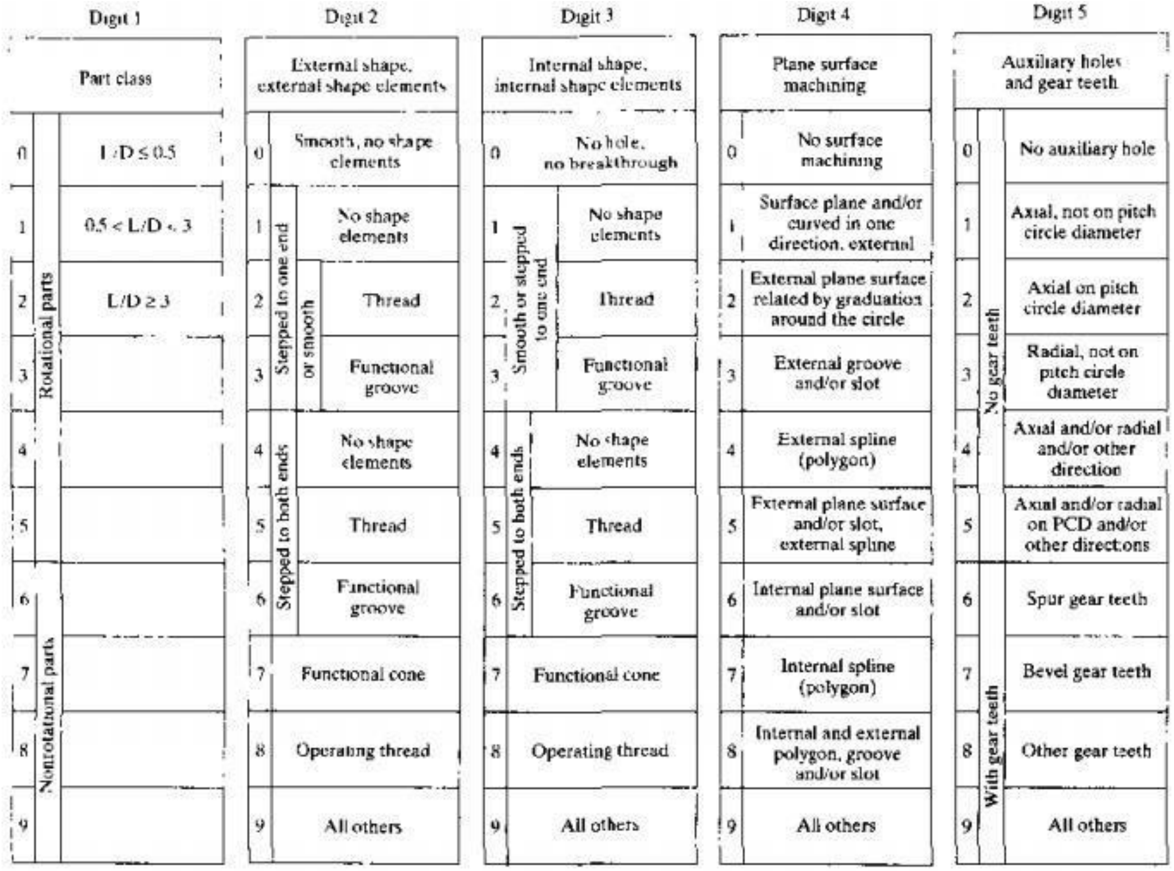
Internal shape: part contains a through hole Digit 3 == 1

Plane surface machining: none Digit 4 == 0

Auxiliary holes, gear teeth, etc.: none Digit 5 = 0

The form code in the Opitz system is 15100.

Multi-Class. Multi-Class is a classification and coding system developed by the Organization for Industrial Research (OIR). The system is relatively flexible, allowing the user company to customize the classification and COlling scheme 10 a large extent to fit its own products and applications. Multi Class can be used for a variety of different types of manufactured items, including machined and sheer metal parts, tooling, electronics, purchased



	Digit 1			Digit 2		Digit 3		Digit 4		Digit 5
		Part class		External shape, external shape elements		Internal shape, internal shape elements		Plane surface machining		Auxiliary holes and gear teeth
0	Rotational parts	L/D ≤ 0.5	0	Smooth, no shape elements	0	No hole, no breakthrough	0	No surface machining	No gear teeth	No auxiliary hole
1		0.5 < L/D < 3	1	Stepped to one end or smooth: No shape elements	1	Smooth or stepped to one end: No shape elements	1	Surface plane and/or curved in one direction, external		Axial, not on pitch circle diameter
2		L/D ≥ 3	2	Thread	2	Thread	2	External plane surface related by graduation around the circle		Axial on pitch circle diameter
3			3	Functional groove	3	Functional groove	3	External groove and/or slot		Radial, not on pitch circle diameter
4			4	Stepped to both ends: No shape elements	4	Stepped to both ends: No shape elements	4	External spline (polygon)		Axial and/or radial and/or other direction
5			5	Thread	5	Thread	5	External plane surface and/or slot, external spline		Axial and/or radial on PCD and/or other directions
6	Nonrotational parts		6	Functional groove	6	Functional groove	6	Internal plane surface and/or slot	With gear teeth	Spur gear teeth
7			7	Functional cone	7	Functional cone	7	Internal spline (polygon)		Bevel gear teeth
8			8	Operating thread	8	Operating thread	8	Internal and external polygon, groove and/or slot		Other gear teeth
9			9	All others	9	All others	9	All others		All others

Figure 15.6 Form code (digits 1–5) for rotational parts in the Opitz coding system. The first digit of the code is limited to the value 0, 1, or 2.

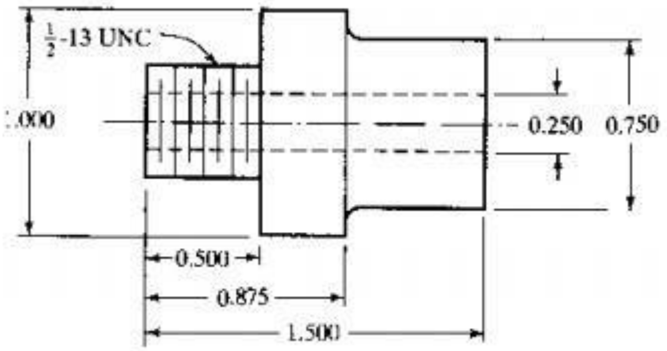


Figure 15.7 Part design for Example 15.1.

parts, assemblies and subassemblies, machine tools, and other elements. Up to nine different types of components can be included within a single MultiClass software structure MultiClass uses a hierarchical or decision- tree coding structure in which the succeeding digits depend on values of the previous digits. In the application of the system, a series of menus, pick lists, tables, and other interactive prompting routines are used to code the part. This helps to organize and provide discipline to the coding procedure.

The coding structure consists of up to 30 digits. These are divided into two regions, one provided by GIR, and the second designed by the user to meet specific needs and requirements. A prefix precedes the code number and is used to identify the type of part (e.g., a prefix value of 1 indicates machined and sheet metal parts). For a machined part, the coding for the first 18 digit positions (after the prefix) is summarized in Table 15.2.

TABLE 15.2 First 18 digits of the Multiclass Classification and Coding System

Digit	Function
o	Code system prefix
1	Main shape category
2,3	External and internal configuration

4	Machined secondary elements
5,6	Functional descriptors
712	Dimensional data !length, diameter, etc.)
13	Tolerances
14,15	Material chemistry
	Raw material shape
	Production quantity
	Machined element orientation

EXAMPLE 15.2 MuitiClass Coding System

Given the rotational part design in Figure 15.8, determine the IS digit code in the MultiClass parts coding system.

TABLE 15.2 First 18 digits of the Multiclass Classification and Coding System

Digit	*Function*
0	Code system prefix
1	Main shape category
2, 3	External and internal configuration
4	Machined secondary elements
5, 6	Functional descriptors
7–12	Dimensional data (length, diameter, etc.)
13	Tolerances
14, 15	Material chemistry
16	Raw material shape
17	Production quantity
18	Machined element orientation

EXAMPLE 15.2 MultiClass Coding System

Given the rotational part design in Figure 15.8, determine the 18-digit code in the MultiClass parts coding system.

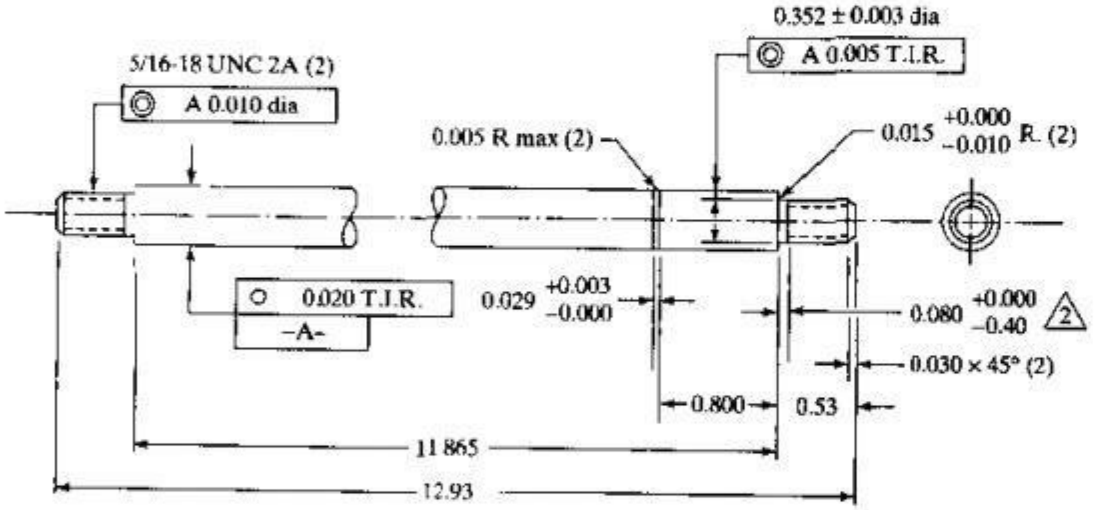


Figure 15.8 Workpart of Example 15.2. (Courtesy of OIR, Organization for Industrial Research.)

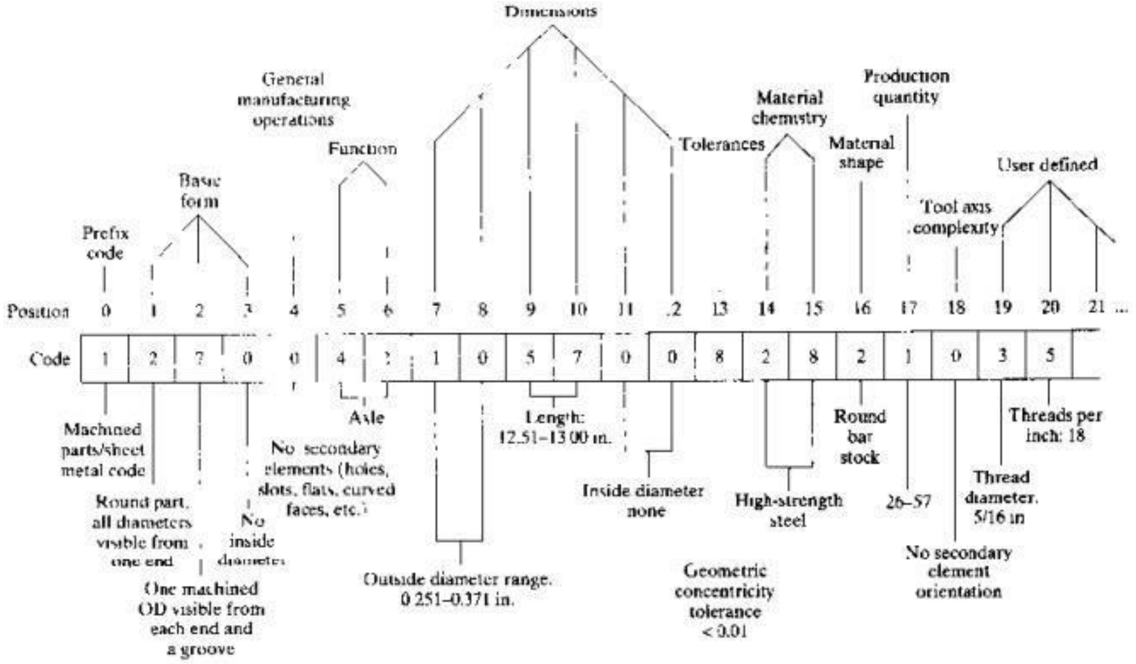


Figure 15.9 MultiClass code number determined for part in Example 15.2. (Courtesy of OIR, Organization for Industrial Research.)

Solution: The MultiClass code number for the given part is developed in Figure 15.9.

PRODUCTION FLOW ANALYSIS

This is an approach to part family identification and machine cell formation that was pioneered by J. Burbidge *[6][R]*. *Production flow analysis* (PFA) is a method for identifying part families and associated machine groupings that uses the information contained 011 production route sheets rather than on part drawings. Work parts with identical or similar routings are classified into part families. Thesefamilies can then be used to form logical machine cells in a group technology layout. Since PFA uses manufacturing data rather than design data to identify part families, it can overcome two possible anomalies that can occur in parts classification and coding. First, parts whose basic geometries are quite different may nevertheless require similar or even identical process routings. Second, parts whose geornetries are quite similar may nevertheless require process routings that are quite different.

The procedure in production flow analysis must begin by defining the scope of the study, which means deciding on the population of parts to be analyzed. Should all of the parts in the shop be Included in the study, or should a representative sample be selected for analysis! Once this decision is made, then the procedure in PFA consists of the following steps:

Data collection. The minimum data needed in the analysis are the part number and operation sequence, which is contained in shop documents called route sheets or operation sheets or some similar name. Each operation is usually associated witha particular machine, so determining the operation sequence also determines the machine sequence. Additional data. such as lot size, time standards, and annual demand might be useful for designing machine cells of the required production capacity.

Soriation of process routings. In this step, the parts are arranged into groups according to the similarity of their process routings. To facilitate this step, all operations or machines included in the shop are reduced to code numbers, such as those shown in Table 15.3. For each part, the operation codes are listed in the order in which they are performed. A sortation procedure is then used to arrange parts into "packs," which are groups of parts with identical routings. Some packs may contain only one part number, indicating the uniqueness of the processing of that part. Other packs will contain many parts, and these will constitute a part family.

PFA chart. The processes used for each pack are then displayed in a PFA chart, a simplified example of which is illustrated in Table 15.4.[1] The chart is a tabulation of the process or machine code numbers for all of the part packs. In recent GT literature [30], the PFA chart has been referred to as *part-machine incidence matrix.* In this matrix, the entries have a value x_{ii}=1 or 0: a value of x_{ij} = 1 indicatesthat the corresponding part *i* requires processing on machine j, and X'I = 0 indicates that no processing of component *i* is accomplished on machine *j.* For clarity of presenting the matrix, the D's are often indicated as blank (empty) entries, as in our table.

Cluster analysis. From the pattern of data in the PFA chart. related groupings are identified and rearranged into a new pattern that brings together packs with similar machine sequences. One possible rearrangement of the original PFA chartis shown in Table 15.5, where different machine groupings are indicated within blocks. The blocks might be considered as possible machine cells. It is often the case (but not in Table 15.5) that some packs do not fit into logical groupings. These parts might be analyzed to see if a revised process sequence can be developed that fits into one of the groups. If not, these parts must continue to be fabricated through a conventional process layout. In Section 15.6.1, we examine a systematic technique called *rank order clustering* that can be used to perform the cluster analysis.

TABLE 15.3 Possible Code Numbers indicating Operations and/or Machines for Sortation in Production Flow Analysis (Highly Simplified)

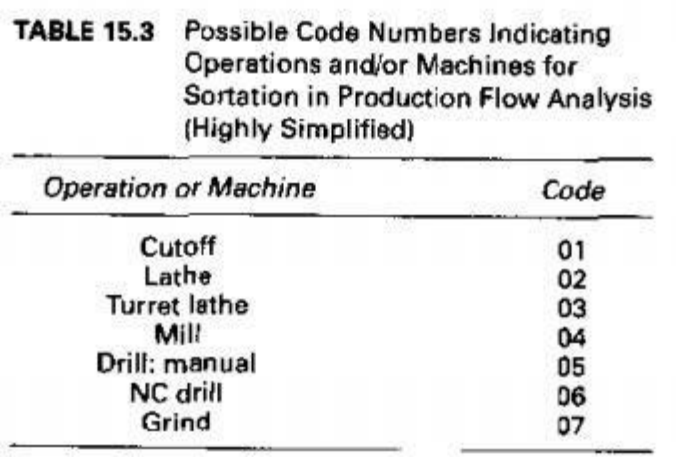


TABLE 15.3 Possible Code Numbers Indicating Operations and/or Machines for Sortation in Production Flow Analysis (Highly Simplified)

Operation or Machine	*Code*
Cutoff	01
Lathe	02
Turret lathe	03
Mill	04
Drill: manual	05
NC drill	06
Grind	07

TABLE 15.4 PFA Chart, Also Known as a Part-Machine Incidence Matrix

	Parts								
Machines	A	B	C	D	E	F	G	H	I
1	1			1				1	
2					1				1
3			1		1				1
4		1				1			
5	1							1	
6			1						1
7		1				1	1		

TABLE 15.5 Rearranged PFA Chart, Indicating Possible Machine Groupings

	Parts								
Machines	C	E	I	A	D	H	F	G	B
3	1	1	1						
2		1	1						
6	1		1						
1				1	1	1			
5				1		1			
7							1	1	1
4							1		1

The weakness of production flow analysis is that the data used in the technique are derived from existing production route sheets. **In** all likelihood, these route sheets have been prepared by different process planners, and the routings may contain operations that are non optimal, illogical, or unnecessary. Consequently, the final machine groupings obtained in the analysis may be suboptimal. Notwithstanding this weakness, PFA has the virtue of requiring less time than a complete parts classification and coding procedure. This virtue is attractive to many firms wishing to introduce group technology into their plant operations.

CELLULAR MANUFACTURING

Whether part families have been determined by visual inspection. parts classification and coding, or production flow analysis, there is advantage in producing those parts using group technology machine cells rather than a traditional process type machine layout. When the machines are grouped. the term cellular manufacturing is used to describe this work organization. *Cellular manufacturing* is an application of group technology in which dissimilar machines or processes have been aggregated into cells, each of which is dedicated to the production of a part or product family or a limited group of families. The typical objectives in cellular manufacturing are similar to those of group technology:

To shorten manufacturing lead times, by reducing setup, workpart handling, waiting times, and batch sizes

To reduce work-in-process inventory. Smaller batch sizes and shorter lead times reduce work-in-process.

To improve quality. This is accomplished by allowing each cell to specialize in producing a smaller number of different parts. This reduces process variations.

To simplify production scheduling. The similarity among parts in the family reduces the complexity of production scheduling. Instead of scheduling parts through a sequence of machines in a process-type shop layout, the parts are simply scheduled though the cell.

To reduce setup times. This is accomplished by using *group tooling* (cutting tools, jigs, and fixtures) that have been designed to process the part family, rather than part tooling, which is designed for an individual part. This reduces the number of individual tools required as well as the time to change tooling between parts.

Additional reasons for implementing cellular manufacturing are given in Table 15.7. In this section, we consider several aspects of cellular manufacturing and the design of machine ceils.

Composite Part Concept

Part families are defined by the fact that their members have similar design and/or manufacturing features. The composite part concept takes this part family definition to its logical conclusion. It conceives of a hypothetical part, a *composite part* for a given family, which 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. The composite part possesses all of the features.

There is always a correlation between part design features and the production operations required 10 generate those features. Round holes are made by drilling, cylindrical shapes are made by turning, flat surfaces by milling, and so on. 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 15.1O(a).1l represents a family of rotational parts with features defined in Figure 15.1O(b). Associated with each feature is a certain machining operation as summarized in Table 15.6. A machine cell to produce this

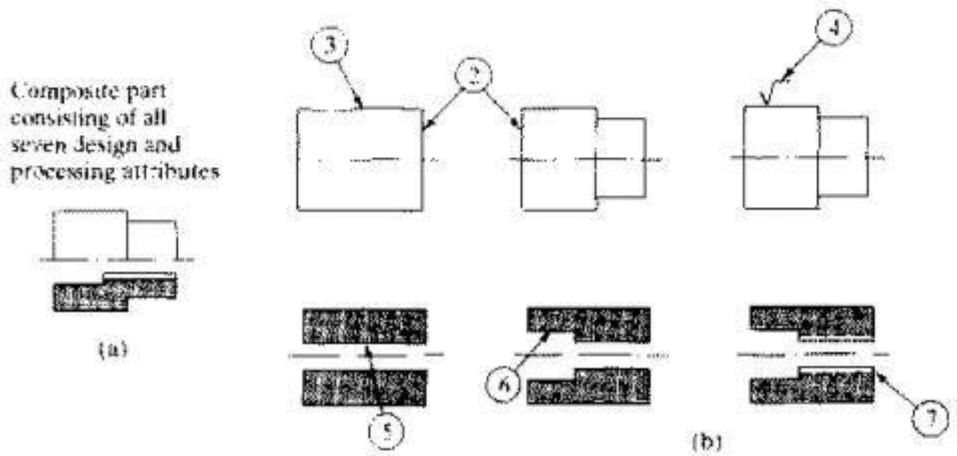
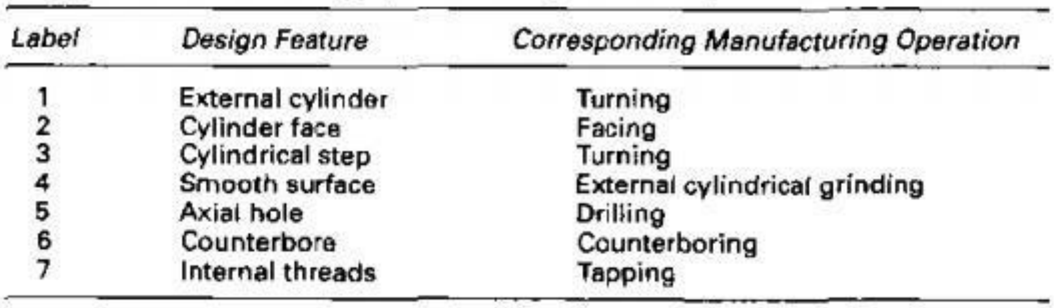


Figure 15.10 Composite part concept: (a) the composite part for a family of machined rotational parts and (b) the individual features of the composite part. See Table 15.6 for key to individual features and corresponding manufacturing operations.

TABLE 15.6 Design Features of the Composite Part in Figure 15.10 and the Manufacturing Operations Required to Shape Those Features



Label	*Design Feature*	*Corresponding Manufacturing Operation*
1	External cylinder	Turning
2	Cylinder face	Facing
3	Cylindrical step	Turning
4	Smooth surface	External cylindrical grinding
5	Axial hole	Drilling
6	Counterbore	Counterboring
7	Internal threads	Tapping

part family would be designed with the capability to accomplish all seven operations required to produce the composite pan (the last column in the table). To produce a specific member of the family, operations would be included to fabricatethe required features of the part. For parts without all seven features, unnecessary operations would simply be omitted. Machines, fixtures, and tools would be organized for efficient flow of work-parts through the cell,

In practice, the number of design and manufacturing attributes is greater than seven, and allowances must be made for variations in overall size and shape of the parts in the family. Nevertheless, the composite part concept is useful for visualizing the machine cell design problem.

Machine Cell Design

Design of the machine cell is critical in cellular manufacturing. The cell design determines to a great degree the performance of the cell. In this subsection, we discuss types of machine cells, cell layouts, and the key machine concept.

Types of Machine Cells and Layouts. GT manufacturing cells can be classified according to the number of machines and the degree to which the material flow is mechanized between machines. In our classification scheme for manufacturing systems (Section 13.2), all GT cells are classified as type X in termsof part or product variety (Section 13.2.4, Table 13.3). Here we identify four common GT cell configurations (with system type identified in parenthesis from Section 13.2):

single machine cell (type I M)

group machine cell with manual handling (type n M generally, type III M less common)

group machine cell with semi-integrated handling (type II M generally, type III M less common)

flexible manufacturing cell or flexible manufacturing system (type IT A generally, type III A less common)

As its name indicates, the *single machine cell* consists of one machine plus supporting fixtures and tooling. This type of cell can be applied to work-parts whose attributes allow them to be made on one basic type of process, such as turning or milling. *For* example, the composite part of Figure 15.10 could beproduced on a conventional turret lathe, with the possible exception of the cylindrical grinding operation (step 4)

The *group machine cell with manual handling* is an arrangement of more than one machine used collectively to produce one or more part families. There is no provision for mechanized parts movement between the machines in the cell. Instead, the human operators who run the cell perform the material handlingfunction. The cell is often organized into a U shaped layout, as shown in Figure 15.11. This layout is considered appropriate when there is variation in the work flow among the parts made in the cell. It also allows the multifunctional workers inthe cell to move easily between machines [29].

The group machine cell with manual handling is sometimes achieved in a conventional process type layout without rearranging the equipment. This is done simply by assigning certain machines to be included in the machine group and restricting their work to specified part families. This allows many of the benefits of cellular manufacturing to be achieved without the expense of rearranging equipment in the shop. Obviously, the material handling benefits of OT are minimized with this organization.

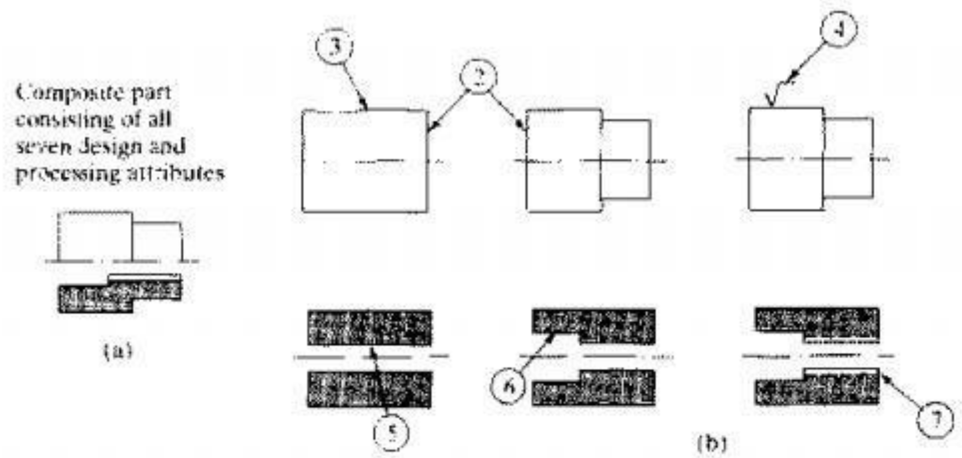


Figure 15.10 Composite part concept: (a) the composite part for a family of machined rotational parts and (b) the individual features of the composite part. See Table 15.6 for key to individual features and corresponding manufacturing operations.

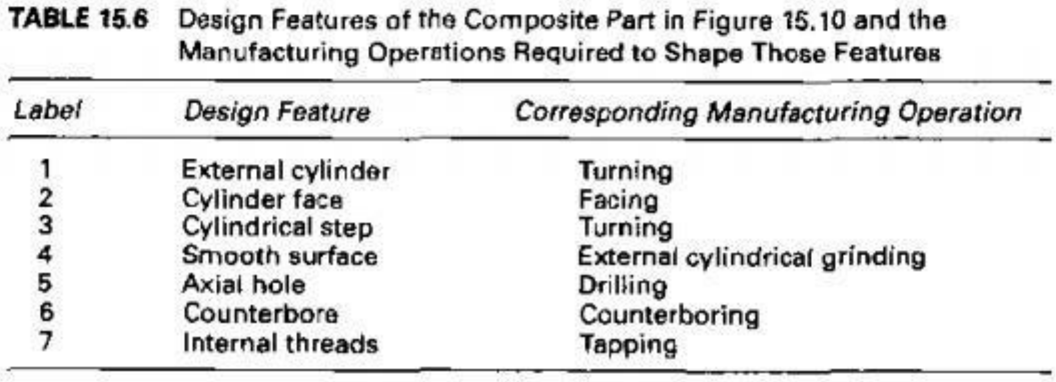


TABLE 15.6 Design Features of the Composite Part in Figure 15.10 and the Manufacturing Operations Required to Shape Those Features

Label	*Design Feature*	*Corresponding Manufacturing Operation*
1	External cylinder	Turning
2	Cylinder face	Facing
3	Cylindrical step	Turning
4	Smooth surface	External cylindrical grinding
5	Axial hole	Drilling
6	Counterbore	Counterboring
7	Internal threads	Tapping

The *group machine cell with semi integrated handling* uses a mechanized handling system, such as a conveyor, to move parts between machines in the cell. *The flexible manufacturing system* (FMS) combines a fully integrated materialhandling system with automated processing stations. The FMS is the most highly automated of the group technology machine cells. The following chapter is devoted to this form of automation, and we defer discussion till then.

A variety of layouts are used in GT cells, The U-shape, as in Figure 15.11, is a popular configuration in cellular manufacturing. Other GT layouts include inline, loop, and rectangular, shown in Figure 15.12 for the case of semi integrated handling.

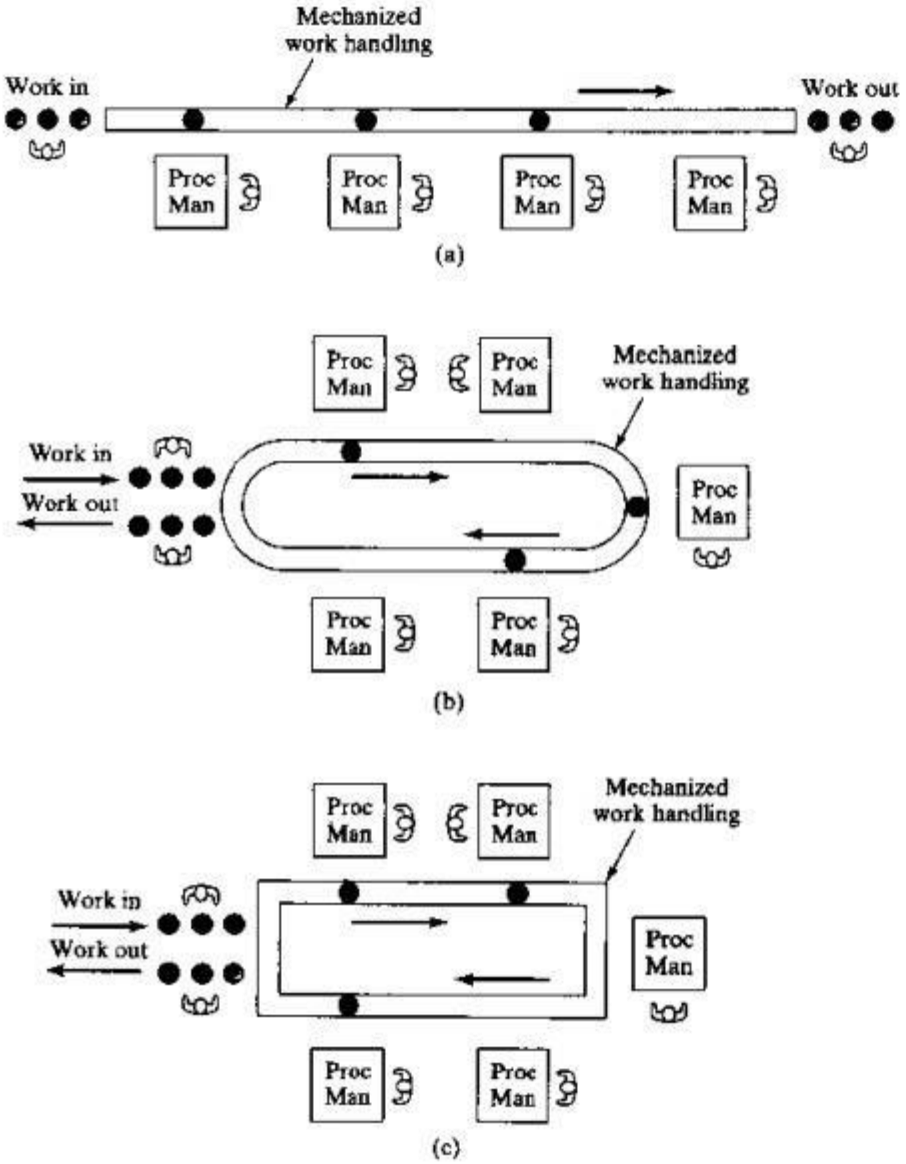


Figure 15.12 Machine cells with semi-integrated handling: (a) in-line layout, (b) loop layout, and (c) rectangular layout. (Key: "Proc" = processing operation (e.g., mill, turn, etc.), "Man" = manual operation; arrows indicate work flow.)

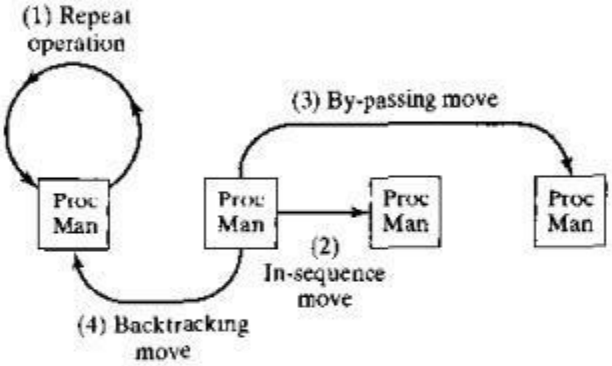


Figure 15.13 Four types of part moves in a mixed model production system. The forward flow of work is from left to right.

Determining the most appropriate cell layout depends on the routings of parts produced in the cell. Four types of part movement can be distinguished in a mixed model part production system. They are illustrated in Figure 15.13 and are defined as follows, where the forward direction of work flow is defined as being from left to right in the figure:(l) re*peat operation*, in which a consecutive operation is carried out on the same machine, so that the part does not actually move; (2) *in- sequence move*, in which the part moves from the current machine to an immediateneighbor in the forward direction; (3) *bypassing move*, in which the part moves forward from the current machine to another machine that is two or more machinesahead; and (4) *backtracking move*, in which the part moves from the current machine in the backward direction to another machine.

When the application consists exclusively of in sequence moves, then an inline layout is appropriate. A V-shaped layout also works well here and has the advantage of closer interaction among the workers in the cell. When the application includes repeated operations, then multiple stations (machines) areoften required. For cells requiring bypassing moves, the U-shape layout is appropriate. When backtracking moves are needed, a loop or rectangular layout is appropriate to accommodate recirculation of parts within the cell. Additional factors that must be accounted for in the cell design include:

Quantity of work to be done by the cell. This includes the number of parts per year and the processing (or assembly) time per part at each station. These factors determine the workload that must be accomplished by the cell and therefore the number of machines that must be included, as well as total operating cost of the cell and the investment that can be justified .

Part size, shape, weight, and other physical attributes. These factors determine the size and type of material handling and processing equipment that must be used.

Key Machine Concept. In some respects, a GT machine cell operates like a manual assembly line (Chapter 17), and it is desirable to spread the workload evenly among the machines in the cell as much as possible. On the other hand, there is typically a certain machine in a cell (or perhaps more than one machine ina large cell) that is more expensive to operate than the other machines or that performs certain critical operations in the plant This machine is referred to as the *key machine*. It is important that the utilization of this key machine be high. even if it means that the other machines in the cell have relatively low utilization. The other machines are referred to *as supporting machines*, and they should be organized in the cell to keep the key machine busy. In a sense, the cell is designed so that the key machine becomes the bottleneck in the system.

The key machine concept is sometimes used to plan the GT machine cell. The approach is to decide what parts should be processed through the key machine and then determine what supporting machines are required to complete the processing of those parts.

There are generally two measures of utilization that are of interest in a GT cell: the utilization of the key machine and the utilization of the overall cell. The utilization of the key machine can be measured using the usual definition (Section 2.4.3). The utilization of each of the other machines can also be evaluated similarly. The cell utilization is obtained by taking a simple arithmetic average of all the machines in the cell. One of the exercise problems at the end of the chapter serves to illustrate the key machine concept and the determination of utilization

APPLICATION CONSIDERATIONS IN GROUP TECHNOLOGY

In this section, we consider how and where group technology is applied, and we report on the results of a survey of industry about cellular manufacturing in the United States [38]

Applications of Group Technology

In our introduction to this chapter, we defined group technology as a "manufacturing philosophy." GT is not a particular technique, although various tools and techniques, such as parts classification and coding and production flow analysis, have been developed to help implement it. The group technology philosophy can be applied in a number of areas, Our discussion focuses on the two main areas of manufacturing and product design.

Manufacturing Applications. The most common applications of GT are in manufacturing. And the most common application III manufacturing involves the formation of cells of one kind or another, Not all companies rearrange machines to form cells. There are three ways in which group technology principles can be applied in manufacturing [24]:

Informal scheduling and routing of similar parts through selected machines. This approach achieves setup advantages. but no formal part families aredefined, and no physical rearrangement of equipment is undertaken.

Virtual machine cell This approach involves the creation of part families and dedication of equipment to the manufacture of these part families, but without the physical rearrangement of machines into formal cells. The machines in the virtual cell remain in their original locations in the factory. Use of virtual cells seems to facilitate the sharing of machines with other virtual cells producing other part families [25J.

Formal machine cells. This is the conventional GT approach in which a group of dissimilar machines are physically relocated into a cell that is dedicated to the production of one or a limited set of parts families (Section 15.4.2). The machines in a formal machine cell are located in close proximity to minimize part handling, throughput name. setup time, and work-in-process.

Other GT applications in manufacturing include process planning (Chapter 25), family tooling, and numerical control (NC) part programs. Process planning of new parts can be facilitated through the identification of part families. The new part is associated with an existing part family. and generation of the process plan for the new part follows the routing of the other members of the part family. This is done in a formalized way through the use of parts classification and coding. The approach is discussed in the context of auto mated process planning (Section 25.2.1).

In the ideal, all members of the same part family require similar setups, tooling, and fixturing. This generally results in a reduction in the amount of tooling and fixturing needed Instead of determining a special tool kit for each part, a tool kit is developed for each part family. The concept of a *modular fixture* can often be exploited, in which a common base fixture is designed and adaptations are made to switch between different parts in the family

A similar approach can be applied in NC part programming. Called *parametric programming*. [28], it involves the preparation of a common *NC* program that covers the entire part family. The program is then adapted for individual members of the family *by* inserting dimensions and other parameters applicable to the particular part. Parametric programming reduces both programming time and setuptime.

Product Design Applications. The application of group technology in product design is found principally in the use of design retrieval systems that reduce part proliferation in the firm. It has been estimated that a company's cost to release a new part design ranges between $2000 and $12.000 [37]. In a survey of industry reported in [36], it was concluded that in about 20% of new part situations, an existing part design could be used. In about 4(J% of the cases, an existing part design could be used with modifications, The remaining cases required new part designs. If the cost savings for a company generating 1000 new part designs per year were 75% when an existing part design could be used(assuming that there would still be some cost oftime associated with the new part for engineering analysis and design retrieval) and 50% when an existing design could be modified, then the total annual savings to the company would lie between
$700,000 and $4,200,000, or 35% of the company's total design expense due to part releases. The kinds of design savings described here require an efficient design retrieval procedure. Most part design retrieval procedures lin: based on parts classification and coding systems (Section 15.2).

Other design applications of group technology involve simplification and standardization of design parameters, such as tolerances inside radii on corners, chamfer sizes on outside edges, hole sizes, thread sizes, and so forth. These measures simplify design procedures and reduce part proliferation. Design standardization also pays dividends in manufacturing by reducing the required number of distinct lathe tool nose radii, drill sizes, and fastener sizes. There is also a benefit in terms of reducing the amount of data and information that the companymust deal with. Fewer part designs, design attributes, tools, fasteners, and so on mean fewer and simpler design documents, process plans, and other data records.

Survey of Industry Practice

A number of surveys have been conducted to learn how industry implements cellular manufacturing [24], [36], [38J. The surveyed companies represent manufacturing industries, such as machinery, machine tools, agricultural and construction equipment, medical equip

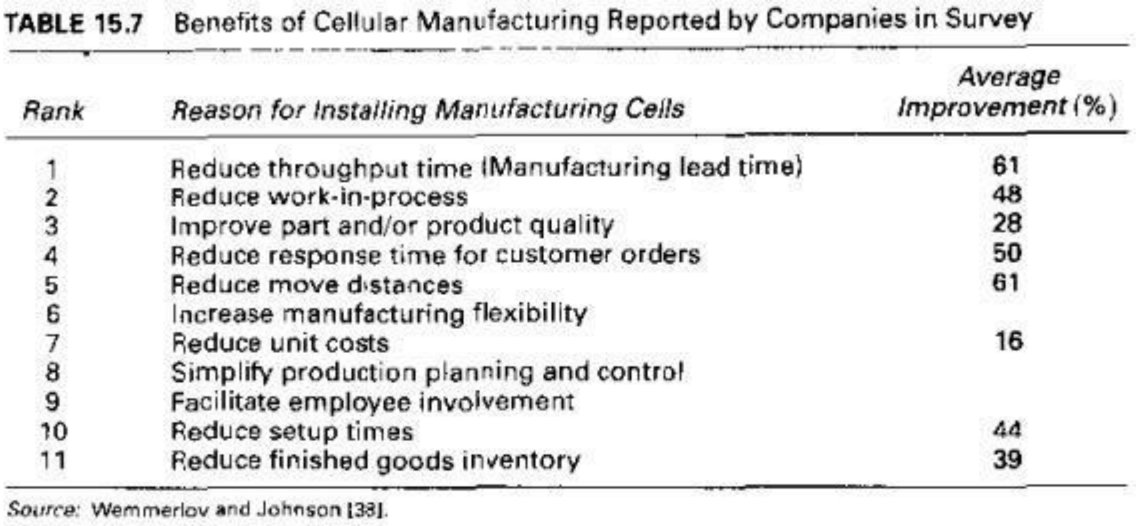


TABLE 15.7 Benefits of Cellular Manufacturing Reported by Companies in Survey

Rank	*Reason for Installing Manufacturing Cells*	*Average Improvement (%)*
1	Reduce throughput time (Manufacturing lead time)	61
2	Reduce work-in-process	48
3	Improve part and/or product quality	28
4	Reduce response time for customer orders	50
5	Reduce move distances	61
6	Increase manufacturing flexibility	
7	Reduce unit costs	16
8	Simplify production planning and control	
9	Facilitate employee involvement	
10	Reduce setup times	44
11	Reduce finished goods inventory	39

Source: Wemmerlov and Johnson [38].

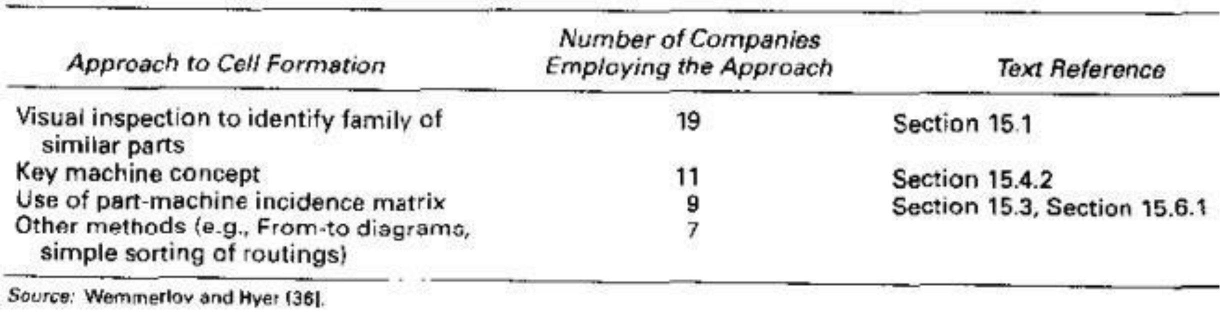
ment. weapons systems. diesel engines. and piece parts. Processes grouped into cells in the companies included machining, joining and assembly,finishing, testing, and metal forming

Companies in the survey were asked to report their reasons forestablishing machine cells and the benefits they enjoyed from implementing cellular manufacturing in the operations. Results are listed in Table 15.7. The reasons are listed in the relative order of importance as indicated by the companies participating in the survey. We also list the average percentage improvement reported by the companies, rounded to the nearest whole percentage point. Reasons 6, 8, and 9 are difficult to evaluate quantitatively, and no percentage improvements are listed in these cases.

One of the questions considered in the 1989 survey [36] was: What are the approaches used by companies to form machine cells? The results are listed in Table 15.8. The most common approach consisted of visually grouping similar parts with no consideration given to existing routing information and no parts classification and coding. The use of a part-machine incidence matrix was not widely reported, perhaps because the formal algorithms for reducing this matrix, such as rank order clustering (Section 15.6.1) were not widely known at the timeof the survey

Companies also reported costs associated with implementing cellular manufacturing. The reported cost categories are listed in Table 15.9 together with the number of companies reporting the cost. No numerical estimates of actual costs are provided in the report.

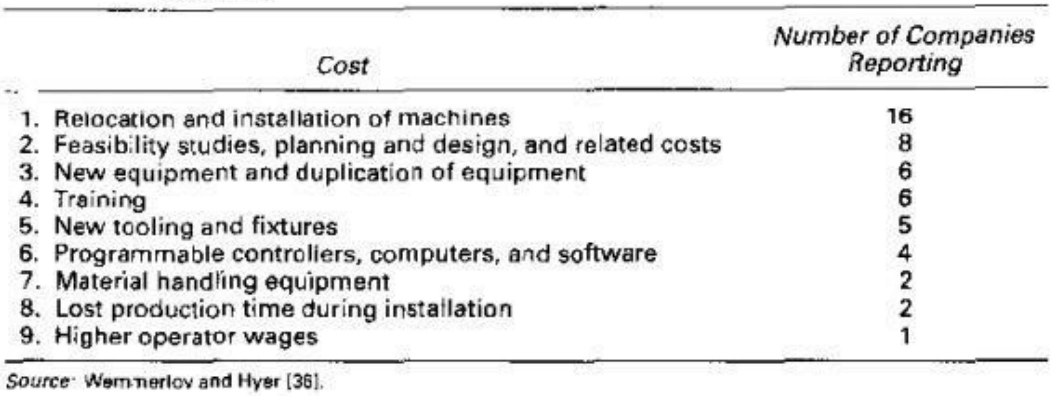
TABLE 15.8 Approaches to Cell Formation Used in Industry



Approach to Cell Formation	Number of Companies Employing the Approach	Text Reference
Visual inspection to identify family of similar parts	19	Section 15.1
Key machine concept	11	Section 15.4.2
Use of part-machine incidence matrix	9	Section 15.3, Section 15.6.1
Other methods (e.g., From-to diagrams, simple sorting of routings)	7	

Source: Wemmerlov and Hyer [36].

TABLE 15.9 Costs of Introducing Cellular Manufacturing Reported by Companies in Survey



Cost	Number of Companies Reporting
1. Relocation and installation of machines	16
2. Feasibility studies, planning and design, and related costs	8
3. New equipment and duplication of equipment	6
4. Training	6
5. New tooling and fixtures	5
6. Programmable controllers, computers, and software	4
7. Material handling equipment	2
8. Lost production time during installation	2
9. Higher operator wages	1

Source: Wemmerlov and Hyer [36].

Topping the list was the expense of equipment relocation and installation. Most of the companies responding to the survey had implemented cellular manufacturing by moving equipment in the factory rather than by installing new equipment to form the cell.

QUANTITATIVE ANALYSIS IN CELLULAR MANUFACTURING

A number of quantitative techniques have been developed to deal with problem areas in group technology and cellular manufacturing. In this section, we consider two problem areas: (1) grouping parts and machines into families, and (2) arranging machines in a GT cell. The first problem area has been and still is an active research area, and several of the more significant research publications are listed in our references . The technique we describe in the current section for salving the part and machine grouping problem is rank order clustering . The second problem area has also been the subject of research, and several reports are listed in the references.

Grouping Parts and Machines by Rank Order Clustering

The problem addressed here is to determine how machines in an existing plant should be grouped into machine cells. The problem is the same whether the cells are virtual or formal (Section 15.5.1).It is basically the problem of identifying part families. By identifying part families, the machines required in the cell to produce the part family can be properly selected. As previously discussed, the three basic methods to identify part families are (1) visual inspection, (2) parts classification and coding, and (3) production flow analysis.

The *rank order clustering* technique. first proposed by King [26J, is specifically applicable in production flow analysis. It is an efficient and easy-to-use algorithm for grouping machines into cells. In a starting part machine incidence matrix that might be compiled to document the part routings in a machine shop (or other job shop), the occupied locations in the matrix are organized in a seemingly random fashion. Rank order clustering works by reducing the part machine incidence matrix to a set of diagonalized blocks that represent part families and associated machine groups. Starting with the initial part machine incidence matrix. the algorithm consist, of the following steps:

In each row of the matrix. read the series of ls and G's (blank entries = D's) from left to fight as a binary number. Rank the rows in 01 del uf decreasing value. In case of a tie, rank the rows in the same order as they appear in the current matrix

Numbering from top to bottom, is the current order of rows the same as the rank order determined in the previous step? If yes, go to step 7, If no, go to the following step.

3, Reorder the rows in the part-machine incidence matrix by listing them in decreasing rank order, starting from the top

In each column of the matrix. read the series of I 's and O's (blank entries = (j's) from top to bottom as a binary number. Rank the columns in order of decreasing value, In case of a tie. rank the columns in the same order as they appear in the current matrix

Numbering from left to right, is the current order of columns the same as the rank order determined in the previous step? If yes. go to step 7. If no. go to thefollowing step.

Reorder the columns in the part-machine incidence matrix by listing them in decreasing rank order, starting with the left column. Go to step I.

7 Stop

For readers unaccustomed to evaluating binary numbers in steps 1 and 4, it might be helpful to convert each binary value into its decimal equivalent (e.g., the entries in the first row of the matrix in Table 15.4 are read as 100100(10). This is converted into its decimal equivalent as follows: $lx2^{8} + Ox2' + Ox2^{b} + 1x2^{5} + Ox2^{4} + Ox2^{3} + Ox2^{2} + Ix2] + Ox2° = 256 + 32 + 2 = 2$ *90*. It should be mentioned that decimal conversion becomes impractical for the large numbers of parts found in practice, and comparison of the binary numbers is preferred

EXAMPLE 15.3 **Rank Order Clustering Technique**

Apply the rank order clustering technique to the part-machine incidence matrix in Table 15.4

Solution: Step I consists of reading the series of 1's and D's in each row as a binary number. We have done this in Table 15.10(a). converting the binary value for each row to its decimal equivalent. The values are then rank ordered in the far right- hand column. In step 2. we see that the row order is different from the starting matrix. We therefore reorder the rows in step 3. In step 4, we read the series of I's and D's in each column from top to bottom as a binary number (again we have converted to the decimal equivalent, and the columns are ranked in order ofdecreasing value, as shown in Table 15.10(b).ln step 5, we see that the column order is different from the preceding matrix. Proceeding from step 6 back to steps 1 and 2, we see that a reordering of the columns provides a row order that is in descending value. and the algorithm is concluded (step 7). The final solution is shown in Table 15.10(c), A close comparison of this solution with Table 15,5 reveals that they are the carne part-machine groupings,

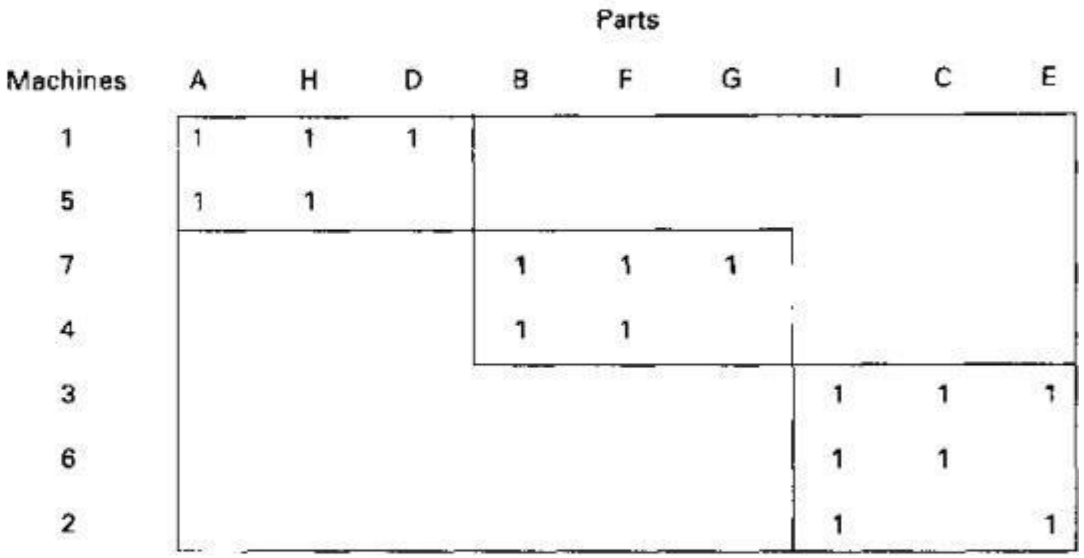
TABLE 15.10(a) First Iteration (Step 1) in the Rank Order Clustering Technique Applied to Example 15.3

Binary Values	2^8	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0		
					Parts					Decimal	
Machines	A	B	C	D	E	F	G	H	I	Equivalent	Rank
1	1			1				1		290	1
2					1				1	17	7
3			1		1				1	81	5
4		1				1				136	4
5	1							1		258	2
6			1						1	65	6
7		1				1	1			140	3

TABLE 15.10(b) Second Iteration (Steps 3 and 4) in the Rank Order Clustering Technique Applied to Example 15.3

					Parts					
Machines	A	B	C	D	E	F	G	H	I	Binary Values
1	1			1				1		2^6
5	1							1		2^5
7		1				1	1			2^4
4		1				1				2^3
3			1		1				1	2^2
6			1						1	2^1
						1			1	2^0
Decimal Equivalent	96	24	6	64	5	24	16	96	7	
Rank	1	4	8	3	9	5	6	2	7	

TABLE 15.10(c) Solution of Example 15.3



	Parts								
Machines	A	H	D	B	F	G	I	C	E
1	1	1	1						
5	1	1							
7				1	1	1			
4				1	1				
3							1	1	1
6							1	1	
2							1		1

In the example problem, it was possible to divide the parts and machines into three mutually exclusive part-machine groups. This represents the ideal case because the part families and associated machine cells are completely segregated. However, it is not uncommon for there to be an overlap in processing requirements between machine groups That is, a given part type needs to be processed by more than one machine group. Let us illustrate this case and how the rank order clustering technique deals with it in the following example.

EXAMPLE 15.4 Overlapping Machine Requirements

Consider the part-machine incidence matrix in Table 15.11. This is the same as the original part-machine incidence matrix in Table 15.4 except that part B requires

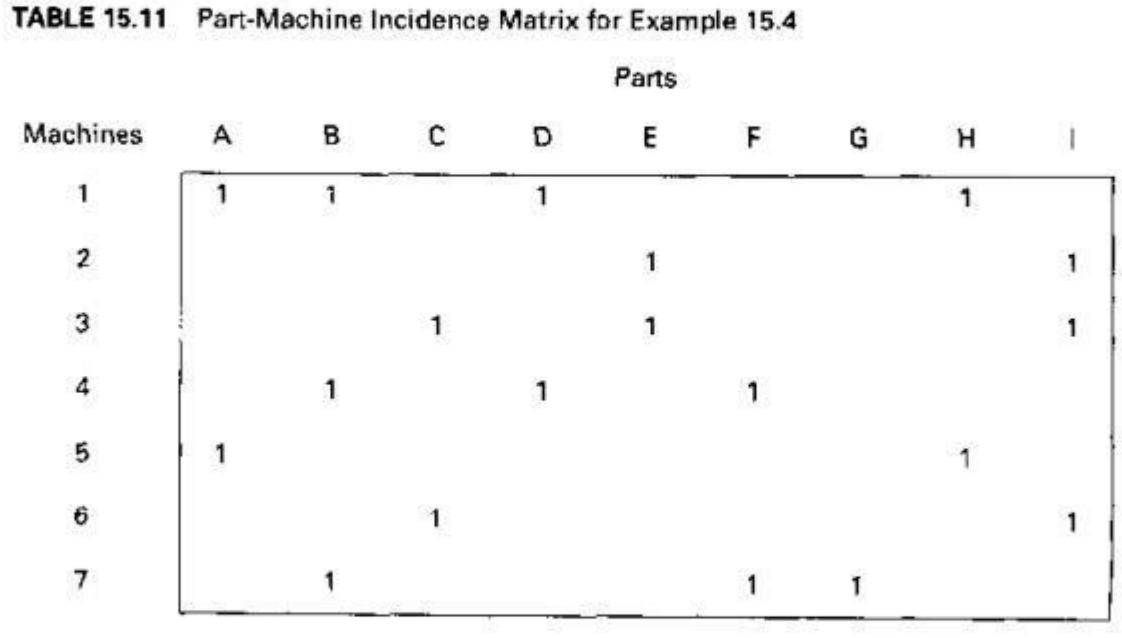


TABLE 15.11 Part-Machine Incidence Matrix for Example 15.4

Parts

Machines	A	B	C	D	E	F	G	H	I
1	1	1		1				1	
2					1				1
3			1		1				1
4		1		1		1			
5	1							1	
6			1						1
7		1				1	1		

processing on machines 1.4, and 7 (1 is the additional machine) and part D now requires processing on machines 1 and 4 (4 is the additional machine). Use the rank order clustering technique to arrange parts and machine into groups.

Solution: The rank order clustering technique converges to a solution in two iterations, shown in Tables 15.12(a) and 15.l2(b), with the final solution shown in Table1.'l.12(c).

TABLE 15.12(a) First Iteration of Rank Order Clustering Applied to Example 15.4

Binary Values	2^8	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0		
					Parts					Decimal	
Machines	A	B	C	D	E	F	G	H	I	Equivalent	Rank
1	1	1		1				1		418	1
2					1				1	17	7
3			1		1				1	81	5
4		1		1		1				168	3
5	1							1		258	2
6			1						1	65	6
7		1				1	1			140	4

TABLE 15.12(b) Second Iteration of Rank Order Clustering Applied to Example 15.4

					Parts					
Machines	A	B	C	D	E	F	G	H	I	Binary Values
1	1			1				1		2^6
5	1							1		2^5
4		1		1		1				2^4
7		1				1	1			2^3
3			1		1				1	2^2
6			1						1	2^1
2					1				1	2^0
Decimal Equivalent	96	88	6	80	5	24	8	96	7	
Rank	1	3	8	4	9	5	6	2	7	

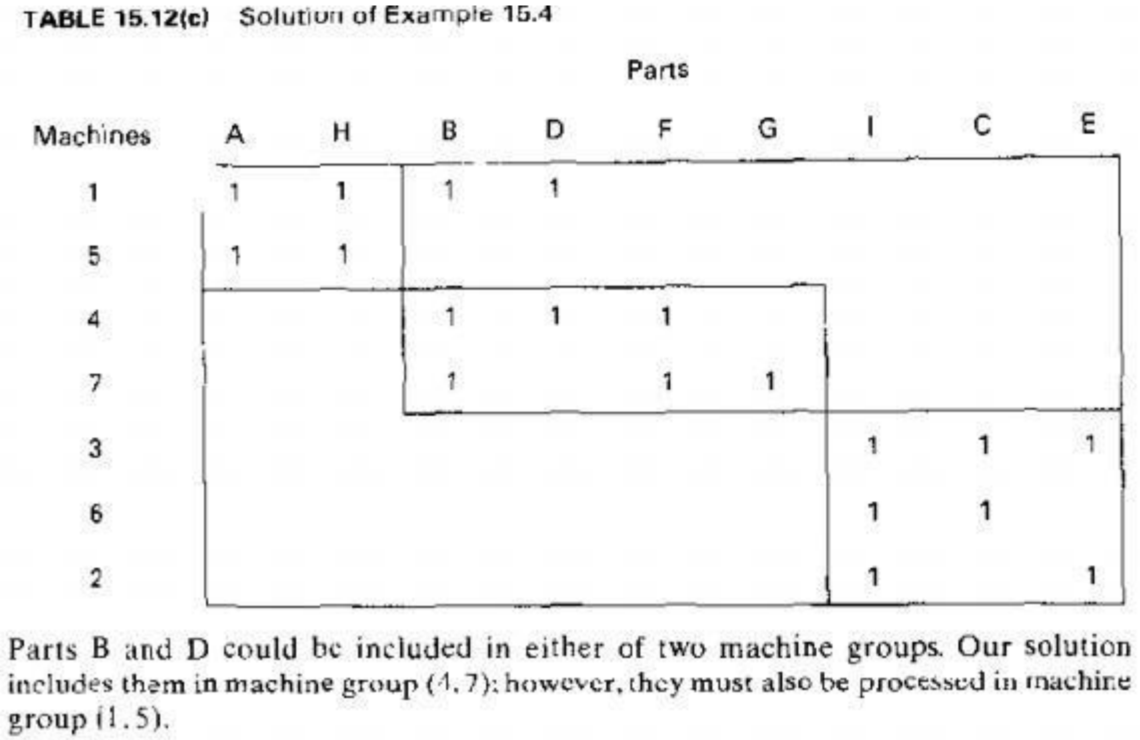


TABLE 15.12(c) Solution of Example 15.4

Machines	A	H	B	D	F	G	I	C	E
	Parts								
1	1	1	1	1					
5	1	1							
4			1	1	1				
7			1		1	1			
3							1	1	1
6							1	1	
2							1		1

Parts B and D could be included in either of two machine groups. Our solution includes them in machine group (4, 7); however, they must also be processed in machine group (1, 5).

Parts B and D could be included in either of two machine groups. Our solution includes them in machine group (1.7); however, they must also be processed in machine group (1. 5)

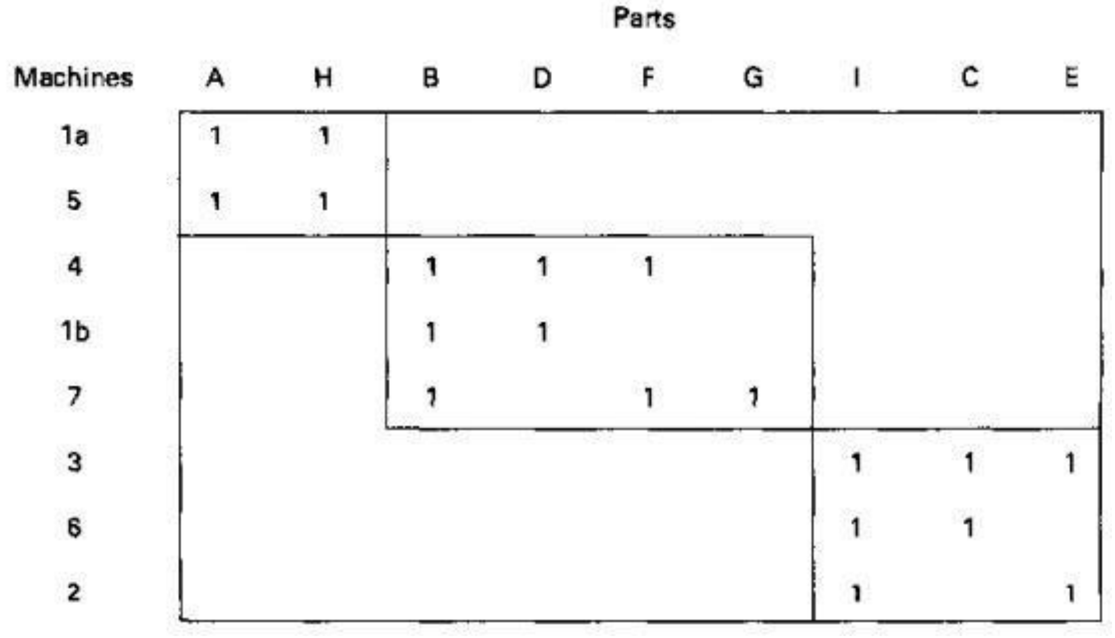
King [26] refers to the matrix elements Bl and Dj (parts Band D processed on machine in Table 15.l2(c) as exceptional elements, He recommends that they each he replaced with an asterisk (*) and treated as zeros when applying the rank order clustering technique. The effect of' this approach in our example problem would be to organize the machines exactly as we have done in our final solution in Table 15.12(c).Another way of dealing with the overlap h simply to duplicate the machine that is used by more than one part family. In Example 15.4, this would mean that two machines of type 1 would be used in the two censTbe result of this duplication is shown in the matrix of Table 15.13.where the two machines are identified as l a and j b. Of course. there may be economic considerations that would inhibit the machine redundancy.

Other approaches to the problem of overlapping machines, attributed to Burbidge [26J, include: (1) change the routing so that all processing can be accomplished in the pn. mary machine group. (2) redesign the part to eliminate the processing requirement outside the primary machine group, and (3) purchase the part from an outside supplier.

Arranging Machines in 8 GT Cell

After part-machine groupings have been identified by rank order clustering or other method. the next problem is to organize the machines into the most logical arrangement. Let us describe two simple yet effective methods suggested by Hollier [17]. Both methods use data contained in From-To charts (Section 10.6.1) and are intended to arrange the machines in an order that maximizes the proportionof in-sequence moves within the cell

TABLE 15.13 Solution to Example 15.4 Using Duplicate Machines of Type 1 (Shown as Machines 1a and 1b in the Matrix)



	Parts								
Machines	A	H	B	D	F	G	I	C	E
1a	1	1							
5	1	1							
4			1	1	1				
1b			1	1					
7			1		1	1			
3							1	1	1
6							1	1	
2							1		1

Hollier Method 1. The first method uses the sums of flow "From" and "To" each machine in the cell. The method can be outlined as follows:

Develop the From-To chart *from part routing data.* The data contained in the chart indicates numbers of part moves between the machines (or workstations) in the cell. Moves into and out of the cell are not included in the chart.

Determine the ―From‖ and ―TO‖ sums for each machine. This is accomplished by summing all of the "From" trips and "To" trips for each machine (or operation). The "From" sum for a machine is determined by adding the entries in the corresponding row, and the "To" sum is found by adding the entries in the corresponding column.

Assign machines to *the cell hosed on minimum "From" or "To" sums*. The machine having the smallest sum is selected. If the minimum value is a "To" sum, then the machine is placed at the beginning of the sequence. If the minimum value is a "From" sum, then the machine is placed at the end of the sequence. TIe breakerrules:

If a tie occurs between minimum "To" sums or minimum "From" sums, then the machine with the minimum "From/To" ratio is selected.

If both "To" and "From" sums are equal for a selected machine,it is passed over and the machine with the next lowest sum is selected.

If a minimum "To" sum is equal to a minimum "From" sum, then both machines are selected and placed at the beginning and end of the sequence, respectively.

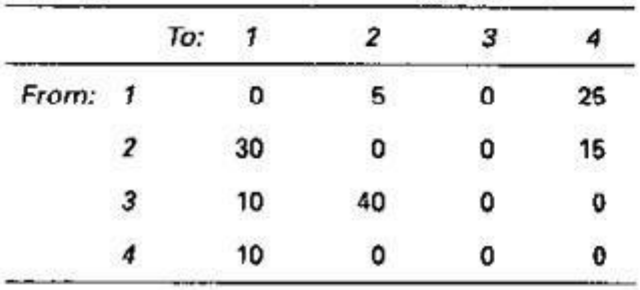
Reformat the From-To chan. After each machine has been selected, restructure the From-To chart by eliminating the row and column corresponding to the selected machine and recalculate the "From" and "To" sums. Repeat steps 3 and 4 until all machines have been assigned.

EXAMPLE 15.5 Group Technology Machine Sequence usingHollier Method 1

Suppose that four machines. I, 2.3, and 4 have been identified as belonging in a GT machine cell. An analysis of 50 parts processed on these machines has been summarized in the From-To chart of Table 15.14. Additional information is that '50 parts enter the machine grouping at machine 3,20 parts leave after processing at machine 1, and 30 parts leave after machine 4. Determine a logical machine arrangement using Hollier Method 1.

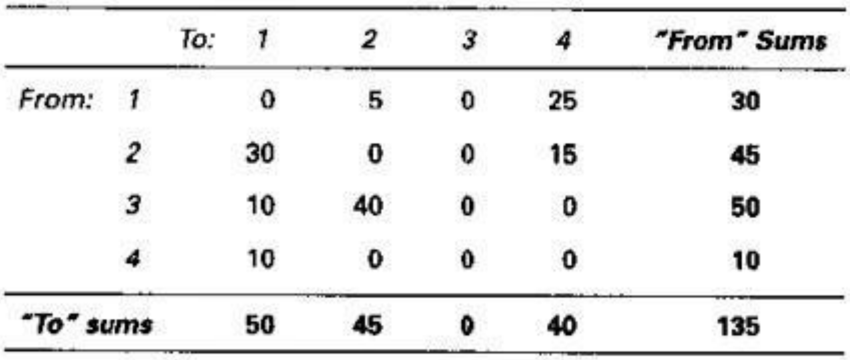
Solution: Summing the From trips and To trips for each machine yields the "From" and "To" sums in Table 15.15(a). The minimum sum value is the "To" sum for machine 3. Machine 3 is therefore placed at the beginning of the sequence. Eliminating the row and column corresponding to machine 3 yields the revised From-To chart in Table 15.15(b). The minimum sum in this chart is the "To"

TABLE 15.14 From-To Chart for Example 15.5



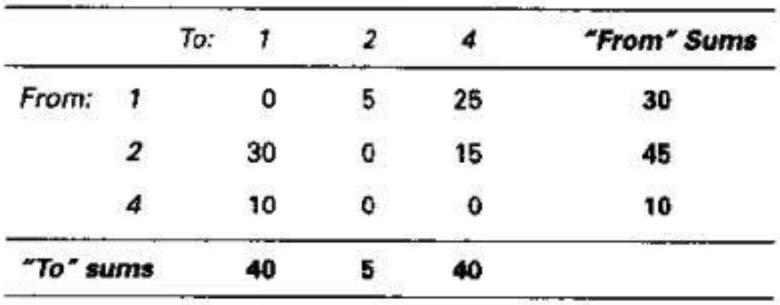
	To:	1	2	3	4
From:	1	0	5	0	25
	2	30	0	0	15
	3	10	40	0	0
	4	10	0	0	0

TABLE 15.15(a) From and To Sums for Example 15.5: First Iteration



	To:	1	2	3	4	*"From" Sums*
From:	1	0	5	0	25	30
	2	30	0	0	15	45
	3	10	40	0	0	50
	4	10	0	0	0	10
"To" sums		50	45	0	40	135

TABLE 15.15(b) From and To Sums for Example 15.5: Second Iteration with Machine 3 Removed



	To:	1	2	4	*"From" Sums*
From:	1	0	5	25	30
	2	30	0	15	45
	4	10	0	0	10
"To" sums		40	5	40	

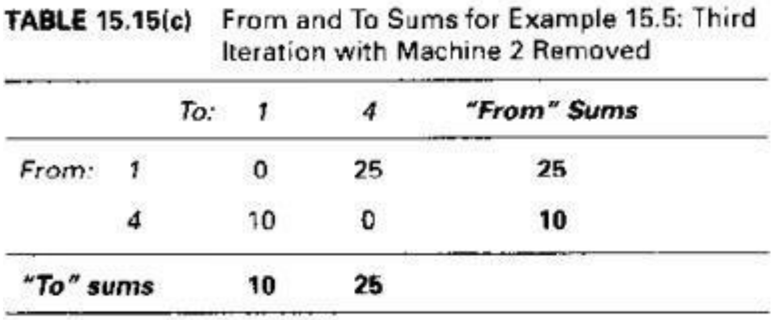


TABLE 15.15(c) From and To Sums for Example 15.5: Third Iteration with Machine 2 Removed

	To:	1	4	"From" Sums
From:	1	0	25	25
	4	10	0	10
"To" sums		10	25	

sum corresponding to machine 2. which is placed at the front at the sequence, immediately following machine 3. Eliminating machine 2 produces the *revised* From-To chart in Table 15.15(c). The minimum sum in this chart is the "To" sum for machine I. Machine I is placed after machine 2 and finally machine 4is placed at the end of the sequence. Thus, the resulting machine sequence is

3-- > 2 -- > 1 -- > 4

Hollier Method 2. This approach is based on the use of From/To ratios formed by summing the total flow from and to each machine in the cell. The method canhe reduced to three steps:

Develop the From-To chart. This is the same step as in Hollier Method 1.

Determine the From/To ratio for each machine. This i~ accomplished by summing up all of the "From" trips and "To" trips for each machine (or operation). The "From" sum for a machine is determined by adding the entries in the corresponding row, and the "To" sum is determined by adding the entries in the corresponding column. For each machine, the From/To ratio is calculated by takingthe "From" sum for each machine and dividing by the respective "To" sum.

Arrange machines in order of decreasing From/To ratio. Machines with ll high From/To ratio distribute work to many machines in the cell but receivework from few machines. Conversely, machines with a low From/To ratio receive more work than they distribute. Therefore, machines are arranged in order of descending Prom/Io ratio. That is, machines with high ratios are placed at the beginning of the work flow, and machine, with low ratios are placed at the end of the work flow. in case of a tie, the machine with the higher "From" value is placed ahead of the machine with a lower value

EXAMPLE 15.6 Group Technology Machine Sequence using Hollier Method 2

Solve Example 15.5 using Hollier Method 2.

Solution: Table 15.15(a), containing the "From" and "To" sums, is repeated in Table 15.16, along with the From/To ratios given in the last column on the right. Arranging the machines III order of descending Prom/To ratio, the machines in the cell should he sequenced as follows'

3 -- > 2 -- > 1 -- > 4

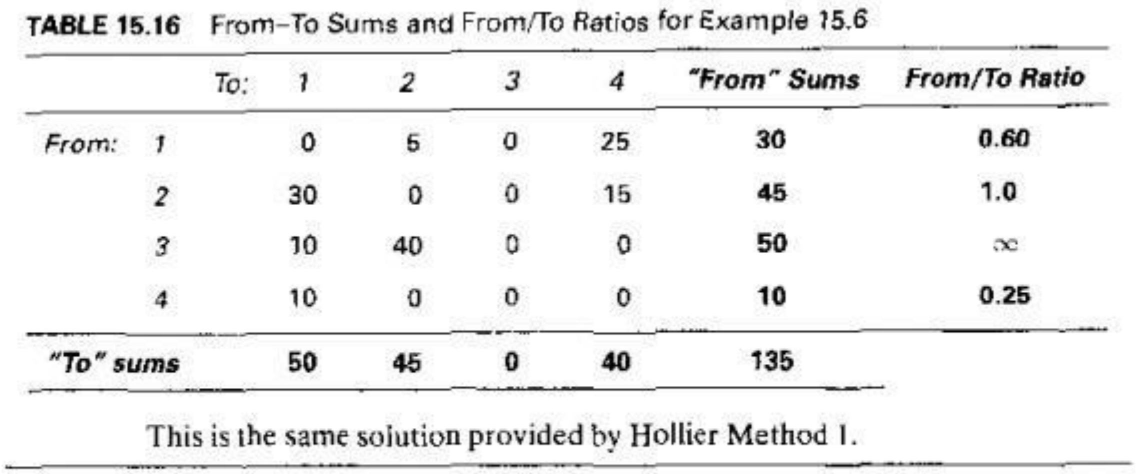


TABLE 15.16 From–To Sums and From/To Ratios for Example 15.6

	To:	1	2	3	4	"From" Sums	From/To Ratio
From:	1	0	5	0	25	30	0.60
	2	30	0	0	15	45	1.0
	3	10	40	0	0	50	∞
	4	10	0	0	0	10	0.25
"To" sums		50	45	0	40	135	

This is the same solution provided by Hollier Method 1.

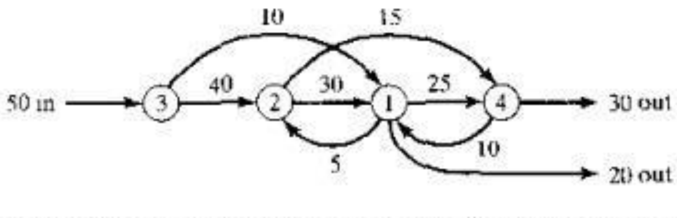


Figure 15.14 Flow diagram for machine cell in Examples 15.5 and 15.6. Flow of parts into and out of the cells has also been included.

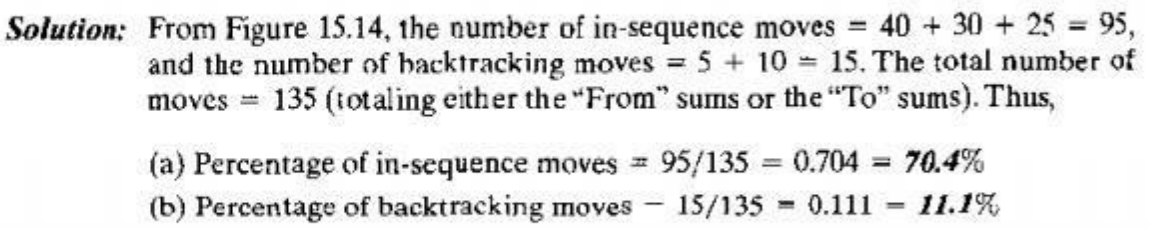
It is helpful to use one of the available graphical techniques, such as the flow diagram (Section 10.6.1), to conceptualize the work flow in the cell. The flow diagram for the machine arrangement in Examples 15.5 and 15.6 is presented in Figure 15,14. The work flow is mostly inline; however, there is some back flow or parts that must be considered in the design of any material handling system that might be used in the cell. A powered convey or would be appropriate for the forward flow between machines. with manual handling for the back flow.

For our example data in Table 1'1.14, Hollier Methods 1 and 2 provide the same solution. This is not always the case. The relative performance of the two methods depends on the given problem. In some problems. Method J will outperform Method 2.and in other problems the opposite will happen. In many problems, the two methods yield identical solutions, as in Examples 15.5 and 15.0. Hollier presents a comparison of these and his other proposed methods with a variety of problems in [17].

Two performance measures can be defined to compare solutions to the machine sequencing problem: (1) percentage of in-sequence moves and (2) percentage of backtracking moves. The *percentage of in-sequence moves* is computed by adding all of the values representing in-sequence moves and dividingby the total number of moves. The *percentage of backtracking moves* is determinedby summing all of the values representing backtracking moves and dividing by the total number of moves.

EXAMPLE 15.7 Performance Measures for Alternative Machine Sequence ••in GT cell

Compute (a) the percentage of in-sequence moves and (b) the percentage of backtracking moves for the solution in Examples 15.5 and 15.6.



Solution: From Figure 15.14, the number of in-sequence moves = 40 + 30 + 25 = 95, and the number of backtracking moves = 5 + 10 = 15. The total number of moves = 135 (totaling either the "From" sums or the "To" sums). Thus,

(a) Percentage of in-sequence moves = 95/135 = 0.704 = ***70.4***%

(b) Percentage of backtracking moves − 15/135 = 0.111 = ***11.1***%

MODULE 5

METHODS OF MEASUREMENTS

These are the methods of comparison used in measurement process. In precision measurement various methods of measurement are adopted depending upon the accuracy required and the amount of permissible error.

The methods of measurement can be classified as:

l. Direct method

2. Indirect method

3. Absolute or Fundamental method

4. Comparative method

5. Transposition method

6. Coincidence method

7. Deflection method

8. Complementary method

9. Contact method

10. Contact less method

1. Direct method of measurement:

This is a simple method of measurement, in which the value of the quantity to be measured is obtained directly without any calculations. For example, measurements by using scales, vernier callipers, micrometers, bevel protector etc. This method is most widely used in production. This method is not very accurate because it depends on human insensitiveness in making judgment.

2. Indirect method of measurement:

In indirect method the value of quantity to be measured is obtained by measuring other quantities which are functionally related to the required value. E.g. Angle measurement by sine bar, measurement of screw pitch diameter by three wire method etc.

3. Absolute or Fundamental method:

It is based on the measurement of the base quantities used to define the quantity. For example, measuring a quantity directly in accordance with the definition of that quantity, or measuring a quantity indirectly by direct measurement of the quantities linked with the definition of the quantity to be measured.

4. Comparative method:

In this method the value of the quantity to be measured is compared with known value of the same quantity or other quantity practically related to it. So, in this method only the deviations from a master gauge are determined, e.g., dial indicators, or other comparators.

5. Transposition method:

It is a method of measurement by direct comparison in which the value of the quantity measured is first balanced by an initial known value A of the same quantity, and then the value of the quantity measured is put in place of this known value and is balanced again by another known value B. If the position of the element indicating equilibrium is the same in both cases, the value of the quantity to be measured is AB. For example, determination of amass by means of a balance and known weights, using theGauss double weighing.

6. Coincidence method:

It is a differential method of measurement in which a very small difference between the value of the quantity to be measured and the reference is determined by the observation of the coincidence of certain lines or signals. For example, measurement by vernier calliper micrometer.

7. Deflection method:

In this method the value of the quantity to be measured is directly indicated by a deflection of a pointer on a calibrated scale.

8. Complementary method:

In this method the value of the quantity to be measured is combined with a known value of the same quantity. The combination is so adjusted that the sum of these two values is equal to predetermined comparison value. For example, determination of the volume of a solid by liquid displacement.

9. Method of measurement by substitution:

It is a method of direct comparison in which the value of a quantity to be measured is replaced by a known value of the same quantity, so selected that the effects produced in the indicating device by these two values are the same.

10. Method of null measurement:

It is a method of differential measurement. In this method the difference between the value of the quantity to be measured and the known value of the same quantity with which it is compared is brought to zero.

GENERALIZED MEASUREMENT SYSTEM

A measuring system exists to provide information about the physical value of some variable being measured. In simple cases, the system can consist of only a single unit that gives an output reading or signal according to the magnitude of the unknown variable applied to it. However, in more complex measurement situations, a measuring system consists of several separate elements as shown in Figure1.1.

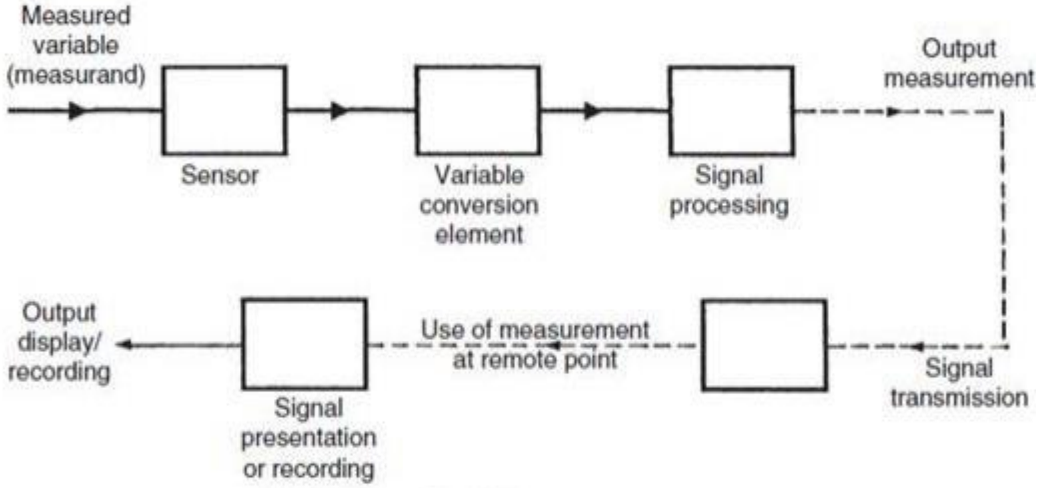


Fig 1.1 Generalised Measurement system

Units

Table 1.1 Physical Quantities and its unit

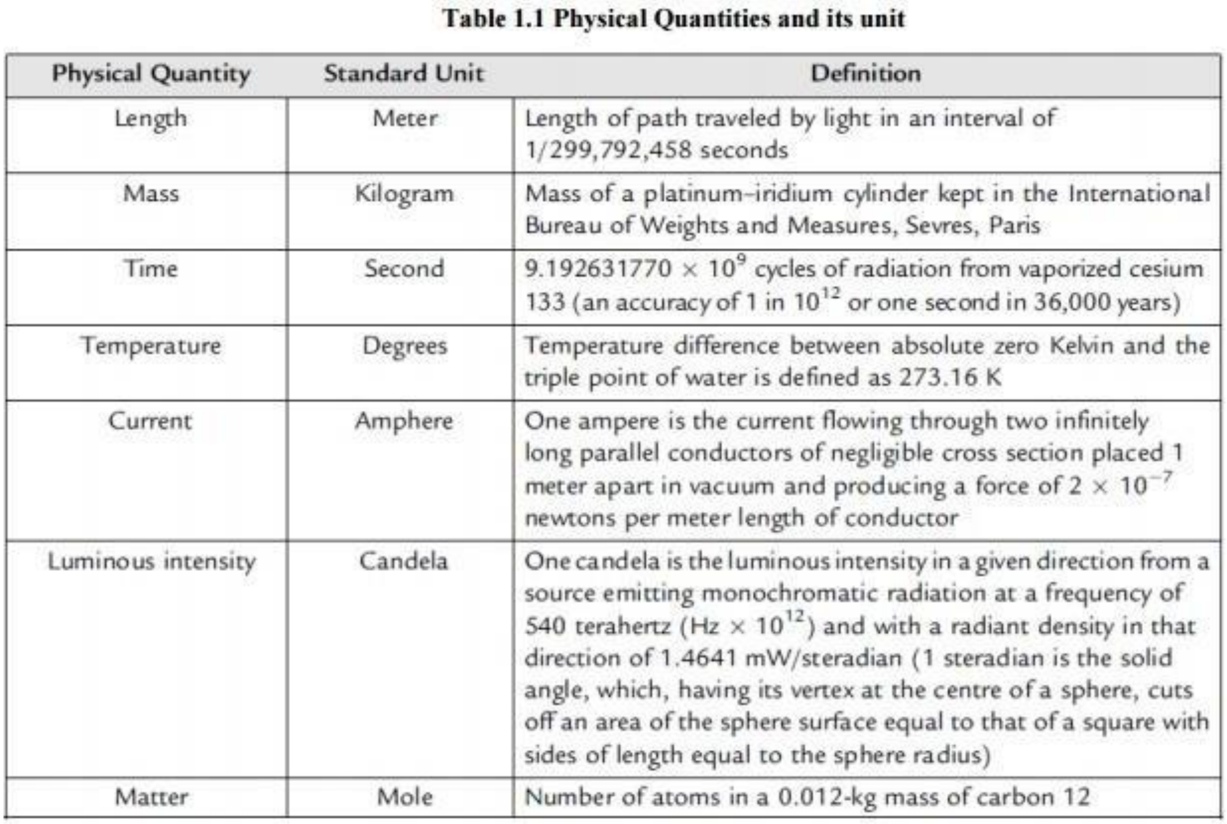


Table 1.1 Physical Quantities and its unit

Physical Quantity	Standard Unit	Definition
Length	Meter	Length of path traveled by light in an interval of 1/299,792,458 seconds
Mass	Kilogram	Mass of a platinum–iridium cylinder kept in the International Bureau of Weights and Measures, Sevres, Paris
Time	Second	9.192631770×10^9 cycles of radiation from vaporized cesium 133 (an accuracy of 1 in 10^{12} or one second in 36,000 years)
Temperature	Degrees	Temperature difference between absolute zero Kelvin and the triple point of water is defined as 273.16 K
Current	Amphere	One ampere is the current flowing through two infinitely long parallel conductors of negligible cross section placed 1 meter apart in vacuum and producing a force of 2×10^{-7} newtons per meter length of conductor
Luminous intensity	Candela	One candela is the luminous intensity in a given direction from a source emitting monochromatic radiation at a frequency of 540 terahertz ($\text{Hz} \times 10^{12}$) and with a radiant density in that direction of 1.4641 mW/steradian (1 steradian is the solid angle, which, having its vertex at the centre of a sphere, cuts off an area of the sphere surface equal to that of a square with sides of length equal to the sphere radius)
Matter	Mole	Number of atoms in a 0.012-kg mass of carbon 12

Standards

The term standard is used to denote universally accepted specifications for devices. Components or processes which ensure conformity and interchangeability throughout a particular industry. A standard provides a reference for assigning a numerical value to a measured quantity. Each basic measurable quantity has associated with it an ultimate standard. Working standards, those used in conjunction with the various measurement making instruments.

The national institute of standards and technology (NIST) formerly called National Bureau of Standards (NBS), it was established by an act of congress in 1901, and the need for such body had been noted by the founders of the constitution. In order to maintain accuracy, standards in a vast industrial complex must be traceable to a single source, which may be national standards.

The following is the generalization of echelons of standards in the national measurement system.

1. Calibration standards

2. Metrology standards

3. National standards

1. **Calibration standards:** Working standards of industrial or governmental laboratories.

2. **Metrology standards:** Reference standards of industrial or Governmental laboratories.

National standards: It includes prototype and natural phenomenonof SI (Systems International), the world wide system of weight and measures standards. Application of precise measurement has increased so much, that a single national laboratory to perform directly all the calibrations and standardization required by a large country with high technical development. It has led to the establishment of a considerable number of standardizing laboratories in industry and in various other areas. A standard provides a reference or datum for assigning a numerical value to a measured quantity.

Classification of Standards

To maintain accuracy and interchangeability it is necessary that Standards to be traceable to a single source, usually the National Standards of the country, which are further linked to International Standards. The accuracy of National Standards is transferred to working standards through achain of intermediate standards in a manner given below.

•National Standards

•National Reference Standards

- Working Standards
- Plant Laboratory Reference Standards
- Plant Laboratory Working Standards
- Shop Floor Standards

Evidently, there is degradation of accuracy in passing from the defining standards to the shop floor standards. The accuracy of particular standard depends on a combination of the number of times it has been compared with a standard in a higher echelon, the frequency of such comparisons, the care with which it was done, and the stability of the particular standards itself.

Accuracy of Measurements

The purpose of measurement is to determine the true dimensions of a part. But no measurement can be made absolutely accurate. There is always some error. The amount of error depends upon the following factors:

- The accuracy and instrument design of the measurement
- The skill of the operator
- Method adopted for measurement
- Temperature variations
- Elastic deformation of the part or in

Thus, the true dimension of the part cannot be determined but can only by approximate. The agreement of the measured value with the true value of the measured quantity is called accuracy. If the measurement of dimensions of a part approximates very closely to the true value of that dimension, it is said to be accurate. Thus the term accuracy denotes the closeness of the measured value with the true value. The difference between the measured value and the true value is the error of measurement. The lesser the error, more is the accuracy.

Precision

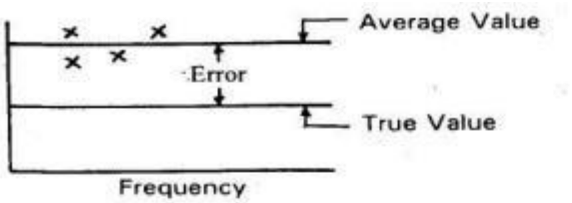
The terms precision and accuracy are used in connection with the performance of the instrument. Precision is the repeatability of the measuring process. It refers to the group of measurements for the same characteristics taken under identical conditions. It indicates to what extent the identically performed measurements agree with each other. If the instrument is not precise it will give different (widely varying) results for the same dimension when measured again and again. The set of observations will scatter about the

mean. The scatter of these measurements is designated as σ, the sta used as an index of precision. The less the scattering more precise is the instrument.

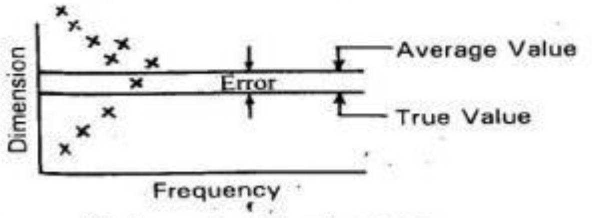
Accuracy

Accuracy is the degree to which the measured value of the quality characteristic agrees with the true value. The difference between the true value and the measured value is known as error of measurement. It is practically difficult to measure exactly the true value and therefore a set of observations is made whose mean value is taken as the true value of the quality measured.

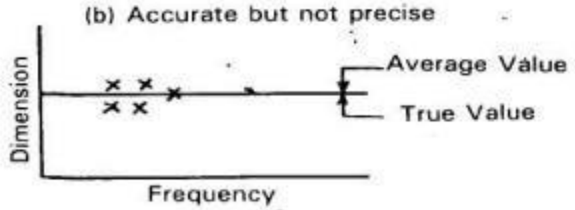
Distinction between Precision and Accuracy



(a) Precise but not accurate



(b) Accurate but not precise



(c) Accurate & precise

Accuracy is very often confused with precision though much different. The distinction between the precision and accuracy will become clear by the following example. Several measurements are made on a component by different types of instruments (A, B and C respectively) and the results are plotted. In any set of measurements, the individual measurements are scattered about the mean, and the precision signifies how well the various measurements performed by same instrument on the same quality characteristic agree with each other. The difference between the mean of set of readings on the same quality characteristic and the true value is called as error. Less the error more accurate is the instrument. Figure shows that the instrument A is precise since the results of number of measurementsare close to the average value. However, there is a large difference (error) between the true value and the average value hence it is not accurate. The readings taken by the instruments are scattered much from the average value and hence it is not precise but accurate as there is a small difference between the average value and true value.

Factors affecting the accuracy of the Measuring System

The basic components of an accuracy evaluation are the five elements of a measuring system such as:

- Factors affecting the calibration standard
- Factors affecting the work piece.
- Factors the inherent affecting characteristics of the instrument.
- Factors affecting the person, who carried measurement
- Factors affecting the environment.

1. **Factors affecting the Standard**: It may be affected by:

-Coefficient of thermal expansion

-Calibration interval

-Stability with time

-Elastic properties

-Geometric compatibility

2. **Factors affecting the Work piece**: These are: -Cleanliness

-Surface finish, waviness, scratch, surface defects etc., -Hidden geometry

-Elastic properties,-adequate datum on the work piece -Arrangement of supporting work piece

-Thermal equalization etc

3. **Factors affecting the inherent characteristics of Instrument**: -Adequate amplification for accuracy objective

-Scale error

-Effect of friction, backlash, hysteresis, zero drift error

-Deformation in handling or use, when heavy work pieces are measured -Calibration errors

-Mechanical parts (slides, guide ways or moving elements) -Repeatability and readability

-Contact geometry for both work piece and standard.

4. **Factors affecting person**:

-Training, skill

-Sense of precision appreciation

-Ability to select measuring instruments and standards -Sensible appreciation of measuring cost

-Attitude towards personal accuracy achievements

-Planning measurement techniques for minimum cost, consistent with precision requirements etc.

5. **Factors affecting Environment**:

-Temperature, humidity etc.

-Clean surrounding and minimum vibration enhance precision -Adequate illumination

-Temperature equalization between standard, work piece, and instrument -Thermal expansion effects due to heat radiation from lights

-Heating elements, sunlight and people

-Manual handling may also introduce thermal expansion.

Higher accuracy can be achieved only if, ail the sources of error due to the above five elements in the measuring system are analyzed and steps taken to eliminate them. The above analysis of five basic metrology elements can be composed into the acronym SWIPE, for convenient reference where,
S –STANDARD W –WORKPIECE I –INSTRUMENT

P –PERSON E –ENVIRONMENT

CO-ORDINATE MEASURING MACHINES

Measuring machines are used for measurement of length over the outer surfaces of a length bar or any other long member. The member may be either rounded or flat and parallel. It is more useful and advantageous than vernier calipers, micrometer, screw gauges etc. the measuring machines are generally universal character and can be used for works of varied nature. The co-ordinate measuring machine is used for contact inspection of parts. When used for computer-integrated manufacturing these machines are controlled by computer numerical control. General software is provided for reverse engineering complex shaped objects. The component is digitized using CNC, CMM and it is thenconverted into a computer model which gives the two surface of the component. These advances include for automatic work part alignment on the table. Savings in inspection 5 to 10 percent of the time is required on a CMM compared to manual inspection methods.

Types of Measuring Machines

1. Length bar measuring machine.

2. Newall measuring machine.

3. Universal measuring machine.

4. Co-ordinate measuring machine.

5. Computer controlled co-ordinate measuring machine.

Constructions of CMM

Co-ordinate measuring machines are very useful for three dimensional measurements. These machines have movements in X-Y-Z co-ordinate, controlled and measured easily by using touch probes. These measurements can be made by positioning the probe by hand, or automatically in more expensive machines. Reasonable accuracies are 5 micro in. or 1 micrometer. The method these machines work on is measurement of the position of the probe using linear position sensors. These are based on moiré fringe patterns (also used in other systems). Transducer is provided in tilt directions for giving digital display and senses positive and negative direction.

Types of CMM

(i) Cantilever type

The cantilever type is very easy to load and unload, but mechanical error takes place because of sag or deflection in Y-axis.

(ii) Bridge type

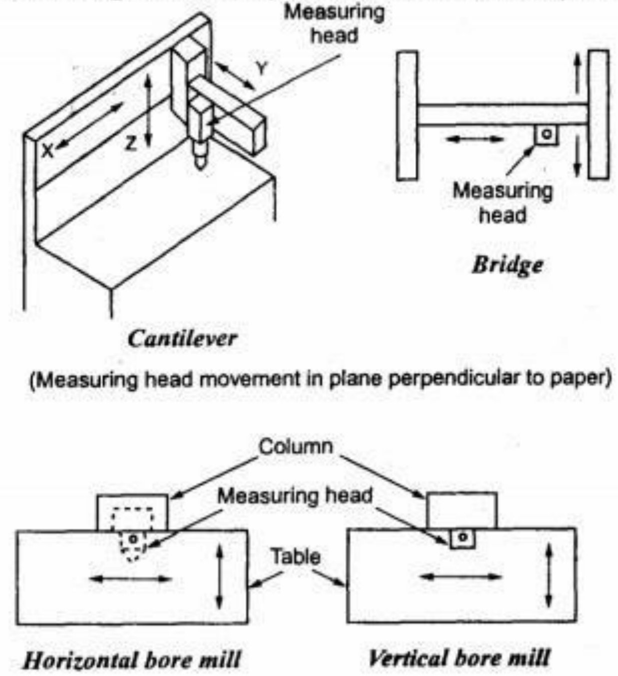
Bridge type is more difficult to load but less sensitive to mechanical errors.

(iii) Horizontal boring Mill type

This is best suited for large heavy work pieces.

(iv) Vertical boring mill type: -

Vertical boring mill is highly accurate but slower to operate.



(Measuring head movement in plane perpendicular to paper)

Fig 4.12 Types of CMM

Fig 4.12 Types of CMM

Working Principle

CMM is used for measuring the distance between two holes. The work piece is clamped to the worktable and aligned for three measuring slides x, y and z. The measuring head provides a taper probe tip which is seated in first datum hole and the position of probe digital read out is set to zero. The probe is then moved to successive holes, the read out represent the co-ordinate part print hole locationwith respect to the datum hole. Automatic recording and data processing units are provided to carry out complex geometric and statistical analysis. Special co-ordinate measuring machines are provided both linear and rotary axes. This can measure various features of parts like cone, cylinder and hemisphere. The prime advantage of co-ordinate measuring machine is the quicker inspection and accurate measurements.

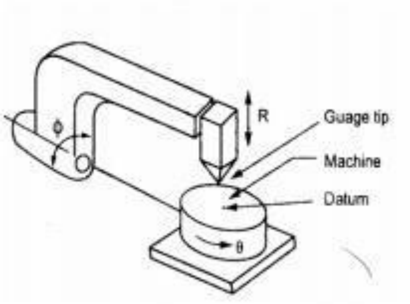


Fig 4.13 Schematic Diagram

Fig 4.13 Schematic Diagram

Causes of Errors in CMM

1) The table and probes are in imperfect alignment. The probes may have a degree of run out and move up and down in the Z-axis may cause perpendicularity errors. So CMM should be calibrated with master plates before using the machine.

2) Dimensional errors of a CMM is influenced by

- Straightness and perpendicularity of the guide ways.
- Scale division and adjustment.
- Probe length.
- Probe system calibration, repeatability, zero point setting and reversal error.
- Error due to digitization.
- Environment

3) Other errors can be controlled by the manufacture and minimized by the measuring software. The length of the probe should be minimum to reduce deflection.

4) The weight of the work piece may change the geometry of the guide ways and therefore, the work piece must not exceed maximum weight.

5) Variation in temperature of CMM, specimen and measuring lab influence the uncertainly of measurements.

6) Translation errors occur from error in the scale division and error in straightness perpendicular to the corresponding axis direction.

7) Perpendicularity error occurs if three axes are not orthogonal.

5 Calibration of Three Co-Ordinate Measuring Machine

The optical set up for the V calibration is shown in figure

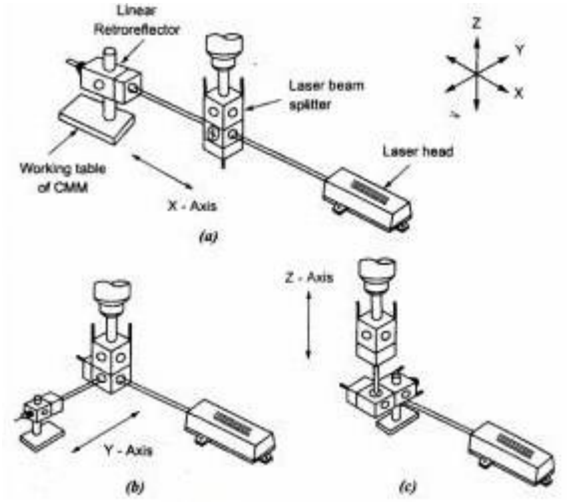


Fig 4.14 Optical setup

The laser head is mounted on the tripod stand and its height is adjusted corresponding to the working table of CMM. The interferometer contains a polarized beam splitter which reflects F1 component of the laser beam and the F2 Component parts through. The retro reflector is a polished trihedral glass prism. It reflects the laser beam back along a line parallel to the original beam by twice the distance. For distance measurement the F1 and F2 beams that leave the laser head are aimed at the interferometer which splits F1 and F2 via polarizing beaming splitter. Component F1 becomes the fixed distance path and F2 is sent to a target which reflects it back to the interferometer. Relative motion between the interferometer and the remote retro reflector causes a Dopper shift in the returned frequency. Therefore the laser head sees a frequency difference given by F1-F2 ± ΔF2. The-F2 ±F1ΔF2 signal that is external interferometer is compared in the measurement display unit to the reference signal. The difference ΔF2 is related to microscope of CMM is set at zero and the laser display unit is also set at zero. The CMM microscope is then set at the following points and the display units are noted.1 to 10mm, every mm and 10 to 200mm, in steps of 10mm. The accuracy of linear measurements is affected by changes in air temperature, pressure and humidity.

Performance of CMM

- Geometrical accuracies such as positioning accuracy, Straightness and Squareness.

APPLICATIONS

- Co-ordinate measuring machines find applications in automobile,machine tool, electronics, space and many other large companies.
- These machines are best suited for the test and inspection of test equipment, gauges and tools.
- For aircraft and space vehicles, hundred percent inspections is carried out by using CMM.
- CMM can be used for determining dimensional accuracy of the components.
- These are ideal for determination of shape and position, maximum metal condition, linkage of results etc. which cannot do in conventional machines.
- CMM can also be used for sorting tasks to achieve optimum pairing of components within tolerance limits.
- CMMs are also best for ensuring economic viability of NC machines by reducing their downtime for inspection results. They also help in reducing cost, rework cost at the appropriate time with a suitable CMM.

Advantages

- The inspection rate is increased.
- Accuracy is more.
- Operators error can be minimized.
- Skill requirements of the operator is reduced.
- Reduced inspection fixturing and maintenance cost.
- Reduction in calculating and recording time.
- Reduction in set up time.
- No need of separate go / no go gauges for each feature.
- Reduction of scrap and good part rejection.
- Reduction in off line analysis time.
- Simplification of inspection procedures, possibility of reduction of total inspection time through use of statistical and data analysis techniques.

Disadvantages

- The table and probe may not be in perfect alignment.
- The probe may have run out.
- The probe moving in Z-axis may have some perpendicular errors.
- Probe while moving in X and Y direction may not be square to each other.
- There may be errors in digital system.

Computer Controlled Co-Ordinate Measuring Machine

- The measurements, inspection of parts for dimension form, surface characteristics and position of geometrical elements are done at the same time.

- Mechanical system can be divided into four basic types. The selection will be depends on the application.

    1. Column type.

    2. Bridge type.

    3. Cantilever type.

    4. Gantry type.

All these machines use probes which may be trigger type or measuring type. This is connected to the spindle in Z direction. The main features of this system are shown in figure

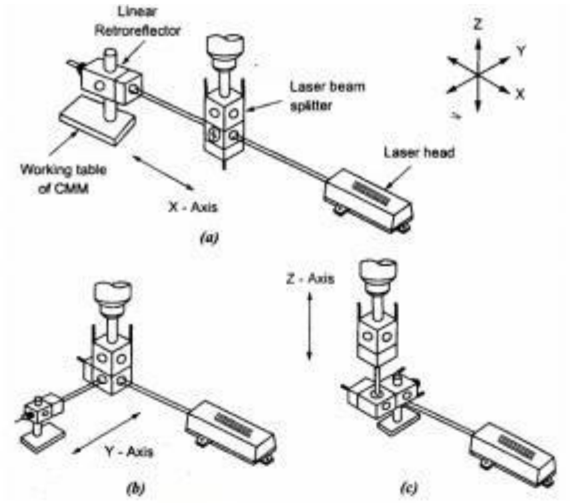
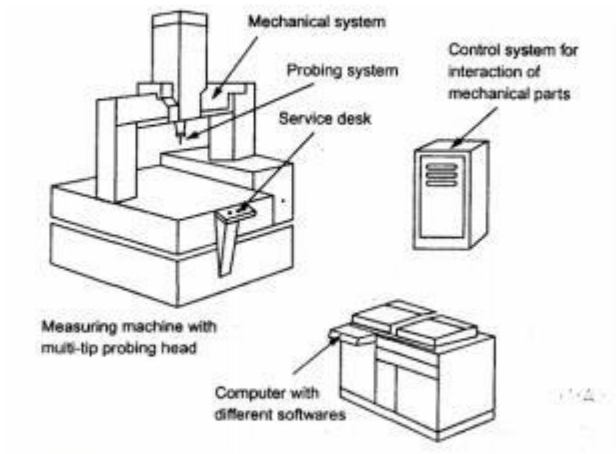
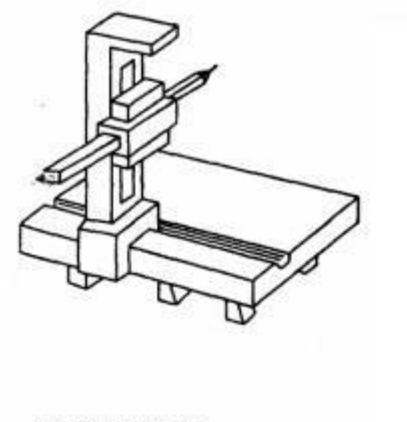


Fig 4.14 Optical setup

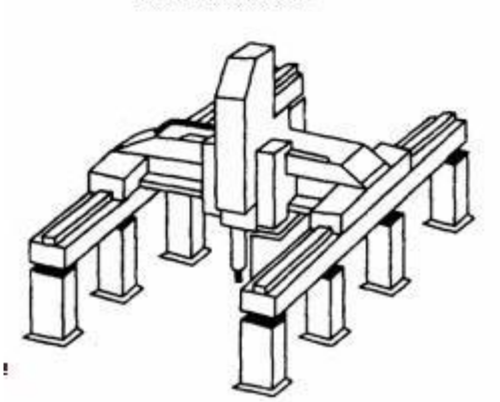


ig 4.16 Bridge Type

Fig 4.15 Column Type
Fig 4.16 Bridge Type

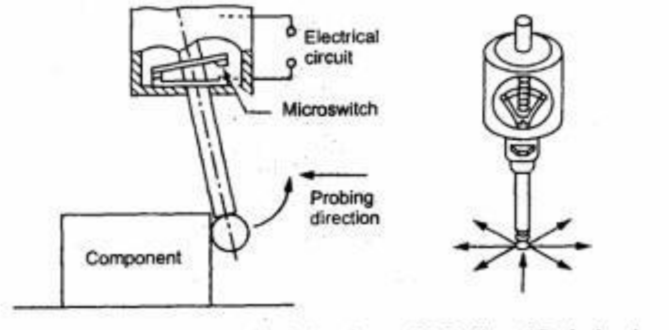


(iii) Cantilever type



(iv) Gantry type

Trigger type probe system



(a) Part section of Probe head (b) Outline of Probe head

Fig 4.17 Trigger Type Probe System

Fig 4.17 Trigger Type Probe System

- The buckling mechanism is a three point hearing the contacts which are arranged at 1200 around the circumference. These contacts act as electrical micro switches.

- When being touched in any probing direction one or f contacts is lifted off and the current is broken, thus generating a pulse, when the circuit is opened, the co-ordinate positions are read and stored.

- After probing the spring ensures the perfect zero position of the three-point bearing. The probing force is determined by the pre stressed force of the spring with this probe system data acquisition is always dynamic and therefore the measuring time is shorter than in static principle.

Measuring type probe system

- It is a very small co-ordinate measuring machine in which the buckling mechanism consists of parallel guide ways when probing the spring parallelogram are deflected from their initial position.

- Since the entire system is free from, torsion, friction, the displacement can be measured easily.

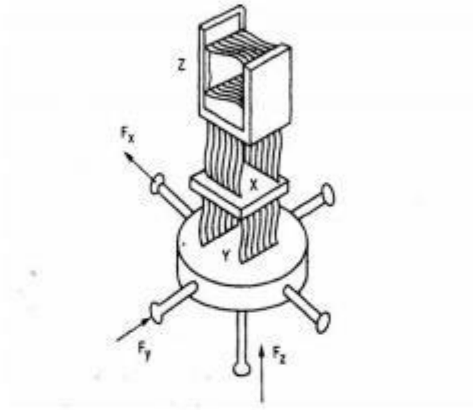


Fig 4.18 Buckling Mechanism

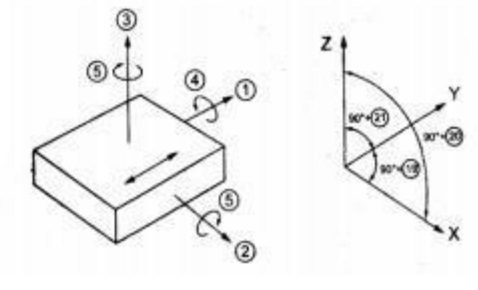


Fig 4.18 Buckling Mechanism

- The mathematical model of the mechanical system is shown in figure. If the components of the CMM are assumed as rigid bodies, the deviations of a carriage can be described by three displacement deviations.

- Parallel to the axes 1, 2 and 3 and by three rotational deviations about the axes 4, 5 and 6.Similarly deviations 7-12 occur for carriage and 13-18 occur for Z carriage and the three squareness deviations 19, 20 and 21 are to be measured and to be treated in the mathematical model.

- Moving the probe stylus in the Y direction the co-ordinate system L is not a straight line but a curved one due to errors in the guide.

- If moving on measure line L further corrections are required in X, Y and Z coordinates due to the offsets X and Z from curve L resulting from the pitch angle 5, the roll angle 4 and the yaw angle 6.

- Similarly the deviations of all three carriages and the squareness errors can be taken into account.

- The effect of error correction can be tested by means of calibrated step gauges.

The following test items are carried out for CMM.

(i) Measurement accuracy

a. Axial length measuring accuracy b.Volumetric length measuring accuracy

(ii) Axial motion accuracy

a. Linear displacement accuracy

b. Straightness

c. Perpendicularity

d. Pitch, Yaw and roll.

The axial length measuring accuracy is tested at the lowest position of the Z-axis. The lengths tested are approximately 1/10, 1/5, 2/5, 3/5 and 4/5 of the measuring range of each axis of CMM. Tile test is repeated five times for each measuring length and results plotted and value of measuring accuracy is derived.

CNC-CMM: Construction and Features of CMM Software

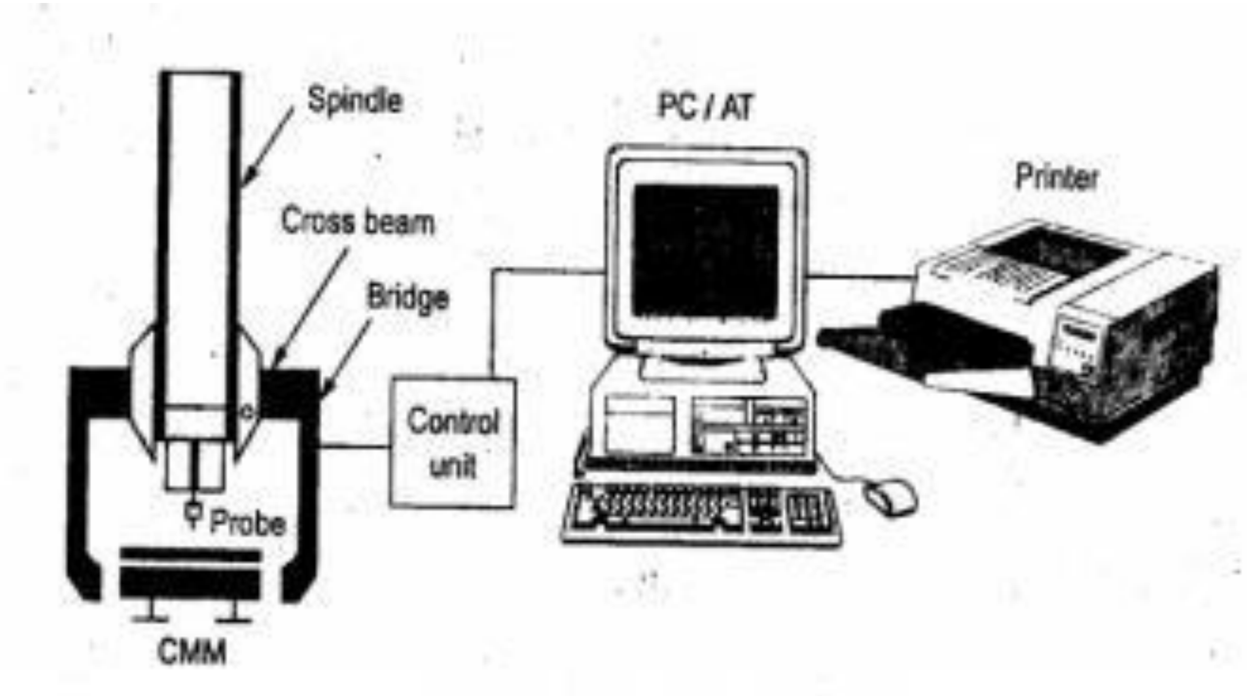


Fig 4.19 CNC - CMM

The main features of CNC-CMM are shown in figure has stationary granite measuring table, Length measuring system. Air bearings; control unit and software are the important parts of CNC & CMM.

CNC-CMM

Construction

The main features of CNC-CMM are shown in figure has stationary granite measuring table, Length measuring system. Air bearings; control unit and software are the important parts of CNC & CMM.

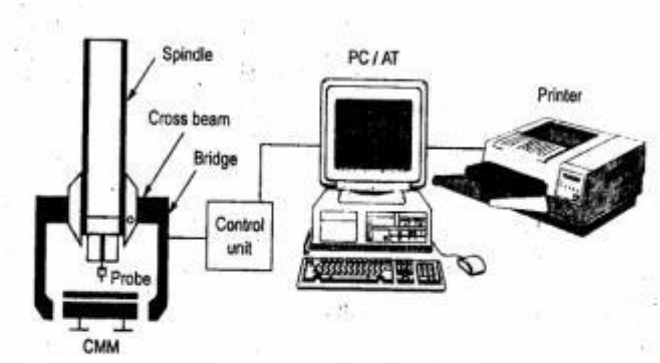


Fig 4.19 CNC - CMM

- **Stationary granite measuring table**

Granite table provides a stable reference plane for locating parts to be measured. It is provided with a grid of threaded holes defining clamping locations and facilitating part mounting. As the table has a high load carrying capacity and is accessible from three sides. It can be easily integrated into the material flow system of CIM.

- **Length measuring system**

A 3- axis CMM is provided with digital incremental length measuring system for

each axis.

- **Air Bearing**

The Bridge cross beam and spindle of the CMM are supported on air bearings.

- **Control unit**

- The control unit allows manual measurement and programme. It is a microprocessor control.

- **Software**

- The CMM, the computer and the software represent one system; the efficiency and cost effectiveness depend on the software.

Features of CMM Software

(i) Measurement of diameter, center distance, length.

(ii) Measurement of plane and spatial carvers.

(iii) Minimum CNC programme.

(iv)Data communications.

(v) Digital input and output command.

(vi) Programme for the measurement of spur

(vii)Interface to CAD software.

A new software for reverse engineering complex shaped objects. The component is digitized using CNC CMM. The digitized data is converted into a computer model which is the true surface of the component. Recent advances include the automatic work part alignment and to orient the coordinate system. Savings in inspection time by using CMM is 5 to 10% compared to manual inspection method.

Flexible Inspection System

The block diagram of flexible inspection system is shown in figure. This system has been developed and the inspection done at several places in industry. This system helps product performance to improve inspection and increase productivity. FIS is the Real time processor to handle part dimensional data and as a multi programming system to perform manufacturing process control. The input devices used with this system are CMM's;

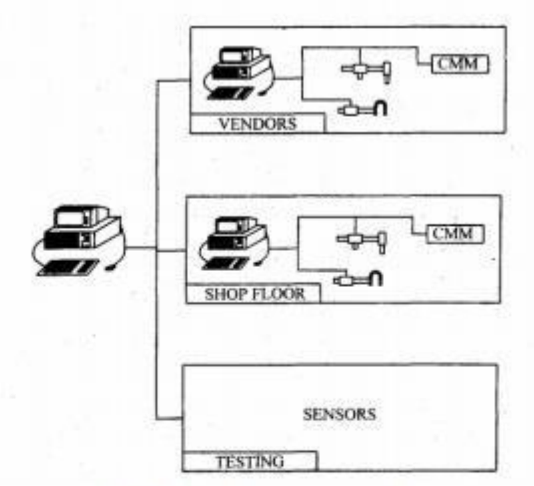


Fig 4.21 Flexible Inspection System

Microprocessor based gauges and other inspection devices. The terminal provides interactive communication with personal computers where the programmes are stored. The data from CMMs and other terminals are fed into the main computer for analysis and feedback control. The equality control data and inspection data from each station are fed through the terminals to the main computer. The data willbe communicated through telephone lines. Flexible inspection system involves more than one inspection station. The objective of the flexible inspection system is to have off time multi station automated dimensional verification system to increase the production rate and less inspection time and to maintain the inspectionaccuracy and data processing integrity.

Machine Vision

A Vision system can be defined as a system for automatic acquisition and analysis of images to obtain desired data for interpreting or controlling an activity. It is a technique which allows a sensor to view a scene and derive a numerical or logical decision without further human intervention. Machine vision can be defined as a means of simulating the image recognition and analysis capabilities of the human system with electronic and electro mechanical techniques. Machine vision system are now a days used to provide accurate and in expensive 100% inspection of work pieces. These are used for functions like gauging of dimensions, identification of shapes, measurement of distances, determining orientation of parts, quantifying motion-detecting surface shading etc. It is best suited for high production. These systems function without fatigue. This is suited for inspecting the masks used in the production of micro-electronic devices. Standoff distance up to one meter is possible.

Vision System

The schematic diagram of a typical vision system is shown. This system involves image acquisition; image processing Acquisition requires appropriate lighting. The camera and store digital image processing involves manipulating the digital image to simplify and reduce number of data points. Measurements can be carried out at any angle along the three reference axes x y and z without contacting the part. The measured values are then compared with the specified tolerance which stores in the memory of the computer.

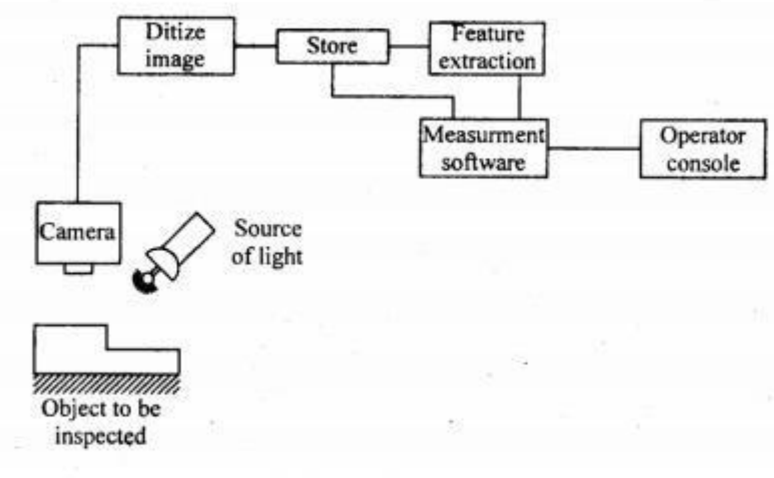


Fig 4.22 Machine Vision

Fig 4.22 Machine Vision

The main advantage of vision system is reduction of tooling and fixture costs, elimination of need for precise part location for handlingrobots and integrated automation of dimensional verification and defect detection

Principle

Four types of machine vision system and the schematic arrangement is shown

(i) Image formation.

(ii) Processing of image in a form suitable for analysis by computer.

(iii) Defining and analyzing the characteristic of image.

(iv)Interpretation of image and decision-making.

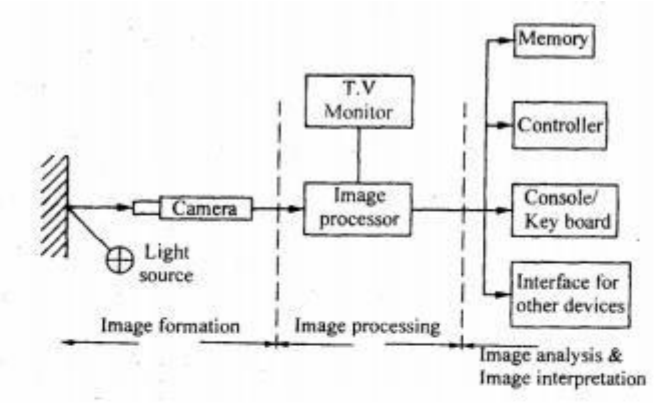


Fig 4.23 Schematic arrangement of Machine Vision

Image formation:

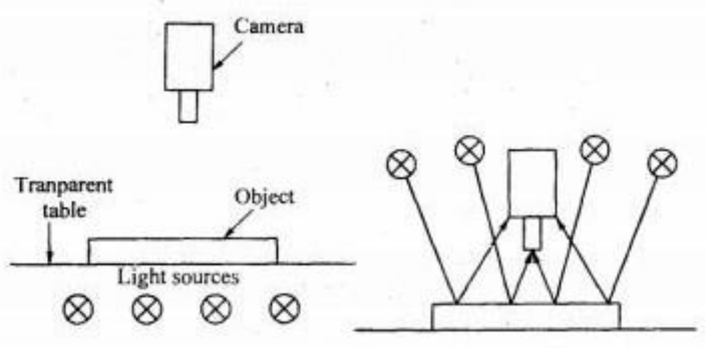


Fig 4.24 Image Formation

Fig 4.24 Image Formation

For formation of image suitable light source is required. It consists of incandescent light, fluorescent tube, fiber optic bundle, and arc lamp. Laser beam is used for triangulation system for measuring distance. Ultraviolet light is used to reduce glare or increase contrast. Proper illumination back lighting, front lighting, structured light is required. Back lighting is used to obtain maximum image contrast. The surface of the object is to be inspected by using front lighting. For inspecting three-dimensional feature structured lighting is required. An image sensor vidicon camera, CCD camera is usedto generate the electronic signal representing the image. The image sensor collects light from the scene through a lens, using photosensitive target, converts into electronic signal.

Vidicon camera

Image is formed by focusing the incoming light through a series of lenses onto the photoconductive faceplate of the vidicon tube. The electron beam scans the photoconductive surface and produces an analog voltage proportional to the variation in light intensity for each scan line of the original scene.

Solid-state camera

The image sensors change coupled device (CCD) contain matrix of small array, photosensitive elements accurately spaced and fabricated on silicon chips using integrated circuit technology. Each detector converts in to analog signal corresponding to light intensity through the camera lens.

Image processor

A camera may form an image 30 times per sec at 33 m sec intervals. At each time interval the entire image frozen by an image processor for processing. An analog to digital converter is used to convert analog voltage of each detector in to digital value. If voltage level for each pixel is given by either 0 or I depending on threshold value. It is called binary system on the other hand grey scale system assigns upto 256 different values depending on intensity to each pixel. Grey scale system requires higher degree of image refinement, huge storage processing capability. For analysis 256 x 256 pixels image array up to 256 different pixel values will require 65000-8 bit storage locations at a speed of 30 images per second. Techniques windowingand image restoration are involved.

Windowing

Processing is the desired area of interest and ignores non-interested part of image.

Image restoration

Preparation of image during the pre-processing by removing the degrade. Blurring of lines, poor contrast between images and presence of noise are the degrading.

The quality may be improved

1) By improving the contrast by brightness addition.
2) By increasing the relative contrast between high and low intensity elements.
3) By Fourier domain processing.
4) Other techniques to reduce edge detection and run length encoding.

Image Analysis

Digital image of the object formed is analyzed in the central processing Unit of the system. Three important tasks performed by machine vision system are measuring the distance of an object from a vision system camera, determining object orientation and defining object position. The distance of an object from a vision system camera can be determined by **triangulation technique.** The object orientation can he determined by the methods of **equivalent ellipse**. The image can be interpreted by two-dimensional image. For complex three-dimensional objects boundary locations are determined and the image is segmented into distinct region.

Image Interpretation

This involves identification of on object. In binary system, the image is segmented on the basis of white and black pixels. The complex images can he interpreted by grey scale technique and algorithms. The most common image interpretation is template matching.

Function of Machine Vision

- Lighting and presentation of object to evaluated.
- It has great compact on repeatability, reliability and accuracy.
- I.ighting source and projection should be chosen and give sharp contrast.
- Images sensor compressor TV camera may he vidicon or solid state.
- For simple processing, analog comparator and a computer controller to convert the video information to a binary image is used.
- Data compactor employs a high speed away processor to provide high speed processing of the input image data.
- System control computer communicates with the operator and make decision about the part being inspected.
- The output and peripheral devices operate the control of the system. The output enables the vision system to either control a process or provide caution and orientation information two a robot, etc.
- These operate under the control of the system control of computer.

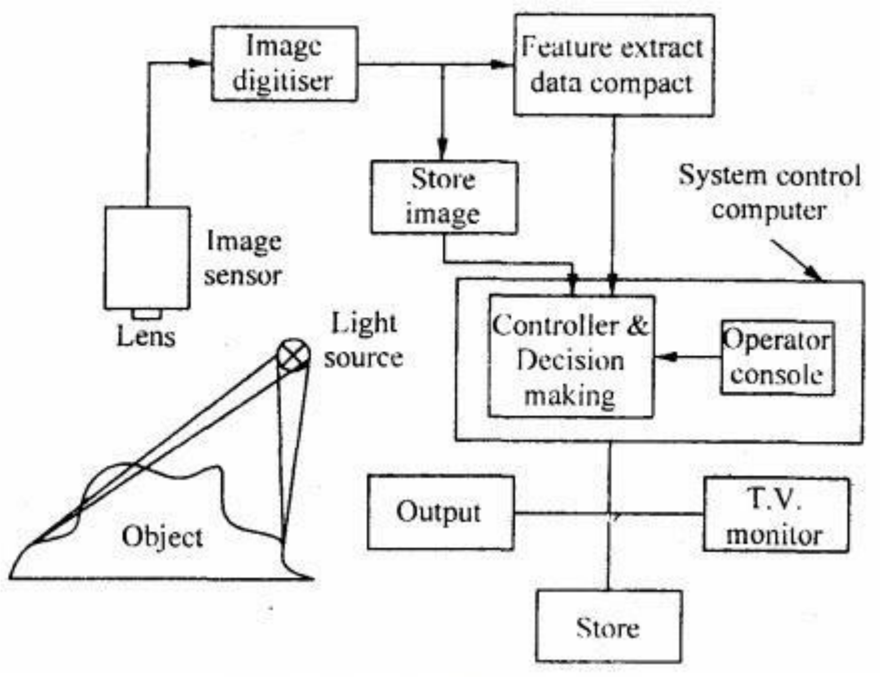


Fig 4.25 Functions of Machine Vision

Fig 4.25 Functions of Machine Vision

Applications

- Machine vision can he used to replace human vision fur welding. Machining and maintained relationship between tool and work piece and assembly of parts to analyze the parts.

  This is frequently used for printed circuit board inspection to ensure minimum conduction width and spacing between conductors. These are used for weld seam tracking, robot guideness and control, inspection of microelectronic devices and tooling, on line inspection in machining operation, assemblies monitoring high-

  speed packaging equipment etc.

- It gives recognition of an object from its image. These are designed to have strong geometric feature interpretation capabilities and pa handling equipment

TYPES OF IMAGE INTERPRETATION

We have studied two major types of Remote Sensing data products, viz. pictorial and digital. The pictorial data products, such as aerial photographs and satellite imageries are interpreted visually. Likewise, digital data products or digital images are interpreted mathematically by using computer software. So, there are two ways of Remote Sensing data interpretation - 1) Visual Interpretation and 2) Digital Interpretation

1 VISUAL INTERPRETATION:

Both aerial photographs and satellite imageries are interpreted visually. Photogrammetry is the science which study interpretation of aerial photographs. To interpret aerial photographs, a number of sophisticated instruments such as pocket stereoscope, mirror stereoscope, plotter is used in photogrammetry for measuring area, height, slopes of different parts of earth photographed and also for plotting different objects

/ Themes from aerial photographs. With the development of science and technology, satellite imageries become more and more popular gradually. Satellite image interpretation is an art of examining images for the purpose of identifying objects and judging their significance. Interpreters study remote sensing image logically and attempt to identify, measure and evaluate the significance of natural and cultural features. Image interpretation technique requires extensive trainingand is labour intensive. Information extraction from imageries is based on the characteristics of image features, such as size, shape, tone, texture, shadow, pattern, association etc. Though this approach is simple and straight forward, it has following short comings: i) The range of gray values product on a film or print is limited in comparison to what can be recorded in digital form, ii) Human eye can recognize limited number of colour tones, so full advantage of radiometric resolution cannot be used, iii) Visual interpretation poses serious limitation when we want to combine data from various sources.

2 DIGITAL INTERPRETATION

Digital interpretation facilitates quantitative analysis of digital data with the help of computers to extract information about the earth surface. Digital interpretation is popularly known as 'Image Processing'. Image processing deals with image correction, image enhancement and information extraction. *Image correction* means to correct the errors in digital image. Errors are resulted due to two reasons. When errors are resulted due to defect in sensor (as for example if one of the detector out of 'n' number of detectors does not work),

it is called radiometric error. When errors are resulted due to earth rotation, space craft velocity, atmosphere attenuation etc., it is called geometric error. Both radiometric and geometric errors /noise in images are reduced through different techniques with the help of computer. Image Enhancement deals with manipulation of data for improving its quality for interpretation. Sometimes digital image lacks adequate contrast, as a result different objects cannot be recognized properly. So, the image requires contrast improvement. Through different image enhancement technique, contrast is improved in digital image. After image correction / rectification, and contrast enhancement, information's are extracted from the digital image, which is the ultimate goal of an interpreter.In *Information Extraction*, spectral values of pixels are analyzed through computer to identify / classify objects on the earth surface. In other words, spectrally homogenous pixels in the image are grouped together and differentiated from othergroups. In this way, different features of earth are recognised and classified. The field knowledge and other sources of information also help in recognition and classification processes.

BASIC ELEMENTS OF IMAGE INTERPRETATION

As we noted in the previous section, analysis of remote sensing imagery involves the identification of various targets in an image, and those targets may be environmental or artificial features which consist of points, lines, or areas. Targets may be defined in terms of the way they reflect or emit radiation. This radiation is measured and recorded by a sensor, and ultimately is depicted as an image product such as an air photo or a satellite image.

What makes interpretation of imagery more difficult than the everyday visual interpretation of our surroundings? For one, we lose our sense of depth when viewing a two-dimensional image, unless we can view it **stereoscopically** so as to simulate the third dimension of height. Indeed, interpretation benefits greatly in many applications when images are viewed in stereo, as visualization (and therefore, recognition) of targets is enhanced dramatically.

Viewing objects from directly above also provides a very different perspective than what we are familiar with. Combining an unfamiliar perspective with a very different scale and lack of recognizable detail can make even the most familiar object unrecognizable in an image.

Finally, we are used to seeing only the visible wavelengths, and the imaging of wavelengths outside of this window is more difficult for us to comprehend. Recognizing targets is the key to interpretation and information extraction. Observing the differences between targets and their backgrounds involves comparing different targets based on any, or all, of the visual elements of **tone, shape, size, pattern, texture, shadow, and association**.

Visual interpretation using these elements is often a part of our daily lives, whether we are conscious of it or not. Examining satellite images on the weather report, or following high speed chases by views from a helicopter are all familiar examples of visual image interpretation. Identifying targets in remotely sensed images based on these visual elements allows us to further interpret and analyze.

Tone refers to the relative brightness or colour of objects in an image. Generally, tone is the fundamental element for distinguishing between different targets or features. Variations in tone also allows the elements of shape, texture, and pattern of objects to be distinguished.

Ground objects of different colour reflect the incident radiation differently depending upon the incident wave length, physical and chemical constituents of the objects. The imagery as recorded in remote sensing is in different shades or tones. For example, ploughed and cultivated lands record differently from fallow fields. Tone is expressed qualitatively as light, medium and dark. In SLAR imagery, for example, the shadows cast by non-return of the microwaves appear darker than those parts where greater reflection takes place. These parts appear of lighter tone. Similarly in thermal imagery objects at higher temperature are recorded of lighter tone compared to objects at lower temperature, which appear of medium to darker tone. Similarly top soil appears as of dark tone compared to soil containing quartz sand. The coniferous trees appear in lighter tone compared to broad leave tree clumps.

Size of objects in an image is a function of scale. It is important to assess the size of a target relative to other objects in a scene, as well as the absolute size, to aid in the interpretation of that target. A quick approximation of target size can direct interpretation to an appropriate result more quickly. For example, if an interpreter had to distinguish zones of land use, and had identified an area with a number of buildings in it, large buildings such as factories or warehouses would suggest commercial property, whereas small buildings would indicate residential use.

Pattern refers to the spatial arrangement of visibly discernible objects. Typically an Orderly repetition of similar tones and textures will produce a distinctive and ultimately recognizable pattern. Orchards with evenly spaced trees and urban streets with regularly spaced houses are good examples of pattern.

Texture refers to the arrangement and frequency of tonal variation in particular areas of an image. Rough textures would consist of a mottled tone where the grey levels change abruptly in a small area, whereas smooth textures would have very little tonal variation. Smooth textures are most often the result of uniform, even surfaces, such as fields, asphalt, or grasslands. A target with a rough surface and irregular structure, such as a forest canopy, results in a rough textured appearance. Texture is one of the most important elements for distinguishing features in radar imagery.

Shadows cast by objects are sometimes important clues to their identification and Interpretation. For example, shadow of a suspension bridge can easily be discriminated from that of cantilever bridge. Similarly circular shadows are indicative of coniferous trees. Tall buildings and chimneys, and towers etc., can easily be identified for their characteristic shadows. Shadows on the other hand can sometimes render interpretation difficult i.e. dark slope shadows covering important detail.

Association takes into account the relationship between other recognizable objects or features in proximity to the target of interest. The identification of features that one would expect to associate with other features may provide information to facilitate identification. In the example given above, commercial properties may be associated with proximity to major transportation routes, whereas residential areas would be associated with schools, playgrounds, andsports fields. In our example, a lake is associated with boats, a marina, and adjacent recreational land.

DIGITAL IMAGE PROCESSING

1 Introduction

As seen in the earlier chapters, remote sensing data can be analysed using visual image interpretation techniques if the data are in the hardcopy or pictorial form. It is used extensively to locate specific features and conditions, which are then geocoded for inclusion in GIS. Visual image interpretation techniques have certain disadvantages and may require extensive training and are labour intensive. In this technique, the spectral characteristics are not always fully evaluated because of the limited ability of the eye to discern tonal values and analyse the spectral changes. If the data are in digital mode, the remote sensing data can be analysed using digital image processing techniques and such a databasecan be used in raster GIS. In applications where spectral patterns are more informative, it is preferable to analyse digital data rather than pictorial data.

In today's world of advanced technology where most remote sensing data are recorded in digital format, virtually all image interpretation and analysis involves some element of digital processing. Digital image processing may involve numerous procedures including formatting and correcting of the data, digital enhancement to facilitate better visual interpretation, or even automated classification of targets and features entirely by computer. In order to process remote sensing imagery digitally, the data must be recorded and available in a digital form suitable for storage on a computer tape or disk. Obviously, the other requirement for digital image processing is a computer system, sometimes referred to as an **image analysis system**, with the appropriate hardware and software to process the data. Several commercially available software systems have been developed specifically for remote sensing image processing and analysis.

For discussion purposes, most of the common image processing functions available in image analysis systems can be categorized into the following four categories:

Preprocessing

Image Enhancement

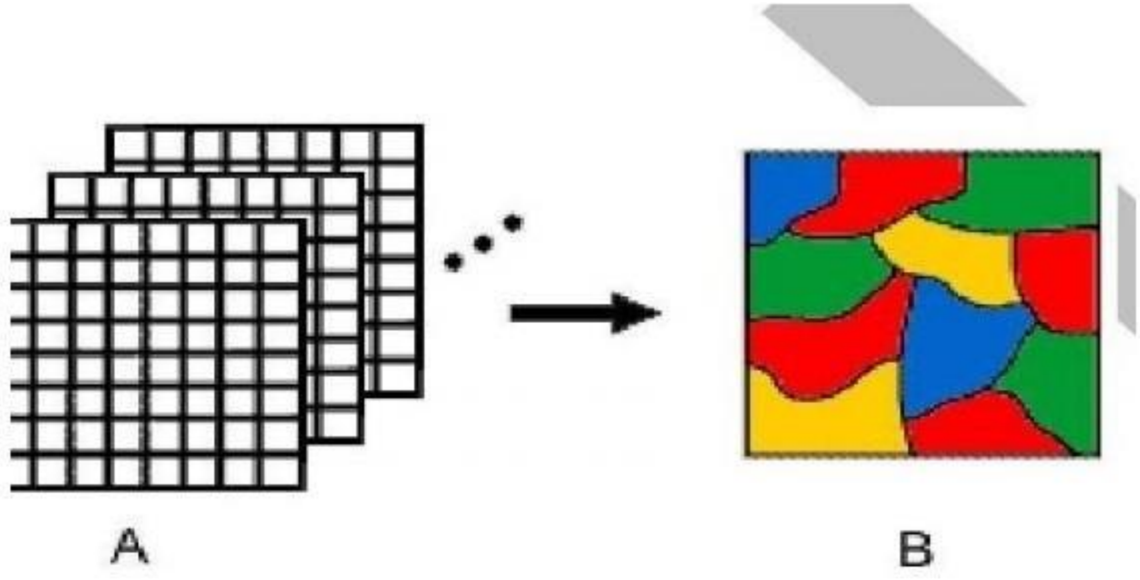
Image Transformation

Image Classification and Analysis

2 PREPROCESSING

Preprocessing functions involve those operations that are normally required prior to the main data analysis and extraction of information, and are generally grouped **as radiometric or geometric corrections**. Radiometric corrections include correcting the data for sensor irregularities and unwanted sensor or atmospheric noise, and converting the data so they accurately represent the reflected or emitted radiation measured by the sensor. Geometric corrections include correcting for geometric distortions due to sensor-Earth geometry variations, and conversion of the data to real world coordinates (e.g. latitude and longitude) on the Earth's surface. The objective of the second group of image processing functions grouped under the term of **image enhancement**, is solelyto **improve the appearance of the imagery** to assist in visual interpretation and analysis. Examples of enhancement functions include contrast stretching to increase the tonal distinction between various features in a scene, and **spatial filtering** to enhance (or suppress) specific spatial patterns in an image.

Image transformations are operations similar in concept to those for image enhancement. However, unlike image enhancement operations which are normally applied only to a single channel of data at a time, image transformations usually involve combined processing of data from multiple spectral bands. Arithmetic operations (i.e. subtraction, addition, multiplication, division) are performed to combine and transform the original bands into "new" images which better display or highlight certain features in the scene. We will look at some of these operations including various methods of **spectral or band** ratioing, and a procedure called **principal components analysis** which is used to more efficiently represent the information



a. **Image classification and analysis** operations are used to digitally identify and classify pixelsin the data. **Classification** is usually performed on multi-channel data sets (A) and this process assigns each pixel in an image to a particular class or theme (B) based on statistical characteristics of the pixel brightness values. There are a variety of approaches taken to perform digital classification. We will briefly describe the two generic approaches which are used mostoften, namely **supervised** and **unsupervised** classification. In the following sections we will describe each of these four categories of digital image processing functions in more detail.

2. Pre-processing operations, sometimes referred to as image restoration and rectification, are intended to correct for sensor- and platform-specific radiometric and geometric distortions of data. Radiometric corrections may be necessary due to variations in scene illumination and viewing geometry, atmospheric conditions, and sensor noise and response. Each of these will vary depending on the specific sensor and platform used to acquire the data and the conditions during data acquisition. Also, it may be desirable to convert and/or calibrate the data to known (absolute) radiation or reflectanceunits to facilitate comparison between data.

3. IMAGE ENHANCEMENT TECHNIQUES

a. Low sensitivity of the detectors, weak signal of the objects present on the earth surface, similar reflectance of different objects and environmental conditions at the time of recording are the major causes of low contrast of the image. Another problem that complicates photographic display of digital image is that the human eye is poor at discriminating the slight radiometric or spectral differences that may characterize the features. The main aim of digital enhancement is to amplify these slight differences for better clarity of the image scene. This means digital enhancement increases the separability (contrast) between the interested classes or features. The digital image enhancement may be defined as some mathematical operations that are to be applied to digital remote sensing input data to improve the visual appearance of an image for better interpretability or subsequent digital analysis (Lillesand and Keifer, 1979). Since the image qualityis a subjective measure varying from person to person , there is no simple rule which may produce a single best result. Normally, two or more operations on the input image may suffice to fulfil the desire of the analyst, although the enhanced product may have a fraction of the total information stored in the original image. This will be realized after seeing the different contrast enhancement techniques in this

4. chapter. There are a number of general categories of enhancement techniques. As in many outer areas of knowledge, the distinction between one type of analysis andanother is a matter of personal taste and need of the interpreter. In remote sensing literature, many digital enhancement algorithms are available.

   a. They are contrast stretching enhancement, ratioing , linear combinations, principal component analysis, and spatial filtering . Broadly, the enhancement techniques are categorised as point operations and local operations. Point operations modify the values of each pixel in an image data set independently, whereas local operations modify the values of each pixel in the context of the pixel values surrounding it. Point operations include contrast enhancement and band combinations, but spatial filtering is an example of local operations. In this section, contrast enhancement, linear contraststretch , histogram equalisation, logarithmic contrast enhancement, and exponential contrast enhancement are considered.

b.

Module 6

FLEXIBLE MANUFACTURING SYSTEMS

CONTENTS

The flexible manufacturing system (FMS) was identified in machine the last chapter as one of the cell types used to implement group technology. It is most automated and technologically scheme sophisticated of the GT cells. In our classification for manufacturing system (Section 13.2), an FMS typically possesses multiple automated stations and is capable of variable routings among stations (type II A).1 Its flexibility allows it to operate as a mixed model system (case X forpart or product variety). An FMS integrates into one highly automated manufacturing system many of the concepts and technologies discussed in previous chapters, including: flexible automation (Section 1.3.1), CNC machines (Chapters 6 and 14),distributed computer control (Section 6.3), automated material handling and storage (Chapters 10 and ll).and group technology (Chapter 15).The concept for FMSs originated in Britain in the early 1960s (Historical Note 16.1).The first FMS installations in the United States were made starting around 19b7.These initial systems performed machining operations on families of parts using NC machine tools.

FMS technology can be applied in situations similar to those identified for group technology and cellular manufacturing; specifically,

Presently, the plant either (1) produces parts in *batches* or (2) uses *manned GT cells* and management wants to automate .

It must be possible to group a portion of the parts made in the plant into *part families.* whose similarities permit them to be processed on the machines in the FMS.

Part similarities can be interpreted to mean that (1) the parts belong to a common product, and/or (2) the parts possess similar geometries. In either case. the processing requirements of the parts must be sufficiently similar to allow them to be made on the FMS.

The parts or products made by the facility are in the *mid-volume*, *mid-variety production range.* The appropriate production volume range is 500075,000 part/yr. If annual production is below this range, than FMS is likely to be an expensive alternative. If' production volume is above this range, then a more specialized production system should probably be considered

The differences between implementing a manually operated machine cell and installing an FMS are: (1) the FMS requires a significantly greater capital investment because new equipment is being installed rather than existing equipment being rearranged. and (2) the FMS is technologically more sophisticated for the human resources who must make it work. However, the potential benefits are substantial. The benefits that can be expected from an FMS include:

- increased machine utilization
- fewer machines required
- reduction in factory floor space required
- greater responsiveness to change
- reduced inventory requirements
- lower manufacturing lead times
- reduced direct labor requirements and higher labor productivity
- opportunity for unattended production

In this chapter, we define and discuss flexible FMSs: what makes them flexible, their components, their applications, and considerations for implementing the technology. In the final section, we present a mathematical model for assessing the performance of FMSs.

WHAT IS AN FMS?

A flexible manufacturing system (FMS) is a highly automated OT machine cell. consisting of a group of processing workstations (usually CNC machine tools), interconnected by an automated material handling and storage system, and controlled by a distributed computer system. The reason the FMS is *called flexible* is that it is capable of processing a variety of different part styles simultaneously at the various workstations, and the mix of part styles and quantities of production can be adjusted in response to changing demand patterns. The FMS is most suited for the mid-variety, mid-volume production range (refer to Figure 1.7).

The initials FMS are sometimes used to denote the *term flexible machiningsystem.* The machining process is presently the largest application area for FMS technology. However, it seems appropriate to interpret *FMS* in its broader meaning, allowing for a wide range of possible applications beyond machining.

An FMS relies on the principles of group technology. No manufacturing system can be completely flexible. There are limits to the range of parts or products that can be made in an FMS. Accordingly, an FMS is designed to produce parts (or products) within a defined 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,

A more appropriate term for an FMS would be *flexible automated manufacturing system.* The use of the word "automated" would distinguish this type of production technology from other manufacturing systems that arc flexible but not automated, such as a manned GT machine cell. On the other hand, tile word "flexible" would distinguish it from other manufacturing systems that are highly automated but not flexible, such as a conventional transfer line. However, the existing terminology is well established

What Makes It Flexible?

The issue of manufacturing system flexibility was discussed previously in Section 13.2.4. In that discussion, we identified three capabilities that a manufacturing system must possess to be flexible: (I) the ability to identify and distinguish among the different part or product styles processed by the system, (2) quick changeover of operating instructions, and (1) quick changeover of physical setup. Flexibility is an attribute that applies to both manual and automated systems. In manual systems, the human workers are often the enablers of the system's flexibility.

To develop the concept of flexibility in an automated manufacturing system, consider a machine cell consisting of two CNC machine tools that are loaded and unloaded by an industrial robot from a parts carousel, perhaps in the arrangement depicted in Figure 16.1. The cell operates unattended for extended periods of time. Periodically, a worker must unload completed parts from the carousel and replace them with new work parts. By any definition, this is an automated manufacturing cell, but is it a flexible manufacturing cell? One might argue that yes, it is flexible, since the cell consists of CNC machine tools, and CNC machines are flexible because they can be programmed to machine different

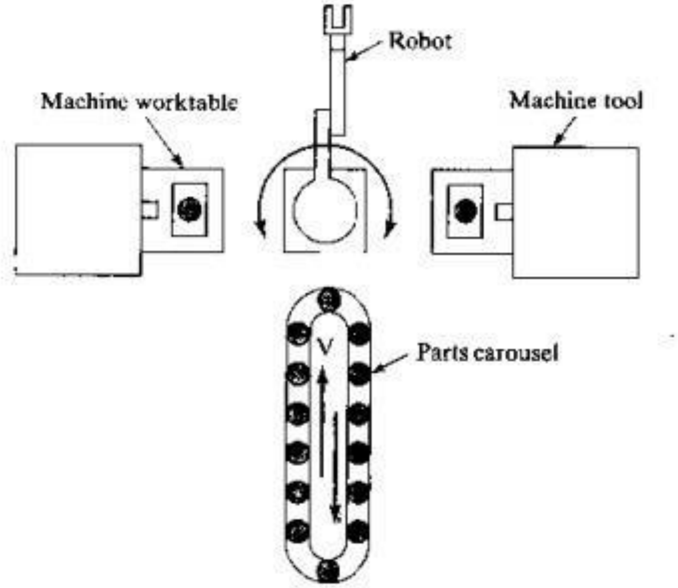


Figure 16.1 Automated manufacturing cell with two machine tools and robot. Is it a flexible cell?

part configurations. However, if the cell only operates in a batch mode, in which the same part style is produced by both machines in lots of several dozen (or several hundred) units, then this does not qualify as flexible manufacturing,

'lb qualify as being flexible, a manufacturing system should satisfy several criteria. The following ale four reasonable tests of flexibility in an automated manufacturing system:

Part variety test. Can the system process different part styles in a non-batch mode?

Schedule change test. Can the system readily accept changes in production schedule, and changes in either part mix or production quantities?

Error recovery test. Can the system recover gracefully from equipment malfunctions and breakdowns, so that production is not completely disrupted'!

New part test. Can new part designs be introduced into the existing product mix with relative ease'!

If the answer to all of these questions is "yes" for a given manufacturing system, then the system can be considered flexible. The most important criteria are (1) and (2). Criteria (3) and (4) are softer and can be implemented at various levels. In fact, introduction of new part designs is not a consideration in some FMSs; such systems are designed to produce a part family whose member are all known in advance.

if the automated system does not meet at least the first three tests, it should not be classified as an FMS. Getting back to our illustration, the robotic work cell satisfies the criteria if it: (1) can machine different part configurations in a mix rather than in batches; (2) permits changes in production schedule and part mix; (3) is capable of continuing to operate even though one machine experiences a breakdown (e.g., while repairs are being made on the broken machine, its work is temporarily reassigned to the other machine); and (4) as new part designs arc developed, NC part programs are written offline and then downloaded to the system for execution. This fourth capability requires that the new part is within the part family intended for the FMS, so that the tooling used by the CNC machines as well as the end effector of the robot are suited to the new part design.

Over the years, researchers and practitioners have attempted to define manufacturing flexibility. These attempts are documented in several of our references and. The result of these efforts IS the conclusion that flexibility in manufacturing has multiple dimensions; there are various types of flexibility. Table

16.1 defines these flexibility types and lists the kinds of factors on which they depend.

To a significant degree, the types of flexibility in Table 16.1 are alternative ways of stating our preceding list of flexibility tests for a manufacturing system. The correlations are indicated in Table 16.2.

Types of FMS

Having considered the issue of flexibility and the different types of flexibility that are exhibited by manufacturing systems, let us now. consider the various types of FMSs. Each FMS is designed for a specific application, that is, a specific family of parts and processes Therefore, each FMS is custom engineered; each FMS is unique. Given these circumstances, one would expect to find a great variety of system designs to satisfy a wide variety of application requirements.

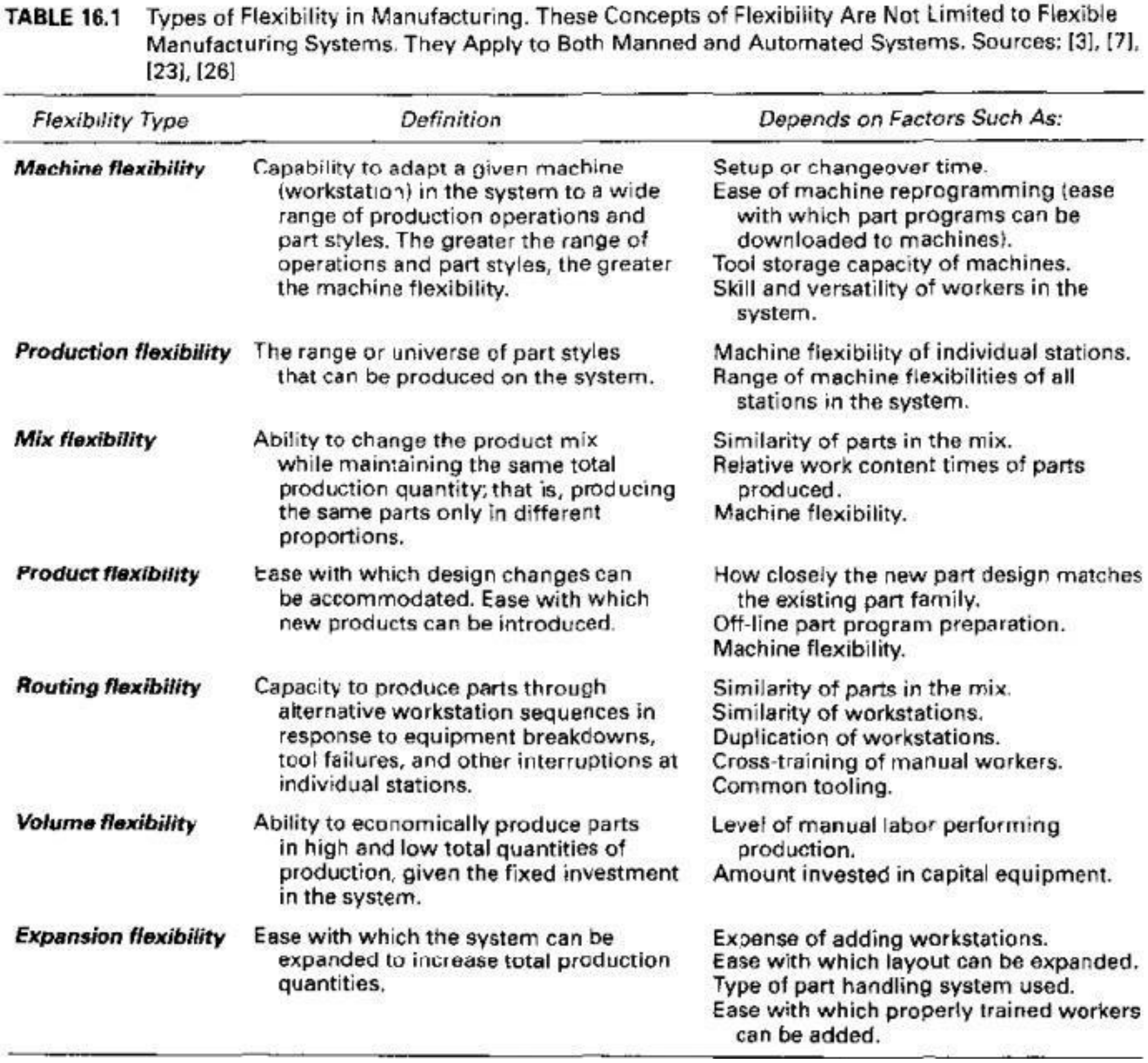


TABLE 16.1 Types of Flexibility in Manufacturing. These Concepts of Flexibility Are Not Limited to Flexible Manufacturing Systems. They Apply to Both Manned and Automated Systems. Sources: [3], [7], [23], [26]

Flexibility Type	*Definition*	*Depends on Factors Such As:*
Machine flexibility	Capability to adapt a given machine (workstation) in the system to a wide range of production operations and part styles. The greater the range of operations and part styles, the greater the machine flexibility.	Setup or changeover time. Ease of machine reprogramming (ease with which part programs can be downloaded to machines). Tool storage capacity of machines. Skill and versatility of workers in the system.
Production flexibility	The range or universe of part styles that can be produced on the system.	Machine flexibility of individual stations. Range of machine flexibilities of all stations in the system.
Mix flexibility	Ability to change the product mix while maintaining the same total production quantity; that is, producing the same parts only in different proportions.	Similarity of parts in the mix. Relative work content times of parts produced. Machine flexibility.
Product flexibility	Ease with which design changes can be accommodated. Ease with which new products can be introduced.	How closely the new part design matches the existing part family. Off-line part program preparation. Machine flexibility.
Routing flexibility	Capacity to produce parts through alternative workstation sequences in response to equipment breakdowns, tool failures, and other interruptions at individual stations.	Similarity of parts in the mix. Similarity of workstations. Duplication of workstations. Cross-training of manual workers. Common tooling.
Volume flexibility	Ability to economically produce parts in high and low total quantities of production, given the fixed investment in the system.	Level of manual labor performing production. Amount invested in capital equipment.
Expansion flexibility	Ease with which the system can be expanded to increase total production quantities.	Expense of adding workstations. Ease with which layout can be expanded. Type of part handling system used. Ease with which properly trained workers can be added.

Flexible manufacturing systems can be distinguished according to the kinds of operations they perform:(l) *processing operations* or (2) *assembly operations* (Section 2.2.1). An FMS is usually designed to perform one or the otherbut rarely both. A difference that is applicable to machining systems is whether thesystem will process *rotational parts* or *non-rotational parts* (Section 13.2.1).Flexible machining systems with multiple stations that process rotational parts are much less common than systems that process non-rotational parts. Two other ways to classify FMSs are by: (1) number of machines and (2) level of flexibility

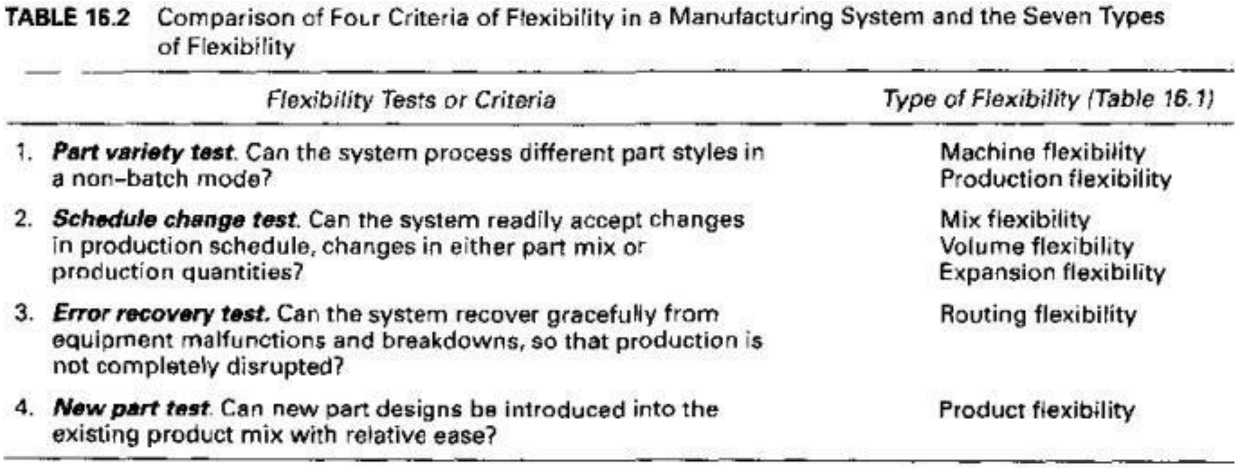


TABLE 16.2 Comparison of Four Criteria of Flexibility in a Manufacturing System and the Seven Types of Flexibility

Flexibility Tests or Criteria	Type of Flexibility (Table 16.1)
1. ***Part variety test.*** Can the system process different part styles in a non–batch mode?	Machine flexibility Production flexibility
2. ***Schedule change test.*** Can the system readily accept changes in production schedule, changes in either part mix or production quantities?	Mix flexibility Volume flexibility Expansion flexibility
3. ***Error recovery test.*** Can the system recover gracefully from equipment malfunctions and breakdowns, so that production is not completely disrupted?	Routing flexibility
4. ***New part test.*** Can new part designs be introduced into the existing product mix with relative ease?	Product flexibility

Number of Machines. Flexible manufacturing systems can be distinguished according to the number of machines in the system. The following are typical categories:

single machine cell (type I A in our classification scheme of Section]3.2)

flexible manufacturing cell (usually type II A, sometimes type III A, in our classification scheme of Section 13.2)

flexible manufacturing system (usually type II A, sometimes type III A, in our classification scheme of Section 13.2)

A *single machine cell* (SMC) consists of one CNC machining center combined with a parts storage system for unattended operation (Section 14.2), as in Figure 16.2. Completed parts are periodically unloaded from the parts storage unit, and raw work-parts are loaded into it. The cell can be designed to operate in either a batch mode or a flexible mode or in combinations of the two. When operated in a batch mode, the machine processes parts of a single style in specified lot sizes and is then changed over to process a batch of the next part style. When operated in a flexible mode, the system satisfies three of the four f1exibili1y tests (Section 16.1.1). It is capable of (1) processing different part styles, (2) responding to changes in production schedule, and (4) accepting new part introductions.

Criterion (3) error recovery, cannot be satisfied because if the single machine breaks down, production stops.

A flexible manufacturing all (FMC) consists of two or three processing workstations (typically CNC machining centers or turning centers) plus a part handling system. The part handling system is connected to a load/unload station. In addition, the handling system usually includes a limited parts storage capacity. One possible FMC is illustrated in Figure

A flexible manufacturing cell satisfies the four flexibility tests discussed previously. *A flexible manufacturing system* (FMS) has four or more processing workstations

connected mechanically by a common part handling system and electronically by a distributed computer system. Thus, an important distinction between an FMS and an FMC is

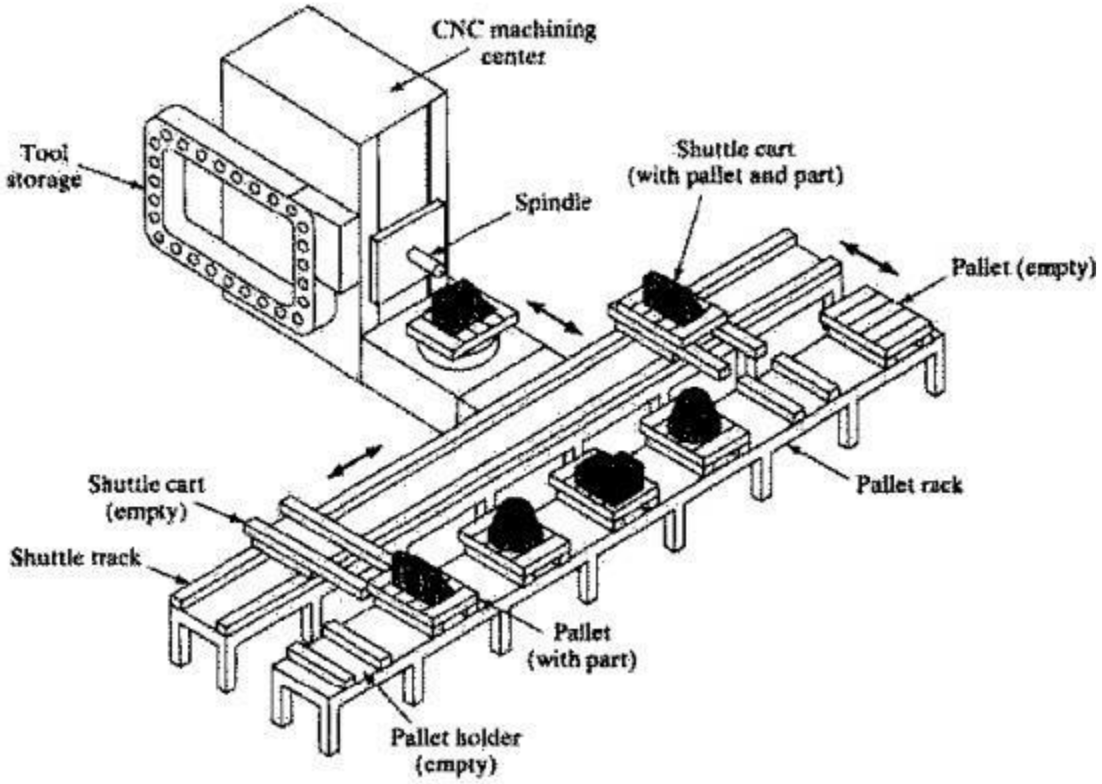


Figure 16.2 Single machine cell consisting of one CNC machining center and parts storage unit.

the number of machines: an FMC has two or three machines, while an FMS has four or more." *A* second difference is that the FMS generally includes non- processing workstations that support production but do not directly participate in it.These other stations include part/pallet washing stations, coordinate measuring machines, and so on. A third difference is that the computer control system of an FMS is generally larger and more sophisticated, often including functions not always found in a cell, such as diagnostics and tool monitoring. These additional functions are needed more in an FMS than in an FMC because the FMS is more complex.

Some of the distinguishing characteristics of the three categories of flexible manufacturing cells and systems are summarized in Figure 16.4. Table 16.3 compares the three systems in terms of the four flexibility tests.

Level of *Flexibility.* Another classification of FMS is according to the level of flexibility designed into the system. This method of classification can be applied to systems with any number of workstations, but its application seems most common with FMCs and FMSs.1 categories are distinguished here:

1. dedicated FMS
2. random-order FMS

A *dedicated FMS* is designed to produce a limited variety of part styles, and the complete universe of parts to be made on the system is known in advance. The term *special manufacturing system* has also been used in reference to this FMS type (c.g., [24». The part family is likely to be based on product commonality rather than geometric similarity. The product design is considered stable, and so the system can be designed with a certain amount of process specialization to makethe operations more efficient. Instead of using general-purpose machines, the machines can be designed for the specific processes required to make the limited part family, thus increasing the production rate of the system. In some instances, the machine sequence may be identical or nearly identical for all parts processed and so a transfer line may be appropriate. in which the workstations possess the necessary flexibility to process the different parts in the mix. Indeed, the term *flexible transfer lint* is sometimes used for this case.

A *random-order EMS* is more appropriate when the part family is large, there are substantial variations in part configurations, there will be new part designs introduced into the system and engineering changes in parts currently produced, and the production schedule is subject to change from day-to-day, To accommodate these variations, the random-order FMS must be more flexible than the dedicated FMS. It is equipped with general-purpose machines to deal with the variations in product and is capable of processing parts in various sequences(random-order). A more sophisticated computer control system is required for this FMS type.

We see in these two system types the tradeoff between flexibility and productivity. The dedicated FMS is less flexible but more capable of higher production rates. The random-order FMS is more flexible but at the price of lower production rates. A comparison of the features of these two FMS types is presented in Figure 16.5. Table 16.4 presents a comparison of the dedicated FMS and random-order FMS in terms of the four flexibility tests

FMS COMPONENTS

As indicated in Out definition. there are several basic components of an FMS: (1) workstations, (2) material handling and storage system, and (3) computer control system. In addition, even though an FMS is highly automated, (4) people are required to manage and operate the system. We discuss these four FMS components in this section.

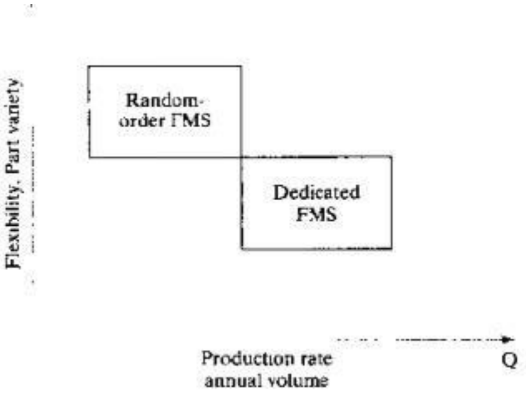


Figure 16.5 Comparison of dedicated and random-order FMS types.

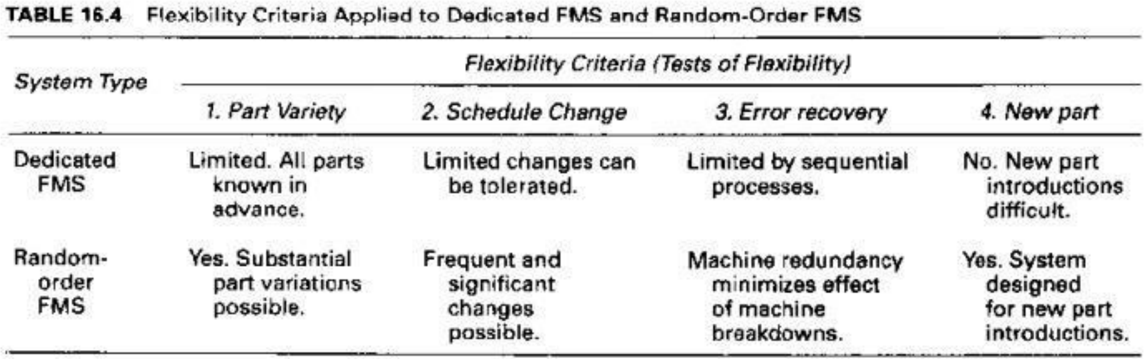


TABLE 16.4 Flexibility Criteria Applied to Dedicated FMS and Random-Order FMS

System Type	*Flexibility Criteria (Tests of Flexibility)*			
	1. Part Variety	*2. Schedule Change*	*3. Error recovery*	*4. New part*
Dedicated FMS	Limited. All parts known in advance.	Limited changes can be tolerated.	Limited by sequential processes.	No. New part introductions difficult.
Random-order FMS	Yes. Substantial part variations possible.	Frequent and significant changes possible.	Machine redundancy minimizes effect of machine breakdowns.	Yes. System designed for new part introductions.

Workstations

The processing or assembly equipment used in an FMS depends on the type of work accomplished by the system. In a system designed for machining operations, the principle types of processing station are CNC machine tools. However, the FMS concept is also applicable to various other processes as well. Following are the types of workstations typically found in an FMS.

Load/Unload Stations. The load/unload station is the physical interface between the FMS and the rest of the factory. Raw work-parts enter the system at this point, and finished parts exit the system from here. Loading and unloading can be accomplished either manually or by automated handling systems. Manual loading and unloading is prevalent in most FMSs today. The load/unload station should be ergonomically designed to permit convenient and safe movement of work parts. For parts that are too heavy to lift by the operator, mechanized cranes and other handling devices are installed to assist the operator.

A certain level of cleanliness must be maintained at the workplace. and air hoses or other washing facilities are often required to flush away chips and ensure clean mounting and locating points. The station is often raised slightly above floor level using an open-grid platform to permit chips and cutting fluid to drop through the openings for subsequent recycling or disposal

The load/unload station should include a data entry unit and monitor for communication between the operator and the computer system. Instructions must be given to the operator regarding which part to load onto the next pallet to adhere to the production schedule. In cases when different pallets are required for different parts, the correct pallet must be supplied to the station. In cases where modular fixturing is used, the correct fixture must be specified. and the required components and tools must be available at the workstation to build it. 'When the part loading procedure has been completed. the handling system must proceed to launch the pallet into the system; however, the handling system must be prevented from moving the pallet while the operator is still working. All of these circumstances require communication between the computer system and the operator at the load/unload station

Machining Stations. The most common applications of FMSs arc machining operations, The workstations used in these systems are therefore predominantly CNC machine tools. Most common is the *CNC machining center* (Section 14.3.3): in particular. the horizontal machining center. CNC machining centers possess features that make them compatible with the FMS, including automatic tool changing and tool storage, use of palletized work-parts, CNC, and capacity for distributed numerical control (DNC) (Section 6.3). Machining centers can be ordered with automatic pallet changers that can be readily interfaced with the FMS part handling system. Machining centers are generally used for non-rotational parts. For rotational parts, *turning centers* are used; and for parts that are mostly rotational hut require multi-tooth rotational cutters (milling and drilling), *mi11·turncenters* can be used.

In some machining systems, the types of operations performed are concentrated in a certain category, such as milling or turning. For milling, special *milling machine modules* can be used to achieve higher production levels than a machiningcenter is capable of. The milling module can be vertical spindle, horizontal spindle, or multiple spindle. For turning operations. Special turning *modules* can be designed for the FMS, In conventional turning, the work-piece IS rotated against a tool that is held in the machine and fed in a direction parallel to the axis of work rotation. Parts made on most FMSs are usually non-rotational: however, they may require some turning in their process sequence. For these cases, the parts are held in a pallet fixture throughout processing on the FMS, and a turning module is designed to rotate the single point tool around the work.

Other Processing Stations. The FMS concept has been applied to other processing operations in addition to machining. One such application is sheet metalfabrication processes. The processing workstations consist of press-working operations, such as punching, shearing, and certain bending and forming processes. Also, flexible systems are being developed to automate the forging process. Forging is traditionally a very labor-intensive operation. The workstations in the system consist principally of a heating furnace, a forging press. and a trimming station.

Assembly. Some FMSs are designed to perform assembly operations. Flexible automated assembly systems are being developed to replace manual labor in the assembly of products typically made in batches. Industrial robots are often used as the automated workstations in these flexible assembly systems. They can be programmed to perform tasks with variations in sequence and motion pattern to accommodate the different product styles assembled in the system. Other examples of flexible assembly workstations are the programmable component placement machines widely used in electronics assembly.

Other Stations and Equipment. Inspection can be incorporated into an FMS, cither by including, an inspection operation at a processing workstation or by including a station specifically designed for inspection. Coordinate measuring machines (Section 23.4), special inspection probes that can be used in a machine tool spindle (Section *23.4.b)*, and machine vision (Section 23.0) are three possible technologies for performing inspection on an FMS. Inspection has been found to be particularly important in flexible assembly systems to ensure that components have been properly added at the workstations. We examine the topic of automated inspection in more detail in Chapter 22 (Section 22.3).

In addition to the above, other operations and functions are often accomplished on an FMS. These include stations for cleaning parts and/or pallet fixtures. central coolant delivery systems for the entire FMS, and centralized chip removal systems often installed below floor level

Material Handling and Storage System

The second major component of an FMS is its material handling and storage system. In this subsection, we discuss the functions of the handling system, material handling equipment typically used in an FMS, and types of FMS layout.

Functions of the Handling System. The material handling and storage system in an FMS performs the fol1owing functions:

Random, independent movement of work-parts between stations. This means that parts must be capable of moving from anyone machine in the system *to* any *other* machine. to provide various routing alternatives for the different parts and to make machine substitutions when certain stations are busy.

Handle a variety of work-part configurations. For prismatic parts, this is usually accomplished by using modular pallet fixtures in the handling system. The fixture is located on the top face of the pallet and is designed to accommodate different part configurations by means of common components, quick change features, and other devices that permit a rapid buildup of the fixture for a given part. The base ofthe pallet is designed for the material handling system. For rotational parts, industrial robots are often used to load and unload the turning machines and to move parts between stations.

Temporary storage. The number of parts in the FMS will typically exceed the number of parts actually being processed at any moment. Thus, each station has a small queue of parts waiting to be processed. which helps to increase machine utilization.

Convenient access for loading and unloading work-parts. The handling system must include locations for load/unload stations.

Compatible with computer control. The handling system must be capable of being controlled directly by the computer system to direct it to the various workstations, load/unload stations, and storage areas

Material Handling Equipment. The types of material handling systems usedto transfer parts between stations in an F.\1S include a variety of conventional material transport equipment (Chapter 10), inline transfer mechanisms (Section 18.1.2),and industrial robots (Charter 7) The material handling function in an FMS is often shared between two systems: (1) a primary handling system and (2) a secondary handling system. The ***prima****ry handling system* establishes the basiclayout of the FMS and is responsible for moving work-parts between stations in thesystem. The types of material handling equipment typically utilized for FMS layouts are summarized in Table 16.5

The *secondary handling system* consists of transfer devices, automatic pallet changers. and similar mechanisms located at the workstations in the FMS. The function of the secondary handling system is to transfer work from the primary system to the machine tool or other processing station and to position the parts with sufficient accuracy and repeatability to perform the processing or assembly operation. Other purposes served by the secondary handling system include: (1) reorientation of the work-part if necessary to present the surface that is to be processed and (2) buffer storage of parts to minimize work change time and maximize station utilization. In some FMS installations, the positioning and requirements at the individual workstations are satisfied by the primary work handling system. In these cases, the secondary handling system is not included,

The primary handling system is sometimes supported by an automated storage system (Section: 1.4). An example of storage in an FMS is illustrated in Figure 16.6. The FMS is integrated with an automated storage/retrieval system (AS/RS), and the S/R machine serves the work handling function for the workstations as well as delivering parts to and from the storage racks

FMS Layout Configurations. The material handling system establishes the FMS layout. Most layout configurations found in today's FMSs can he divided intofive categories: (1) inline layout, (2) loop hl)'OU1, (3) ladder layout. (4) open field layout, and (5) robot-centered cell.

In the *inline layout,* the machines and handling system are arranged in a straight line, as illustrated in Figure, 16.6 and 16.7. In its simplest form. the parts progress from one workstation to the next in a well defined sequence, with work always moving in one direction and no back flow, as in Figure 16.7(a). The operation of this type of system is similar to a transfer lin., (Chapter 18). except that a variety of work-parts are processed in the

TABLE 16.5 Material Handling Equipment Typically Used as the Primary Handling System for the Five FMS Layouts

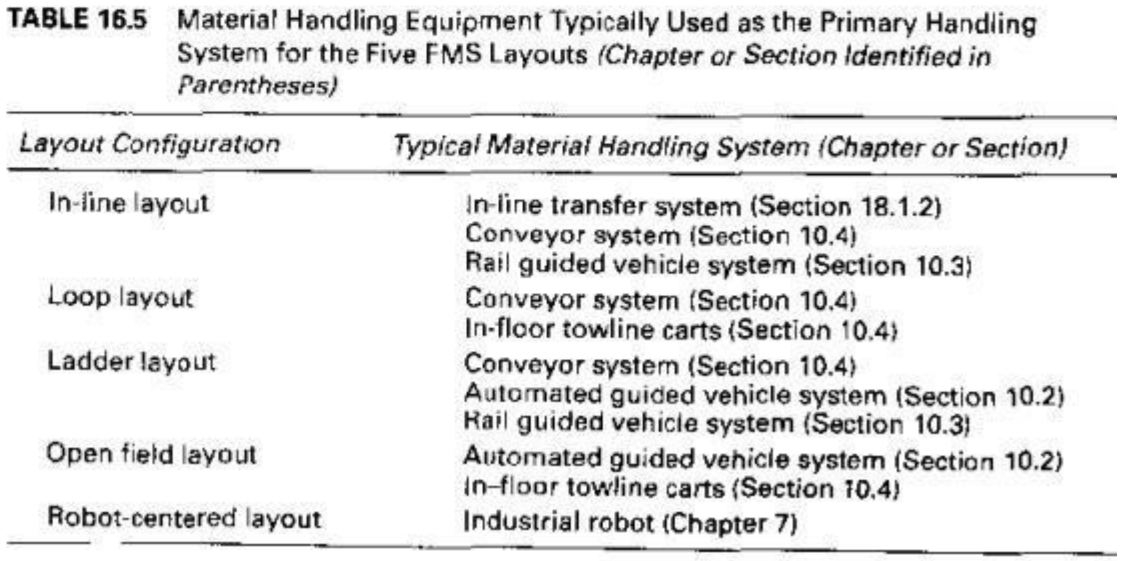


TABLE 16.5 Material Handling Equipment Typically Used as the Primary Handling System for the Five FMS Layouts *(Chapter or Section Identified in Parentheses)*

Layout Configuration	*Typical Material Handling System (Chapter or Section)*
In-line layout	In-line transfer system (Section 18.1.2) Conveyor system (Section 10.4) Rail guided vehicle system (Section 10.3)
Loop layout	Conveyor system (Section 10.4) In-floor towline carts (Section 10.4)
Ladder layout	Conveyor system (Section 10.4) Automated guided vehicle system (Section 10.2) Rail guided vehicle system (Section 10.3)
Open field layout	Automated guided vehicle system (Section 10.2) In–floor towline carts (Section 10.4)
Robot-centered layout	Industrial robot (Chapter 7)

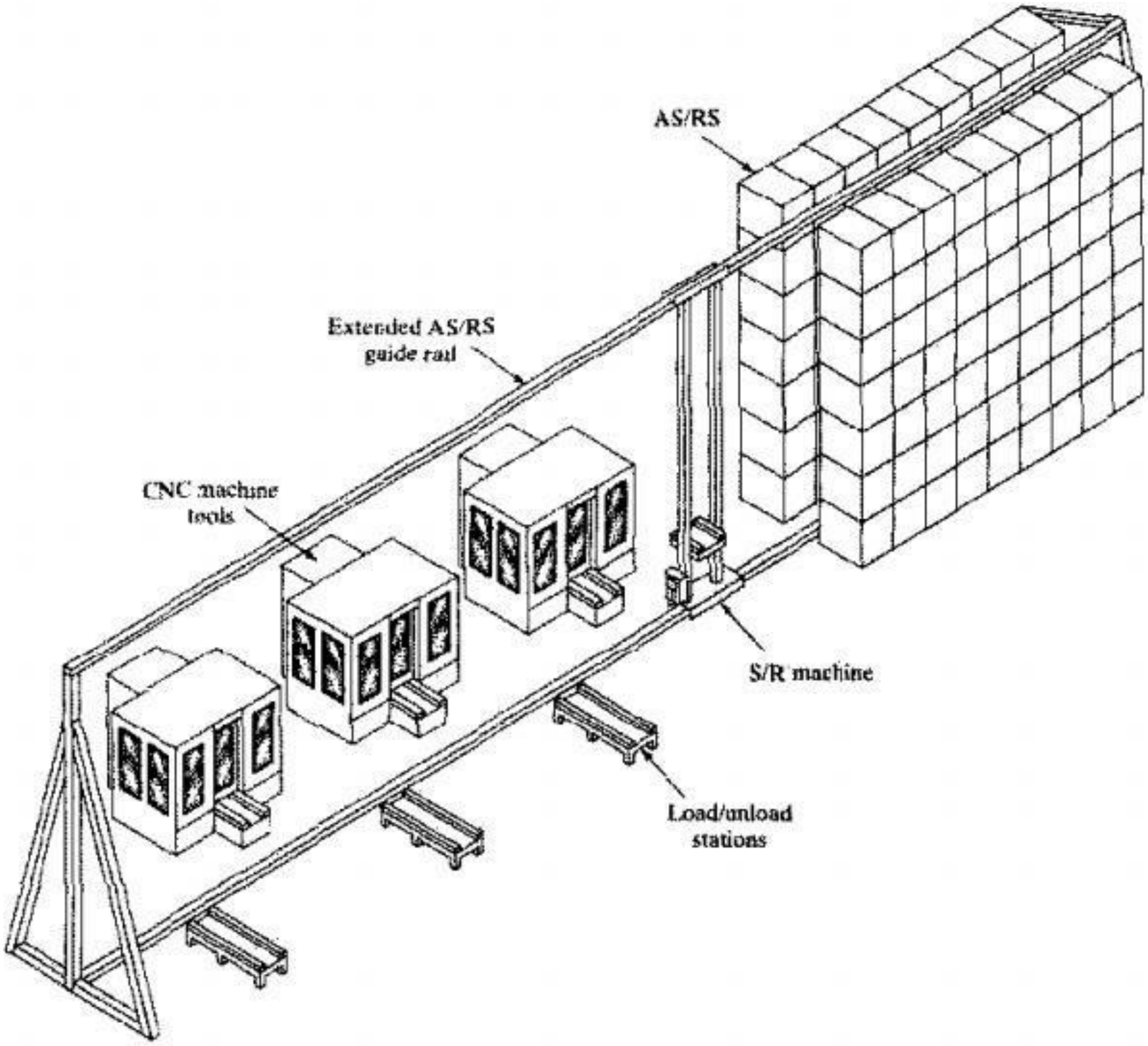
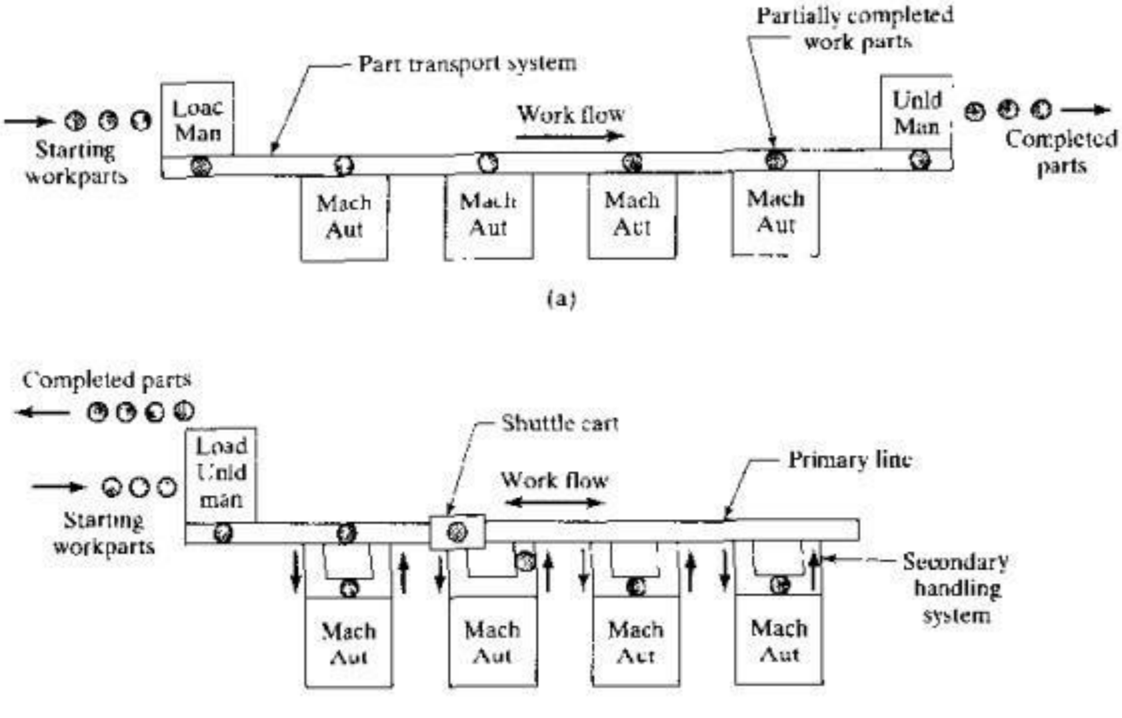


Figure 16.6 FMS that incorporates an automated storage and retrieval system for handling and storing parts. Key: AS/RS = automated storage/retrieval system, S/R = storage/retrieval machine (also known as a stacker crane), CNC = computer numerical control.

system. Since all work units follow the same routing sequence, even though the processing varies at each station, this system is classified as type III A in our manufacturing systems classification system. For inline systems requiring greater routing flexibility, a linear transfer system that permits movement in two directions can be installed. One possible arrangement for doing this is shown in Figure 16.7(b), in which a secondary work handling system is provided at each workstation to separate most of the parts from the primary line. Because of the variations in routings, this is II type II A manufacturing system.

In the *loop layout*, the workstations are organized in a loop that is served by ll part handling system in the same shape, as shown in Figure 16.8(a). Parts usually flow in one direction around the loop, with the capability to stop and be transferred to any station. A secondary



(a)

(b)

Figure 16.7 In-line FMS layouts: (a) one direction flow similar to a transfer line and (b) linear transfer system with secondary part handling system at each station to facilitate flow in two directions. Key: Load = parts loading station, UnLd = parts unloading station, Mach = machining station, Man = manual station, Aut = automated station.

handling system is shown at each workstation to permit parts to move without obstruction around the loop. The load/unload station(s) arc typically located at one end of the loop. An alternative form of loop layout is the *rectangular layout.* As shown in Figure 16.8(b), this arrangement might be used to return pallets to the starting position in a straight line machine arrangement.

The *ladder layout* consists of a loop with rungs between the straight sections of the loop, on which workstations are located, as shown in Figure 16.9.The rungs increase the possible ways of getting from one machine to the next, and obviate the need for a secondary handling system. This reduces average travel distance and minimizes congestion in the handling system, thereby reducing transport time between workstations.

The *open field layout consists* of multiple loops and ladders and may include sidings as well. as illustrated in Figure 16.m This layout type is generally appropriate for processing a large family of parts. The number of different machinetypes may be limited, and parts are routed to different workstations depending on which one becomes available first.

The *robot-centered cell* (Figure 16.1) uses one or more robots as the material handling system. Industrial robots can be equipped with grippers that make them well suited for the handling of rotational parts, and robot centered FMS layouts are often used to process cylindrical or disk shaped parts

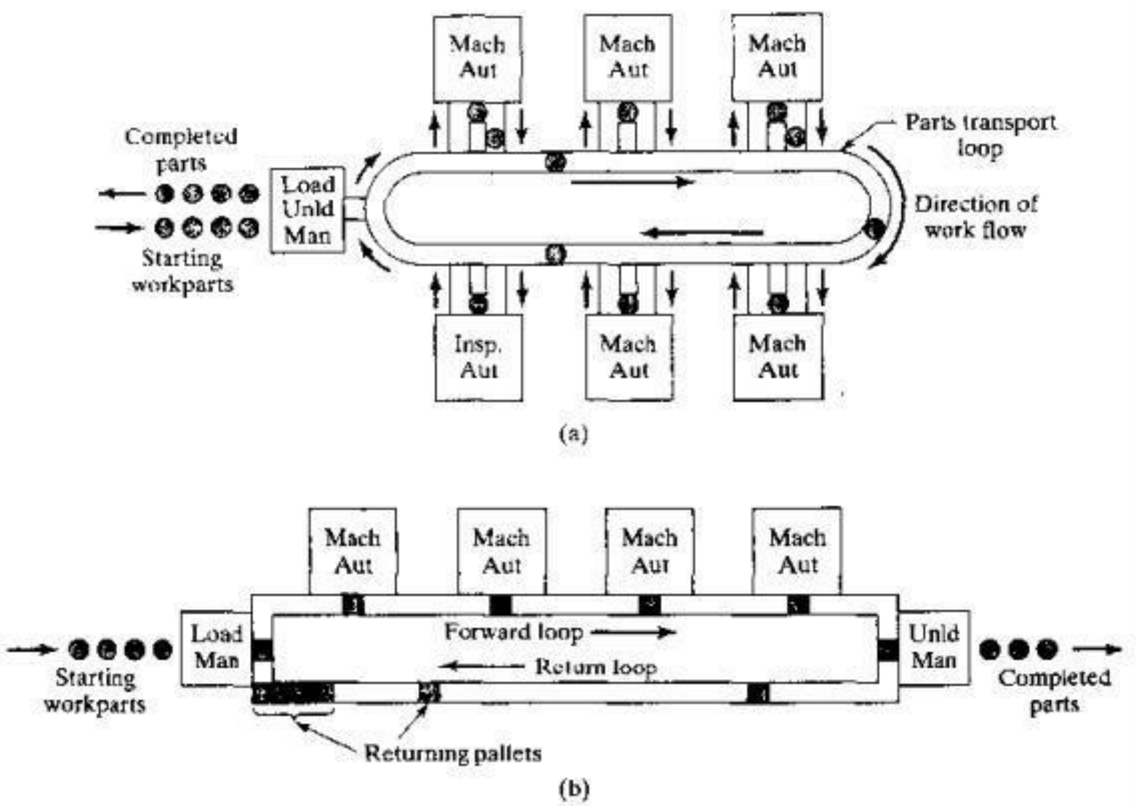


Figure 16.8 (a) FMS loop layout with secondary part handling system at each station to allow unobstructed flow on loop and (b) rectangular layout for recirculation of pallets to the first workstation in the sequence. Key: Load = parts loading station, UnLd = parts unloading station, Mach = machining station, Man = manual station, Aut = automated station.

Computer Control System

The FMS includes a distributed computer system that is interfaced to the workstations, material handling system, and other hardware components. A typical FMS computer system consists of a central computer and microcomputers controlling the individual machines and other components. The central computer coordinates the activities of the components to achieve smooth overall operation of the system. Functions performed by the FMS computer control system can be grouped into the following categories:

Workstation control. In a fully automated FMS, the individual processing or assembly stations generally operate under some form of computer control. For a machining system, CNC is used to control the individual machine tools.

Distribution of control instructions to workstations. Some form of central intelligence is also required to coordinate the processing at individual stations. In a machining FMS, part programs must be downloaded to machines, and DNC is used for this purpose, The DNC system stores the programs, allows submission of new programs and editing of existing programs as needed, and performs other DNC functions (Section 6.3).

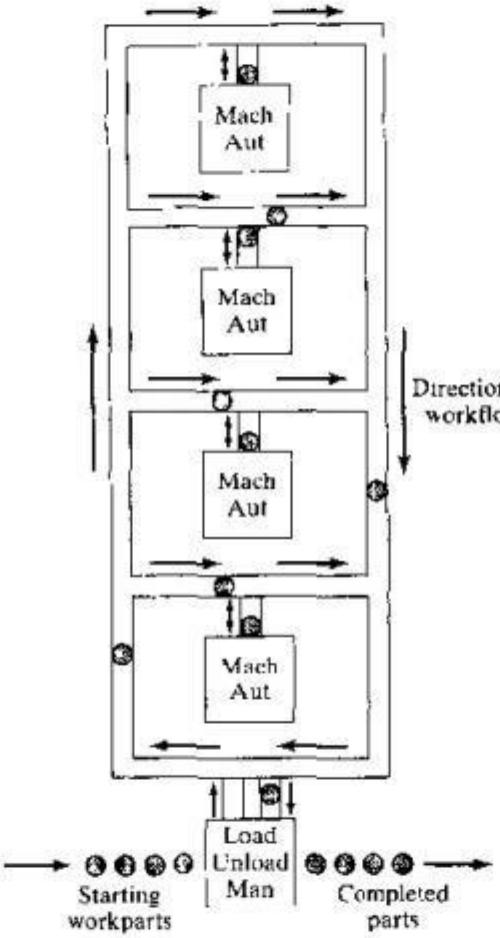


Figure 16.9 FMS ladder layout. Key: Load = parts loading station, UnLd = parts unloading station, Mach = machining station, Man = manual station, Aut = automated station.

Production control. The part mix and rate at which the various parts are launched into the system must be managed. Input data required for production control includes desired daily production rates per part. numbers of raw work-parts available, and number of applicable pallets.' The production control function is accomplished by routing an applicable pallet 10 the load/unload area and providinginstructions to the operator for loading the desired work-part.

Traffic control. This refers to the management of the primary material handling system that moves work parts between stations. Traffic control is accomplished by actuating switches at branches and merging points. stopping parts at machine tool transfer locations, and moving pallets to load/unload stations.

Shuttle control. This control function is concerned with the operation and control of the secondary handling system at each workstation. Each shuttle must be coordinated with the primary handling system and synchronized with the operation of the machine tool it serves,

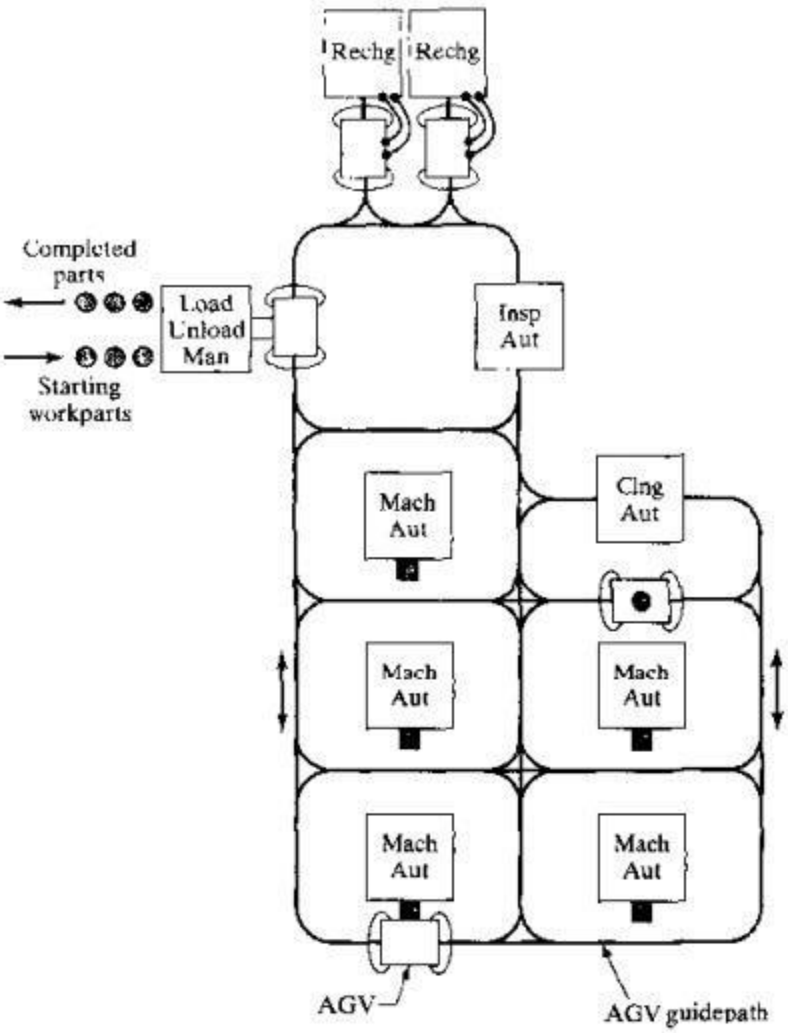


Figure 16.10 Open field FMS layout. Key: Load = parts loading, UnLd = parts unloading, Mach = machining, Clng = cleaning, Insp = inspection, Man = manual, Aut = automated, AGV = automated guided vehicle. Rechg = battery recharging station for AGVs.

Work-piece monitoring. The computer must monitor the status of each cart and/or pallet in the primary and secondary handling systems as well as the status ofeach of the various workpiece types.

Tool control. In a machining system, cutting tools are required. Tool control is concerned with managing two aspects of the cutting tools:

Tool location. This involves keeping track of the cutting tools at each workstation, If one or mere tools required to process a particular workpiece is not present at the station that is specified in the part's routing, the tool control subsystem takes one or both of the following actions: (a) determines whether an alternative workstation that has the required tool is available and/or (b) notifies the opera tor responsible for tooling in the system that the tool storage unit at the station must be loaded with the required cutter(s).

Tool life monitoring. 1.nthis aspect of tool control, a tool life is specified to the computer for each cutting tool in the FMS. A record of the machining time usage maintained for each of the tools, and when the cumulative machining time reaches the specified life of the tool, the operator is notified that a tool replacementis needed.

Performance monitoring and reporting. The computer control systemis programmed to collect data on the operation and performance of the FMS. This data is periodically summarized, and reports are prepared for management on system performance. Some of the important reports that indicate FMS performanceare listed in Table 16.6

Diagnostics. This function is available to a greater or lesser degree on many manufacturing systems to indicate the probable source of the problem when a malfunction occurs. It can also be used to plan preventive maintenance iu the system and to identify Impending failures. The purpose of the diagnostics function is to reduce breakdowns and downtime and increase availability of the system.

The modular structure of the FMS application software for system control is illustrated in Figure 16.11. It should be noted that an FMS possesses the characteristic architecture or a DNC system. As in other DNC systems. Two-way communication is used. Data and commands an: sent from the central computer to the individual machines and other hardware components, and data on execution and performance are transmitted from the components hack up to the central computer. In addition, an uplink from the FMS to the corporate host computer is provided

Human Resources

One additional component in the FMS is human labor. Humans are needed to manage the operations of the FMS. Functions typically performed by humans include: (1) loading raw work parts into the system, (2) unloading finished parts(or assemblies) from the system.

(3) changing and setting tools. (4) equipment maintenance and repair, (5) NC part programming in a machining system, (6) programming and operating the computer system, and (7) overall management of the system

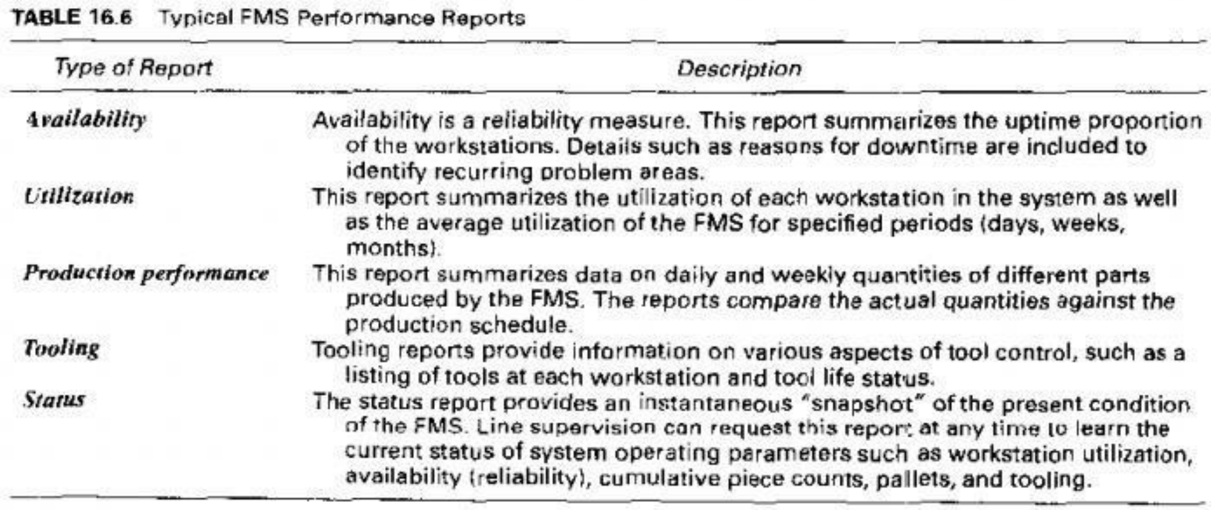


TABLE 16.6 Typical FMS Performance Reports

Type of Report	*Description*
Availability	Availability is a reliability measure. This report summarizes the uptime proportion of the workstations. Details such as reasons for downtime are included to identify recurring problem areas.
Utilization	This report summarizes the utilization of each workstation in the system as well as the average utilization of the FMS for specified periods (days, weeks, months).
Production performance	This report summarizes data on daily and weekly quantities of different parts produced by the FMS. The reports compare the actual quantities against the production schedule.
Tooling	Tooling reports provide information on various aspects of tool control, such as a listing of tools at each workstation and tool life status.
Status	The status report provides an instantaneous "snapshot" of the present condition of the FMS. Line supervision can request this report at any time to learn the current status of system operating parameters such as workstation utilization, availability (reliability), cumulative piece counts, pallets, and tooling.

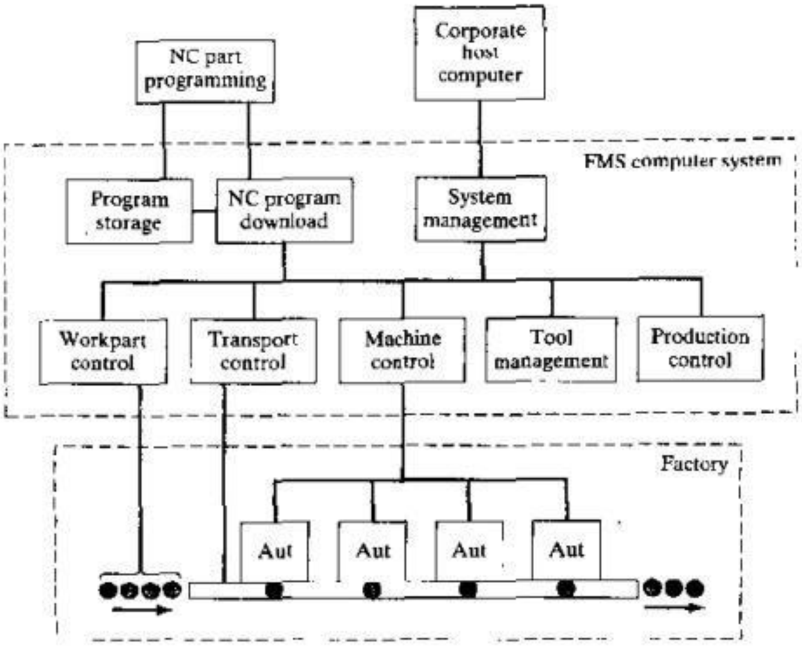


Figure 16.11 Structure of FMS application software system. Key: NC = numerical control, Aut = automated workstation.

FMS APPLICATIONS AND BENEFITS

In this section, we explore the applications of FMSs and the benefits that result from these applications. Many of the findings from the industrial survey on cellular manufacturing (reported in Section 15.5.2) are pertinent to FMSs, and we refer the reader to that report

FMS Applications

The concept of flexible automation is applicable to a variety of manufacturing operations. **In** this section, some of the important FMS applications are reviewed. FMS technology most widely applied in machining operations. Other applications include sheet metal press working, forging, and assembly. Here some of the applications are examined using case study examples to illustrate.

Flexible Machining Systems. Historically. most of the applications of flexible machining systems have been in milling and drilling type operations (non rotational parts), using NC and subsequently CNC machining centers. FMS applications for turning (rotational parts) were much less common until recently, and the systems that are installed tend to consist of fewer machines. For example, single machine cells consisting of parts storage units, part loading robots, and CNC turning centers are widely used today, although not always in a flexible mode. Let us explore some of the issues behind this anomaly in the development of flexible machining systems.

By contrast with rotational parts, nonrotational parts are often too heavy for a human operator to easily and quickly load into the machine tool. Accordingly, pallet fixtures were developed so that these parts could be loaded onto the pallet offline and then the part on. pallet could be moved into position in front of the machine tool spindle. Non rotational pans also tend to be more expensive than rotational parts, and the manufacturing lead times tend to be longer. These factors provide a strong incentive to produce them as efficiently as possible, using advanced technologies such as FMSs. For these reasons, the technology for FMS milling and drilling applications is more mature today than for FMS turning applications

EXAMPLE 16.1 FMS at Ingersoll-Rand in Roanoke, Virginia

One of the first FMS installations in the United States was at the Roanoke, Virginia. plant of the Tool and Hoist Division of Ingersoll-Rand Corp. The system was installed by Sundstrand in the late 1960& It consists of two five-axis machining centers, two four axis machining centers, and two four-axis drilling machines. The machines are each equipped with 6Otool storage drums and automatic 1001 changers and pallet changers. A powered roller conveyor system is used for the primary and secondary work part handling systems. Three operators plus one foreman run the system three shifts. Up to 140 part numbers are machinedon the system. The parts begin as cast iron and aluminum castings and are machined into motor cases, hoist casings, and so on. Part size capability ranges up to a 0.9 m cube (36.0 in). Production quantities for the various part numbers range from 12 per year to 20,000 per year. The layout of the system is presented in Figure 16.12.

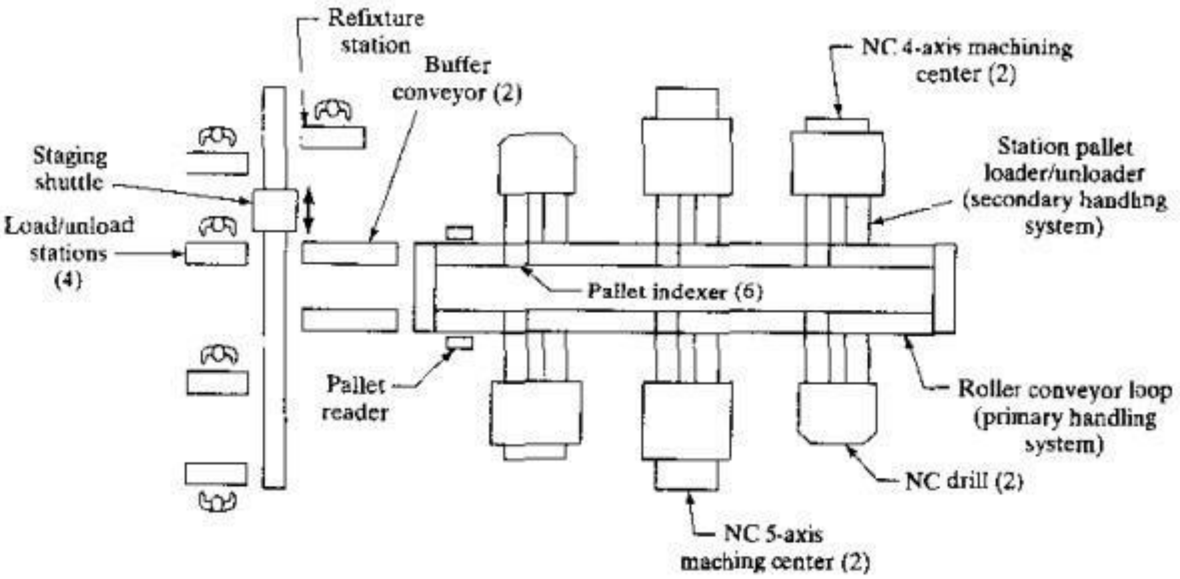


Figure 16.12 Layout of Ingersoll-Rand FMS in Roanoke, Virginia.

EXAMPLE 16.2 FMS at Avco-Lycoming

An FMS was designed and installed by Kearney & Trecker Corporation at the Avco-Lycoming plant in Williamsport, Pennsylvania, to manufacture aluminum

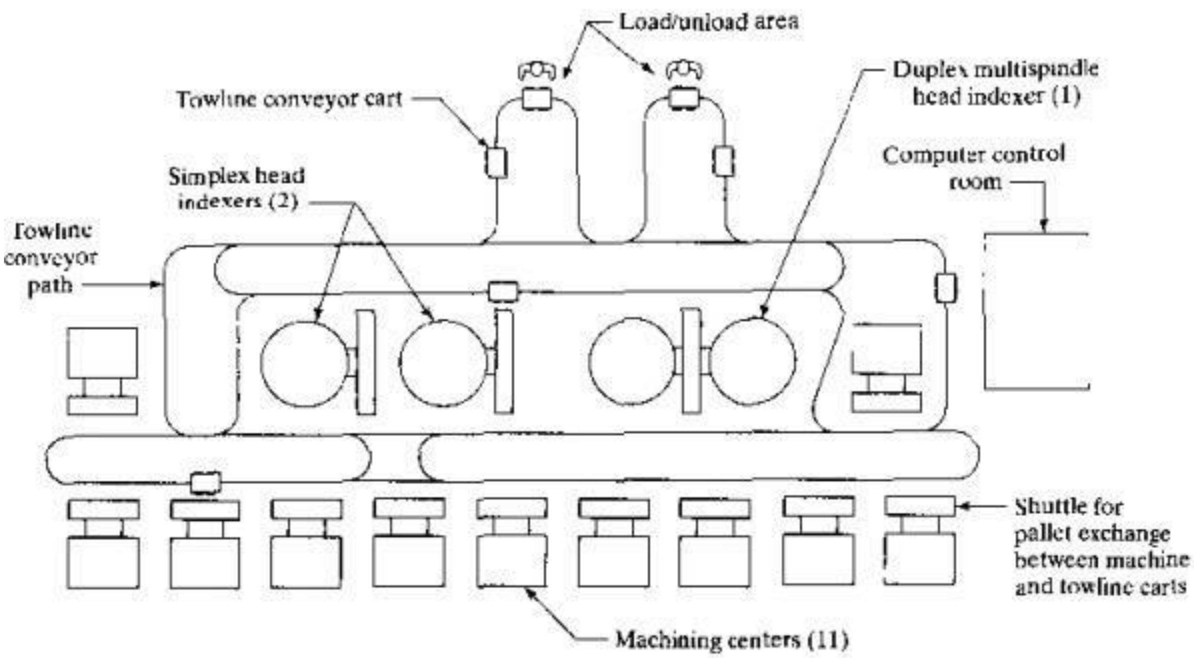


Figure 16.13 FMS layout at Avco-Lycoming in Williamsport. Pennsylvania.

crankcase halves for aircraft engines. The layout is an open field type and is illustrated in Figure 16.13. The handling of work-parts between machines is performed by an in-floor towline cart system with a total of 2 pallet carts. The system contains 14 machine tools: one duplex multi spindle bead indexer, two simplex multi-spindle head indexers, and 11 machining centers. In a multi spindle head indexer, machining heads are attached to an indexing mechanism that indexes (rotates in specified angular amounts) to bring the correct machining head into position to address the work. A simplex unit processes the work on one side only, while a duplex has two indexers on opposite sides of the work. Machining centers are described in Section 14.3.3.

EXAMPLE 16.3 Vought Aerospace FMS

An FMS installed at Vought Aerospace in Dallas. Texas, by Cincinnati Milacron is shown in Figure 16.14. The system is used to machine approximately 600 different aircraft components. The FMS consists of eight CNC horizontal machining centers plus inspection modules. Part handling is accomplished by an automated guided vehicle system using four vehicles. Loading and unloading of the system is done at two stations. These load/unload stations consist of storage carousels that permit parts to be stored on pallets for subsequent transfer to the machining stations by the AGVS. The system is capable of processing a sequence of single, one-of-a-kind parts in a continuous mode. permitting a complete set of components for one aircraft to be made efficiently without batching.

Other FMS Applications. Press working and forging arc two other manufacturing processes in which efforts are being made to develop flexible automated systems.

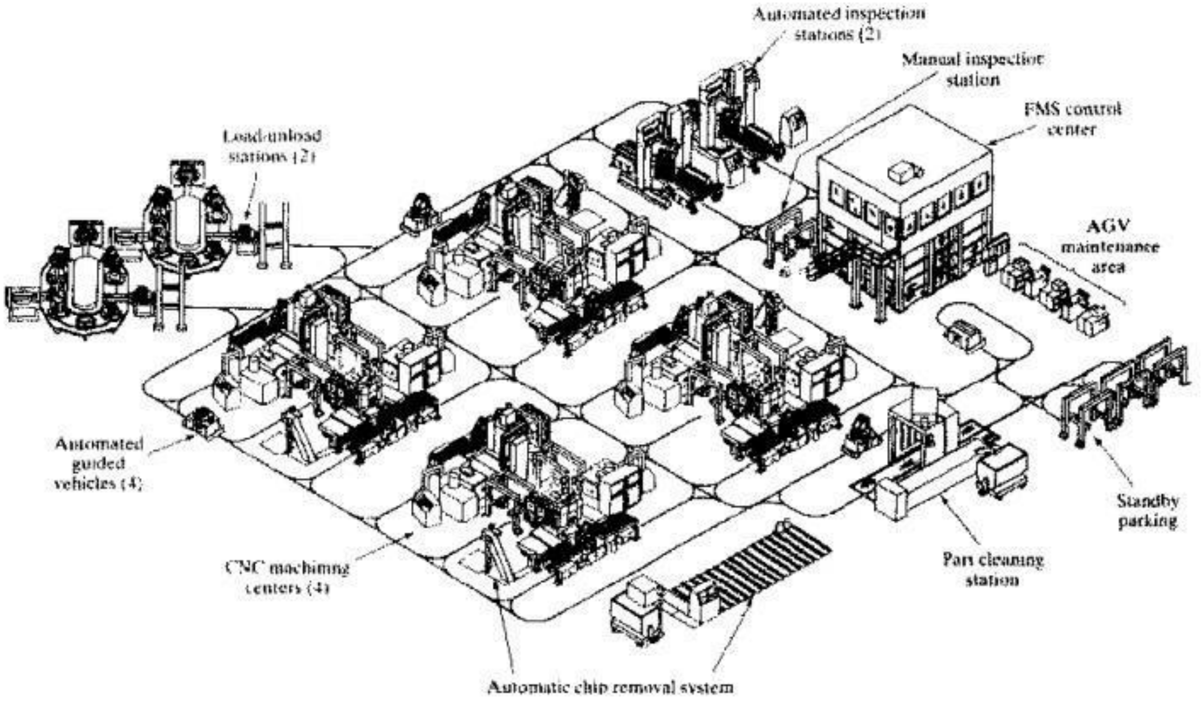


Figure 16.14 FMS at Vought Aircraft (line drawing courtesy of Cincinnati Milacron).

The following example illustrates the development efforts in the press working area.

EXAMPLE 16.4 Flexible Fabricating System

The term flexible fabricating system (FFS) is sometimes used in connection with systems that perform sheet metal press working operations. One FFS concept by Wiedemann is illustrated in Figure 16,15. The system is designed to unload sheet metal stock from the automated storage/retrieval system (AS/RS), move the stock by rail-guided cart to the CNC punch press operations, and then move the finished parts back to the AS/RS, all under computer control.

Flexible automation concepts can be applied to assembly operations. Although some examples have included industrial robots to perform the assembly tasks, the following example illustrates a flexible assembly system that makes minimal use of industrial robots.

EXAMPLE 16.5 Assembly FMS at Allen-Bradley

An FMS for assembly installed by Allen-Bradley Company is reported in {421. The "flexible automated assembly line" produces motor starters in 125 model styles. The line boasts a 1 day manufacturing lead time on Jot sizes as low as

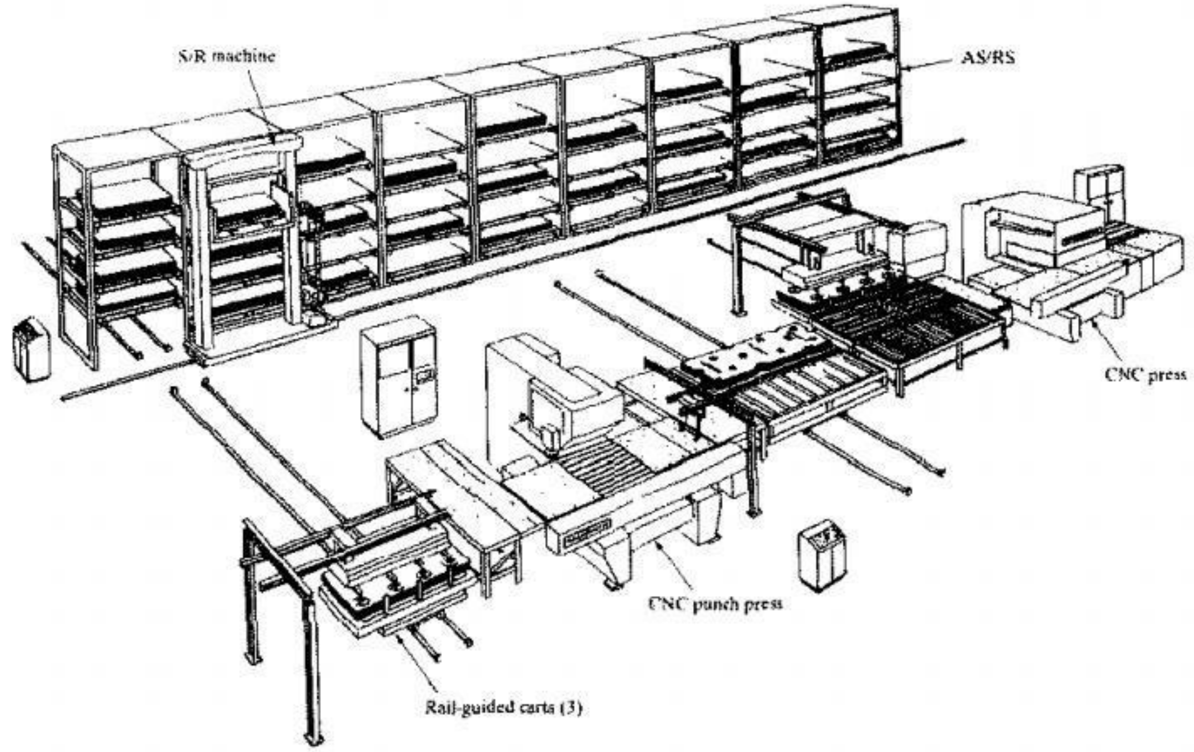


Figure 16.15 Flexible fabricating system for automated sheet metal processing (based on line drawing provided courtesy of Wiedemann Division, Cross & Trecker Co.)

one and production rates of 600 units/hr. The system consists of 26 workstations that perform all assembly, subassembly, testing, packaging required to make the product. The stations are linear and rotary indexing assembly machines with pick- and-place robots performing certain handling functions between the machines. 100% automated testing at each step in the process is used to achieve very high quality levels. The flexible assembly line is controlled by a system of Allen- Bradley programmable logic controllers.

FMS Benefits

A number of benefits can be expected in successful FMS applications. The principal benefits are the following:

***Increased machine** utilization.* FMSs achieve a higher average utilization than machines in a conventional batch production machine shop. Reasons for this include:

(1) 24 hr/day operation. (2) automatic tool changing ar machine tools. (3) automatic pallet changing at workstations. (4) queues of parts at stations, and (5) dynamic scheduling of production that takes into account irregularities from normal operations. It should be possible to approach *80-90%* asset utilization by implementing FMS technology

Fewer machines required Because of higher machine utilization. fewer machines are required.

Reduction in factory floor space required. Compared with a job shop of equivalent capacity, an FMS generally requires less floor area. Reductions in floor space requirements are estimated to he 40-50%

Greater responsiveness to change. An FMS improves response capability to part design changes. introduction of new part s, changes in production schedule and product mix. machine breakdowns. and cutting tool failures. Adjustments can be made in the production schedule from one day to the next to respond to rush orders and special customer requests.

Reduced inventory requirements, Because different parts are processed together rather than separately in batches. Work-in-process (WIP) is less than in a batch production mode. The inventorv of starting and finished parts can be reducedas well. Inventory reductions of 60-80% are estimated.

Lower manufacturing lead times. Closely correlated with reduced WIP is the time spent in process by the parts. This means faster customer deliveries

Reduced direct labor requirements and *higher labor productivity*. Higher production rates and lower reliance on direct labor translate to greater productivity per labor hour with an FMS than with conventional production methods. Labor savings of 30-.50%, are estimated

Opportunity for unattended production. The high level of automation in an FMS allows it to operate for extended periods of time without human attention. In the most optimistic scenario, parts and tools are loaded into the system at the end of the day shift, and the FMS continues to operate throughout the night so that the finished parts can be unloaded the next morning.

FMS PLANNING AND IMPLEMENTATION ISSUES

Implementation of an FMS represents a major investment and commitment by the user company. It is important that the installation *of* the system be preceded by thorough planning and design, and that its operation be characterized by good management of all resources: machines, tools, pallets, parts, and people. Our discussion of these issues is organized along these lines: (1) FMS planning and design issues and (2) FMS operational issues.

FMS Planning and Design Issues

The initial phase of FMS planning must consider the parts that will he produced by the *sys*tem. The issues are similar to those in GT machine cell planning (Section 15.4.2).They include:

Part family considerations. Any FMS must be designed to process a limited range of part (or product) styles. The boundaries of the range must be decided. In effect, the part family that will be processed 011the FMS must be defined. rhe definition of part families to be processed un the FMS can be based on product commonality as well as on part similarity. The term *product commonality* refers 10 different components used on the same product. Many successful FMS installations arc designed to accommodate part families defined by this criterion. This allows all of the components required to assemble a given product unit to be completed just prior to beginning of assembly

Processing requirements. The types of parts and their processing requirements determine the types of processing equipment that will be used in the system. In machining applications. Non-rotational parts are produced by machining centers, milling machines, and like machine tools: rotational parts are machined by turning centers and similar equipment.

Physical characteristics of the workparts, The size and weight of the parts determine the size of the machines at the workstations and the size of the material handling system that must be used

Production volume, Quantities to be produced by the system determine how many machines Will be required. Production volume is also a factor in selectingthe most appropriate type of material handling equipment for the system.

After the part family, production volumes, and similar part issues have beendecided. design of the system can proceed. Important factors that must be specifiedin FMS design include:

Types of workstations. The types of machines are determined by part processing requirements. Consideration of workstations must also include the load/unload station(s).

Variations in process routings and *FMS layout.* If variations in process sequence are minimal. then an inline flow is most appropriate. As product variety increases, a loop is more suitable. If there is significant variation in the processing, a ladder layout or open field layout are the most appropriate

Material handling system. Selection of the material handling equipment and layout are closely related, since the type of handling system limits the layout selection to some extent. The material handling system includes both primary and secondary handling systems

Work-in-process and *storage capacity.* The level of WIP allowed in the FMS is an important variable in determining utilization and efficiency of the FMS. lf the WIP level is too low, then stations may become starved for work, causing reduced utilization. If the WIP level is too high, then congestion may result. The WIP level should be planned, not just allowed to happen. Storage capacity in the FMS must be compatible with WIP level,

Tooling. Tooling decisions include types and numbers of tools at each station. Consideration should also be given to the degree of duplication of tooling at the different stations. Tool duplication tends to increase routing flexibility (Table16.1).

Pallet fixtures. In machining systems for nonrotational parts, the number of pallet fixtures required in the system must be decided. Factors influencing the decision include: levels of WIP allowed in the system and differences in part style and size. Parts that differ too much in configuration and size require different fixturing.

FMS Operational Issues

Once the FMS is installed, then the existing resources of the FMS must be optimized to meet production requirements and achieve operational objectivesrelated to profit. quality, and customer satisfaction

Scheduling: and dispatching. Scheduling of production in the FMS is dictated the master production schedule . Dispatching is concerned with launching of parts into the system at the appropriate times. Several of the problem areas below are related to the scheduling issue.

Machine loading. This problem is concerned with allocating the operations and tooling resources among the machines in the system to accomplish the required production schedule.

Part routing. Routing decisions involve selecting thc routes that should be followed by each part in the production mix to maximize use of workstationresources.

Part grouping. This IS concerned with the selection of groups of part types for simultaneous production, given limitations on available tooling and other resources a' workstations.

•*Tool management.* Managing the available tools includes decisions on when to change tools, allocation of tooling to workstations in the system, and similar issues.

Pallet and fixture allocation. This problem is concerned with the allocation ofpal lets and fixtures to the parts being produced in the system.

AGILE MANUFACTURING

As an observed "system of doing business:' agile manufacturing emerged after lean production yet shares many aspects. *Agile manufacturing* can he defined as (1) an enterprise level manufacturing strategy of introducing new products into rapidly changing markets and (2) an organizational ability to thrive in a competitive environment characterized by continuous and sometimes unforeseen change.

The 1991 study identified four principles of agility" Manufacturing companies that are agile competitors tend to exhibit these principles or characteristics. The four principles are:

Organize to Master Change " An agile company is organized in a way that allows it to thrive on change and uncertainty'? In a company that is agile, the human and physical resources can be rapidly reconfigured to adapt to changing environment and market opportunities.

Leverage the Impact of People and Information - In an agile company,knowledge is valued, innovation is rewarded, authority is distributed to the appropriate level of the organization. Management provides the resources that personnel need. The organization is entrepreneurial in spirit. There is a "climate of mutual responsibility for joint success'"

Cooperate to Enhance Competitiveness - "Cooperation internally and with other companies is an agile competitor's operational strategy of first choice."? The objective is to bring products 10 market as rapidly as possible. The required resources and competencies (Ire found and melt wherever they exist. This may involve partnering with other companies, possibly even competing companies. to form *virtual enterprises*

Enrich the Customer" - An agile company is perceived by its customers as enriching them in a significant way. not only itsclf.'" The products of an agile company are perceived as solutions to customers' problems. Pricing of the product can be based on he value of the solution to the customer rather than on manufacturing cost

our definition and the list of four agility principles indicate, agile manufacturing involves more than Just manufacturing. It involves the firm's organizational structure, it involves the way the firm treats it people. it involves partnerships with other organizations, and it involves relationships with customers. Instead of "agile manufacturing," it might be more appropriate to just call this new system of doing business "agility:"

Market Forces and Agility

A number of market forces Can be identified that are driving the evolution of agility and agile manufacturing in business. These forces include:

Intensifying competition Signs of intensifying competition include (I) global competition, (2) decreasing cost of information, (3) growth in communication technologies (4)pressure to reduce time to market, (5) shorter product lives. and (6) increasing pressures on costs and profits

Fragmentation of mass markets Mass production was justified by the existence of very large markets for mass produced products. The signs of the trend toward fragmented markets include: (1) emergence of niche markets, for example, different sneakers for different sports and non sports applications; (2) high rate of model changes; declining barriers to market entry from global competition; and (4) shrinking windows of market opportunity. Producers must develop new product styles in shorter development periods.

Cooperative business relationships There is mare cooperation occurring among corporations in the United States. The cooperation takes many forms. Including increasing inter enterprise cooperation, (2) increased outsourcing, (3) global sourcing. (4) improved labour management relationships. and (5) the formation of virtual enterprises among companies. One might view the increased rate of corporate mergers that are occurring at time of writing as an extension of these cooperative relationships.

Changing customer expectations Market demands are changing. Customers are becoming more sophisticated and individualistic in their purchases. Rapid delivery of the product. support throughout the product life. and high quality are attributes expected by the customer of the product and of the company that manufactured the product. Quality is no longer the basis of competition that it was in the 1970s and 19S0s.Today products me likely to have an increased information content.

Increasing societal pressures Modern companies are expected to be responsive to social issues, including workforce training and education, legal pressures, environmental impact issues. gender issues, and civil rights issues.

Modern firms are dealing with these market forces by becoming agile. Agility is a strategy for profiting from rapidly changing and continually fragmenting global markets for customized products and services. Becoming agile is certainly not the only objective of the firm. There are important other objectives, such as making a profit and surviving into the future. However. becoming more agile is entirely compatible with these other objectives. Indeed, becoming agile represents a working strategy for company survival and future profitability.

How does a company become more agile? Two important approaches are: (1) to re organize the company's production systems to make them more agile and (2) to manage relationships differently and value the knowledge that exists in the organization. Let us examine each of these approaches in a company's operationsas it seeks to become an agile manufacturing firm.

Reorganizing the Production System for Agility

Companies seeking to be agile must organize their production operations differently than the traditional organization. Let us discuss the changes in three basic areas: (1) product design. (2) marketing, and (3) production operations.

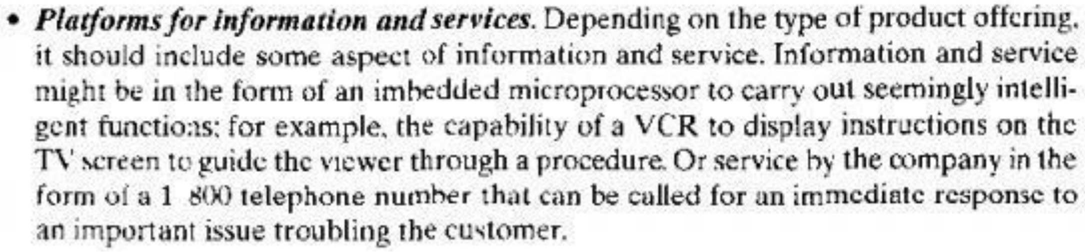
Product Design. Reorganizing production for agility includes issues related to product design. As we have noted previously, decisions made in product design determine approximately 70'1(,of the manufacturing cost of a product. For a company to be more agile, the design engineering department must develop products that can be characterized as follows'

Customizable, Products can be customized for individual niche markets. In some cases, the product must be customized for individual customers.

Upgradeable. It should be possible for customers who purchased the base model to subsequently buy additional options to upgrade the product.

Reconfigurable. Through modest changes in design, the product can be altered to provide it with unique features. A new model can be developed from the previous model without drastic and time consuming redesign effort.

Design modularity. The product should be designed so that it consists of several modules (e.g .. subassemblies) that can he readily assembled to create the finished item. In this way. if a module needs to be redesigned, the entire product does not require redesign. The other modules can remain the same *Frequent model changes* within stable market families. Even for products that succeed in the marketplace. the company should nevertheless introduce new versions of the product to remain competitive.



- ***Platforms for information and services.*** Depending on the type of product offering, it should include some aspect of information and service. Information and service might be in the form of an imbedded microprocessor to carry out seemingly intelligent functions; for example, the capability of a VCR to display instructions on the TV screen to guide the viewer through a procedure. Or service by the company in the form of a 1 800 telephone number that can be called for an immediate response to an important issue troubling the customer.

In addition. the company must achieve rapid. Cost effective development of new products, and it must have a life cycle design philosophy (the life cycle running from initial concept through production. distribution, purchase. disposal. and recovery).

Marketing. A company's design and marketing objectives must be closely linked The best efforts of design may be lost if the marketing plan is flawed. Beingan agile marketing company suggests the following objectives. several of which arc related directly to the preceding product design attributes

- *Aggressive and proactive product marketing.* The sales and marketing functions of the firm should make change happen in the marketplace. The company should bc the change agent that introduces the new models and products
- *Cannibalize successful products.* The company should introduce new models to replace and obsolete its most successful current models.
- *Frequent new product introductions.* The company should maintain a high rate of new product introductions.
- *Life cycle product support.* The company must provide support for the product throughout its life cycle
- *Pricing by 'customer value.* The price of the product should be established according to its value to the customer rather than according to its own cost
- *Effective niche market competitor.* Many companies have become successful by competing effectively in niche markets. Using the same basic product platform, the product has been reconfigured to provide offerings for different markets. The sneaker industry is a good example here

Production Operations. A substantial impact on the agility of the production system can be achieved by reorganizing factory operations and the procedure, and systems that support these operations. Objectives in production operations and procedures that are consistent with an agility strategy are the following:

Be a cost effective, low volume producer. This is accomplished using flexible production systems and low setup times.

Be able to produce to customer order. Producing to customer order reduces inventories of unsold finished goods

Master mass customization, The agile company is capable of economically producing a unique product for an individual customer

Use reconfigurable and reusable processes, tooling, and resources . Examples include computer numerical control machine tools, parametric part programming, robots that arc reprogrammed for different jobs, programmable logic controllers, mixed model production lines, and modular fixtures (fixtures designed with a group technology approach, which typically possess a common base assembly to which are attached components that accommodate the different sizes or styles of work units).

Bring customers closer to the production process. Provide systems that enable customers to specify or even design their own unique products. As an example, it has become every common in the perxunal computer market for customers to be able to order exactly the PC configuration (monitor size, hard drive, and other options) and software that they want.

Integrate business procedures with production. The production system should include sales. marketing, order entry, accounts receivable, and other business functions These functions are included in a computer integrated production planning and control system based on manufacturing resource planning

Treat production as a system that extends from suppliers through to customers. The company's own factory is a component in a larger production system that includes suppliers that deliver raw materials and parts to the factory. It also includes the suppliers' suppliers.

To summarize, some of the important enabling technologies and management practices to reorganize the production function for agile manufacturing are listed in Tatble27.2.

Managing Relationships for Agility

Cooperation should be the business strategy of first choice (third principle of agility). The general policies and practices that promote cooperation in relationships and, in general, promote agility in an organization include the following:

- management philosophy that promotes motivation and support among employees
- trust based relationships
- empowered workforce
- shared responsibility for success or failure
- pervasive entrepreneurial spirit

TABLE 27.2 Enabling Technologies and Management Practices for Agile Manufacturing

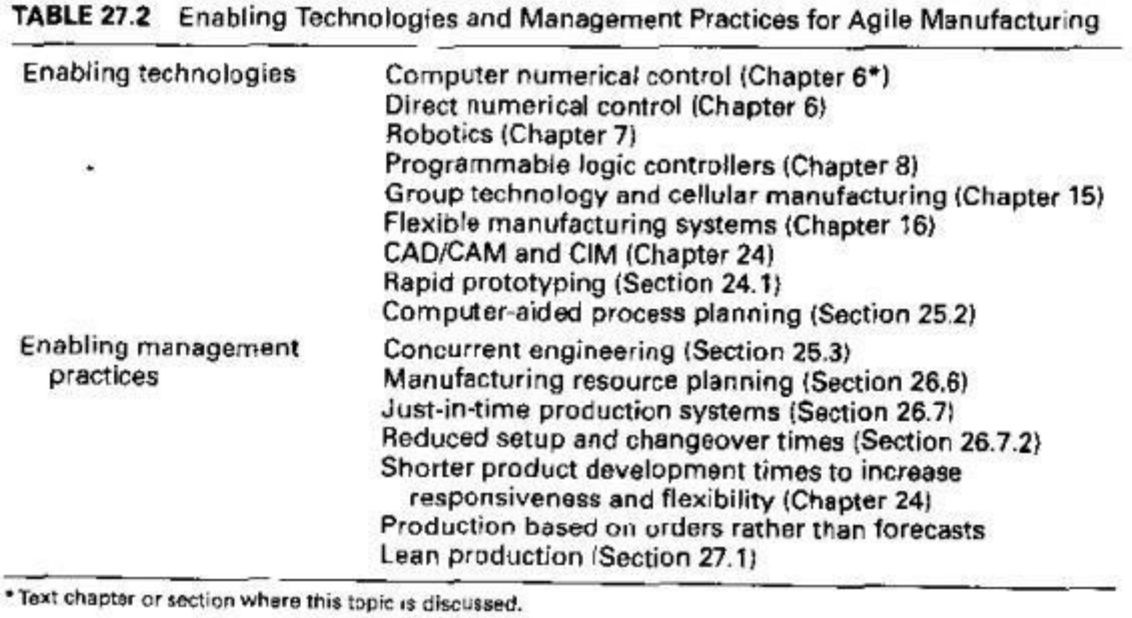


TABLE 27.2 Enabling Technologies and Management Practices for Agile Manufacturing

Enabling technologies	Computer numerical control (Chapter 6*) Direct numerical control (Chapter 6) Robotics (Chapter 7) Programmable logic controllers (Chapter 8) Group technology and cellular manufacturing (Chapter 15) Flexible manufacturing systems (Chapter 16) CAD/CAM and CIM (Chapter 24) Rapid prototyping (Section 24.1) Computer-aided process planning (Section 25.2)
Enabling management practices	Concurrent engineering (Section 25.3) Manufacturing resource planning (Section 26.6) Just-in-time production systems (Section 26.7) Reduced setup and changeover times (Section 26.7.2) Shorter product development times to increase responsiveness and flexibility (Chapter 24) Production based on orders rather than forecasts Lean production (Section 27.1)

* Text chapter or section where this topic is discussed.

There are two different types of relationships that should be distinguished in the context agility; (1) internal relationships and (2) relationships between the company and other organizations.

Internal Relationships. Internal relationships arc those that exist within the firm. between co workers and between supervisors and subordinates. Relationships inside the firm must be managed to promote agility. Some of the important objectives include

(1) make the work organization adaptive. (2) provide cross functional training, (3) encourage rapid partnership formation. and (4) provide effective electronic communications capability

External relationships. External relationships are those that exist betweenthe company and external suppliers. customers, and partners, It is desirable to formand cultivate external relationships for the following reasons: (1) to establishinteractive. proactive

relationships with customers; (2) to provide rapid identification and certification of suppliers: (3) to install effective electronic communications and commerce capability and (4) to encourage rapid partnership formation formutual commercial advantage, The fourth reason raises the issue of the virtual enterprise. A *virtual enterprise* (the terms *virtual organization* and *virtual corporation* are also used) is defined as a temporary partnership of independent resources (personnel, assets. and other resources) intended to exploit a temporary market opportunity. Once the market opportunity is passed and the objective is achieved. the organization is dissolved. In such a partnership, resources are shared among the partners. and benefits (profits) are also shared. Virtual enterprises arc sometimes created by competing firms.

The formation of a virtual enterprise bas the following potential benefits: (1) It may provide access to resources and technologies not available in house, (2) it may provide access to new markets and distribution channels. (3) it may reduce product development time, and (4) it accelerates technology transfer. Some of the guidelines and potential problems associated With virtual enterprise are listed in Table 27.3.

Valuing Knowledge. We must begin discussion of this topic by stating a fundamental premise. It is that the people in an organization, their skills and knowledge and their

TABLE 27.3 Virtual Enterprises: Guidelines and Problems

Guidelines

- Marry well; choose the right partners for good reasons.
- Play fair win; win opportunity for all concerned
- Put your best people into these relationships,
  - Define the objectives.
  - Build a common infrastructure Problems
  - legal issues protection of intellectual property rights.
  - How to valuate each participant's contribution, so profits can be equitably snared.
  - Reluctance of companies to share proprietary information
  - Loss of competitive advantage by sharing knowledge

ability to use information effectively and innovatively, are distinguishing characteristics of an agile competitor. To whatever extent this premise applies to a given organization. the skill and knowledge base must be encouraged, developed. and exploited for the good of the organization. Some of the important objectives include: (1) open communication and information access, (2) openness to learning is pervasive in the organization, (3) learning and knowledge arc basic attributes of an organization's ability to adapt to change, (4) the organization provides and encourages continuous education and training for all employees, and (5) there is effective management of competency inventory, meaning that the organization knows and capitalizes on the skills and knowledge of its employees.

Agility Versus Mass Production

Like lean production, agility is often compared with mass production. In this comparison we must interpret mass production to include all of the requisites that made it successful, such as the availability of mass markets and the ability to forecast demand for a given product in such mass markets. Our comparison is summarized in Table 27.4. Let us elaborate on the items listed in the table

In mass production, companies produce large quantities of standardized products. The purest form of mass production provides huge volumes of identical products. Over the years, the technology of mass production has been refined to allow for minor variations in the product (we call it "mixed model production"). In agile manufacturing, the products are customized. The term used to denote this form of production is *mass customization*, which means large quantities of products having unique individual features that have been specified by and/or customized for their respective customers. Referring to our PO model of production in Chapter 2 (Section 2.3),

In mass production, Q is very large, P is very small, and

in mass customization, P is very large, Q is very small (in the extreme $Q = 1$),

where P = product variety (number of models), and Q = production quantity (units of each model per year).

Along with the trend toward more customized products, today's products have shorter expected market lives. Mass production was justified by the existence of very large markets for its mass produced goods. Mass markets have becomefragmented, resulting in a greater level of customization for each market.

In mass production, products are produced based on sales forecasts. If the forecast is wrong. this can sometimes result in large inventories of finished goods that are slow in selling.

TABLE 27.4 Comparison of Mass Production and Agile Manufacturing

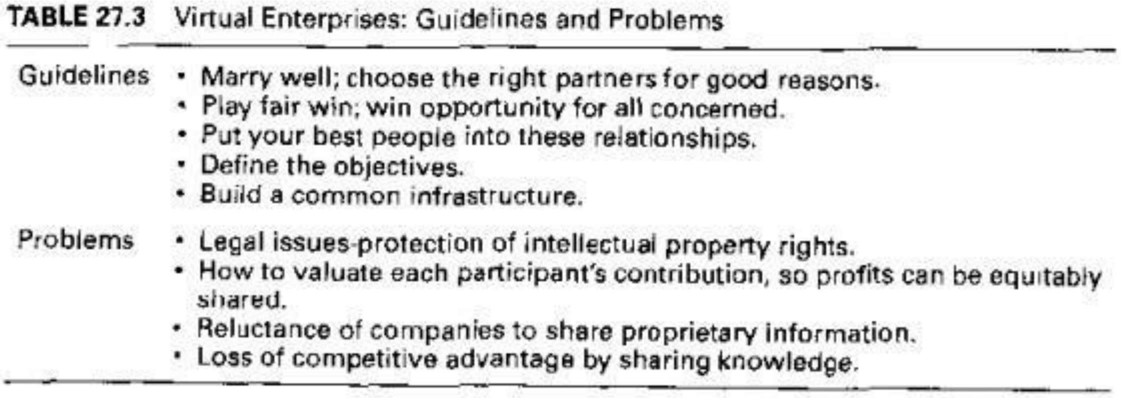


TABLE 27.3 Virtual Enterprises: Guidelines and Problems

Guidelines	• Marry well; choose the right partners for good reasons. • Play fair win; win opportunity for all concerned. • Put your best people into these relationships. • Define the objectives. • Build a common infrastructure.
Problems	• Legal issues-protection of intellectual property rights. • How to valuate each participant's contribution, so profits can be equitably shared. • Reluctance of companies to share proprietary information. • Loss of competitive advantage by sharing knowledge.

Agile companies produce to order: customized products for individual customers. Inventories of finished products are minimized.

Products today have a higher information content than products of yesterday. This is made possible by computer technology. Think of the many products today that operate based on integrated circuits. Nearly all consumer appliances are controlled by l C chips, Modern automobiles use engine controllers that are based on microprocessors. The personal computer market relies on the ability of the customer to be able to telephone an 800 number for assistance. The same is true of many appliances that are complicated to operate, for example, video cassette recorders (VCRs). Manufacturers of these appliances keep adding more and more features to gain competitive advantage, further complicating the products

Single time sales was the expectation of the merchandiser before agility. The customer bought the product and was not expected to be seen again. Today, companies want to nave continuing relationships with their customers, Automobile companies want their customers to nave their new cars serviced at the dealer where the car was purchased. This provides continuing service business for the dealer, and when the customer finally decide, that the time is right to purchase a new car, the first logical place to look for that new car is at the same dealer.

Finally, pricing of the product is traditionally based on its cost. The manufacturer calculates the costs that went into making the product find adds a markup to determine the price (Example 2.8). But some customers are willing and able to pay more. The product may be more valuable to them, especially if it is customized for them. The marketplace allows different pricing structures for different customers. Instead of standard prices for everyone, different prices are used, according to the value to the customer, The airline industry is a good example of multilevel pricing structure. Tourists who fly and stay over Saturday night pay sometimes one third the airfare of business travelers who travel round trip during the same week. Automobiles produced in the same final assembly plant on the same body frame can vary in price by two to one depending on options and nameplate. In the higher education industry, we have different tuition rates for different students. We use a different lexicon *tor* the lower rates than other industries use: We give a discount on the tuition price and call it a scholarship.

LEAN PRODUCTION

Lean production is a term that embraces many of the topics that we have covered in earlier chapters, topics such as flexible manufacturing, minimizing work in process, "pull" systems of production control, and setup time reduction. The term itself was coined by MIT researchers to describe the collection of efficiency improvements that Toyota Motors undertook to survive in the Japanese automobilebusiness after World War II . Because of its origins at Toyota Motors, the same collection of Improvements has also been called the "Toyota production system'

Let us provide two definitions of lean production. Our first definition is a paraphrase of two of the authors of *The Machine that Changed the World*. Womack and Jones define *lean* as doing "more and more with less and less less human effort, less equipment, less time, and less space while coming closer and closer to providing customers with exactly what they want". We are taking some liberties in using this quote, It comes from their book titled *Lean Thinking* (p.15), and they use these words to define "lean thinking," which is lean production but expanded in scope to include distribution and other functions beyond the factory.

The second definition is developed to introduce our discussion of the principles of lean production. *Lean production* can he 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. According to another author of *The Machine that Changed the World*, lean production is based on four principles:

minimize waste

perfect firsttime quality

flexible production lines

continuous improvement

Let us explain these principles and at the same time compare Jean production with its predecessor, mass production. The comparison is summarized in Table 27.1.

Minimize Waste. All four principles of lean production are derived from the first principle: minimize waste. 'Taiichi Ohno's list of waste forms can be listed as follows:

(1) production of defective parts, (2) production of more than till: number uf items needed, (3) unnecessary inventories, (4) unnecessary processing steps, (5) unnecessary movement of people, (6) unnecessary transport of materials, and (7) workers waiting. The various procedures used in the Toyota plants were developed to minimize these forms of waste. A number of these procedures have been discussed in previous chapters. For example, lean principle 2 (perfect first time quality), discussed next, is directed at eliminating production of defective parts (waste form 1). The just in time production system (Section 26.7) was intended to produce no more than the minimum number of parts needed at the next workstation(waste form 2). This reduced unnecessary inventories (waste form 3). And so on,as we will see now.

Perfect First Time Quality. In the area of quality, the comparison between mass production and lean production provides a sharp contrast. In mass production, quality control is defined in terms of an acceptable quality level or AQT. (Section 22.2.1). This means that a certain level of fraction defects is sufficient, even satisfactory. In lean production, by contrast, perfect quality is required. The just in time delivery discipline (Section 26.7) used in lean productionnecessitates a zero defects level in parts quality, because if the part delivered to the downstream workstation is defective, production stops. There is minimum in

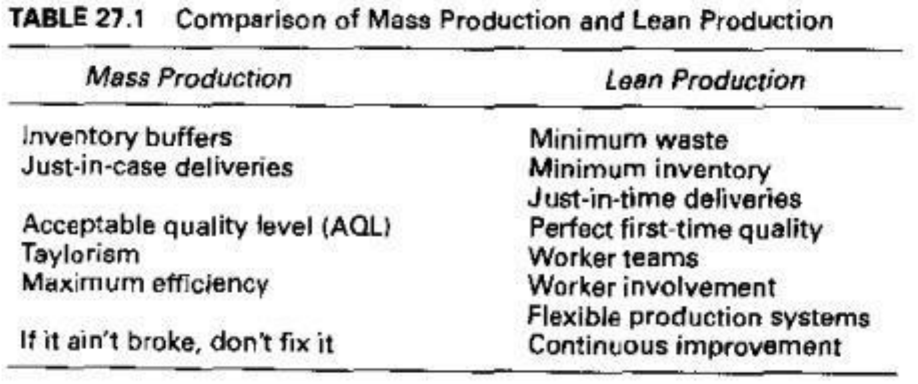


TABLE 27.1 Comparison of Mass Production and Lean Production

Mass Production	*Lean Production*
Inventory buffers	Minimum waste
Just-in-case deliveries	Minimum inventory
	Just-in-time deliveries
Acceptable quality level (AQL)	Perfect first-time quality
Taylorism	Worker teams
Maximum efficiency	Worker involvement
	Flexible production systems
If it ain't broke, don't fix it	Continuous improvement

ventory in lean system to act as a buffer. In mass production, inventory buffers are used just in case these quality problems occur. The defective work units are simply taken off the line and replaced with acceptable units, However, the prohlem is that such a policy tends to perpetuate the cause of the poor quality. Therefore, defective parts continue to be produced. In lean production. a single defect draws attention to the quality problem, forcing corrective action and a permanent solution.Workers inspect their own production. minimizing the delivery of defects to the downstream production station

Flexible Production Systems. Mass production is predicated largely on the principles of Frederick W. Taylor. one of the leaders of the scientific management movement in the early 1901}s(Historical Note 2.1). According to Taylor, workers had to be told every detail of their work methods and were incapable of planning their own tasks. By comparison. Iean production makes use of worker teams to organize the tasks to be accomplished and worker involvement to solve technical problems. One of the findings reported in *The Machine that Changed the World* was that workers in Japanese "lean production" plants received many more hours of training than their U.S, counterparts (380 hours of training vs.46 hours. Another finding was the lower number of job classifications in Japanese lean plants. The study showed an average of 11.9 job classifications in Japanese plants versus an average of 67.1 in LS. plants. Fewer job classifications mean more cross training among workers and greater flexibility in the work force

In mass production, the goal is to maximize efficiency. This is achieved using long production runs of identical parts. Long production runs tolerate long setup changeovers, In lean production. procedures are designed to speed the changeover. Reduced setup times allow for smaller batch sizes. thus providing the production system with greater flexibility. Flexible production systems were needed in Toyota's comeback period because of the much smaller car market in Japan and the need to be as efficient as possible.

Continuous Improvement. In mass production, there is a tendency to set up the operation, and ifits working, leave it alone. Mass production lives by the motto: –lf it ain't broke, don't fix it." By contrast. lean production supports the policy of continuous improvement. Called *kaizen* by the Japanese, continuous improvement means constantly searching for and implementing ways to reduce cost, improve quality, and increase productivity. The scope of continuous improvement goes beyond factory operations and involves design improvements as well. Continuous improvement is carried out one project at a time. The projects may be concerned with any of the following problem areas: cost reduction. quality improvement, productivity improvement, setup time reduction, cycle time reduction, manufacturing lead time and working process inventory reduction, and improvement of product design to increase performance and customer appeal. The procedure for carrying out a continuous improvement project in the quality area is outlined in Section 21.4.2, Similar procedures can be applied to other problem areas.

COMPARISON OF LEAN AND AGILE

Lean production and agile manufacturing are sometimes compared, and in this final section we attempt such a comparison. Are lean and agile really different? They certainly use different statements of principles. The four principles of lean production are compared with the four principles of agility in Table 27.S. We also compare the main features of the

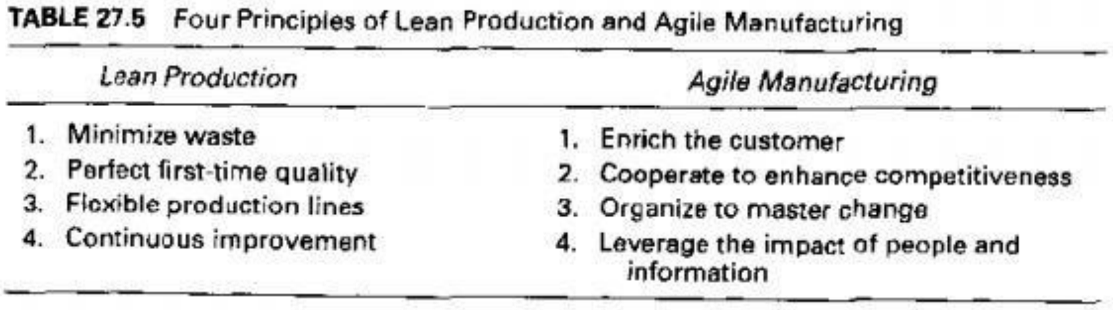


TABLE 27.5 Four Principles of Lean Production and Agile Manufacturing

Lean Production	*Agile Manufacturing*
1. Minimize waste	1. Enrich the customer
2. Perfect first-time quality	2. Cooperate to enhance competitiveness
3. Flexible production lines	3. Organize to master change
4. Continuous improvement	4. Leverage the impact of people and information

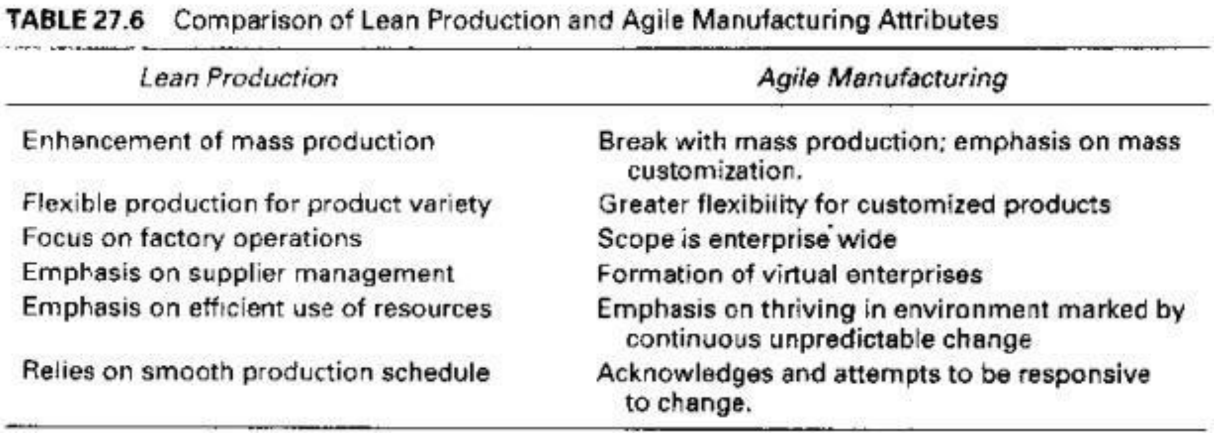


TABLE 27.6 Comparison of Lean Production and Agile Manufacturing Attributes

Lean Production	*Agile Manufacturing*
Enhancement of mass production	Break with mass production; emphasis on mass customization.
Flexible production for product variety	Greater flexibility for customized products
Focus on factory operations	Scope is enterprise wide
Emphasis on supplier management	Formation of virtual enterprises
Emphasis on efficient use of resources	Emphasis on thriving in environment marked by continuous unpredictable change
Relies on smooth production schedule	Acknowledges and attempts to be responsive to change.

two systems in Table 27.6. The emphasis in lean seems to be more on technicaland operational issues, whereas agility emphasizes organization and people issues. Lean applies mainly to the factory. Agility is broader in scope, applicable to the enterprise level and even beyond to the formation of virtual enterprises. One might argue that agility represents an evolutionary next phase of lean production. Certainly the two systems do not compete. If anything, agility complements lean. It extends lean thinking to the entire organization Agility is to lean a, manufacturing resource planning is to material requirements planning.

If there is a difference between these two production paradigms, it is in the area of change and change management. Lean tries to minimize change, at least external change. It attempts to smooth out the ups and downs in the production schedule. It attempts to reduce the impact of changeovers on factory operations so that smaller batch sizes and lower inventories are feasible. It uses flexible production technology to minimize disruptions caused by design changes. Bycontrast, the philosophy of agility is to embrace change. The emphasis is on thriving in an environment marked by continuous and unpredictable change. It acknowledges and attempts to be responsive to change, even to be the change agent if it leads to competitive advantage.

Is this distinction in the way change seems to be viewed in the two systems a fundamental difference? This author would argue that although there may be a difference in viewpoint and perhaps strategy with regard to change, there is no difference in method or approach. The capacity of an agile company to adapt to change or to be a change agent depends on its capabilities to have a flexible production system, to minimize the time and cost of changeover, to reduce onhand inventories of finished products, and to avoid other forms of waste. These capabilities belong to a lean production system. For a company to be agile, it must also be lean.