Unit-1 Introduction to Industrial Automation

1.1 History of Industrial Automation

Automation describes a wide range of technologies that reduce human intervention in processes, mainly by predetermining decision criteria, subprocess relationships, and related actions, as well as embodying those predeterminations in machines. Automation has been achieved by various means including mechanical, hydraulic, pneumatic, electrical, electronic devices, and computers, usually in combination. Complicated systems, such as modern factories, airplanes, and ships typically use combinations of all of these techniques. The benefit of automation includes labor savings, reducing waste, savings in electricity costs, savings in material costs, and improvements to quality, accuracy, and precision.

Throughout the history of automation, the emergence of newer techniques, processes and machines eventually shaped a path for automation to play a larger role in our society. The main goal for the evolution of automation in everyday life has been to help improve efficiency, productivity, safety, and convenience. We will discuss the history of industrial automation to gain a better understanding of how the different stages of automation's evolution have developed and advanced to the technologies we use today.

1st Century BC: Water Wheels

The true date of origin for water wheels is difficult to confirm, however, they became more common use by the Greeks and Romans for grinding grain into flour around the 1st century BC. Other simpler machines which date back much earlier still required a fair amount of human intervention or animal labor to work. The utilization of falling water from watermills to drive a mechanical process can be viewed as the beginning of "semi-automation" and the early stages of automation evolution.

Early water wheels

9th Century: Mill Machinery Advancements

Watermills and windmills are both types of mill machinery that uses renewable energy to drive a mechanical process. The earliest recorded design of a windmill for practical use originates around the 7-9th century and was made by the Persians. These windmills were also used to grind grain and then later developed for many other mechanical processes.

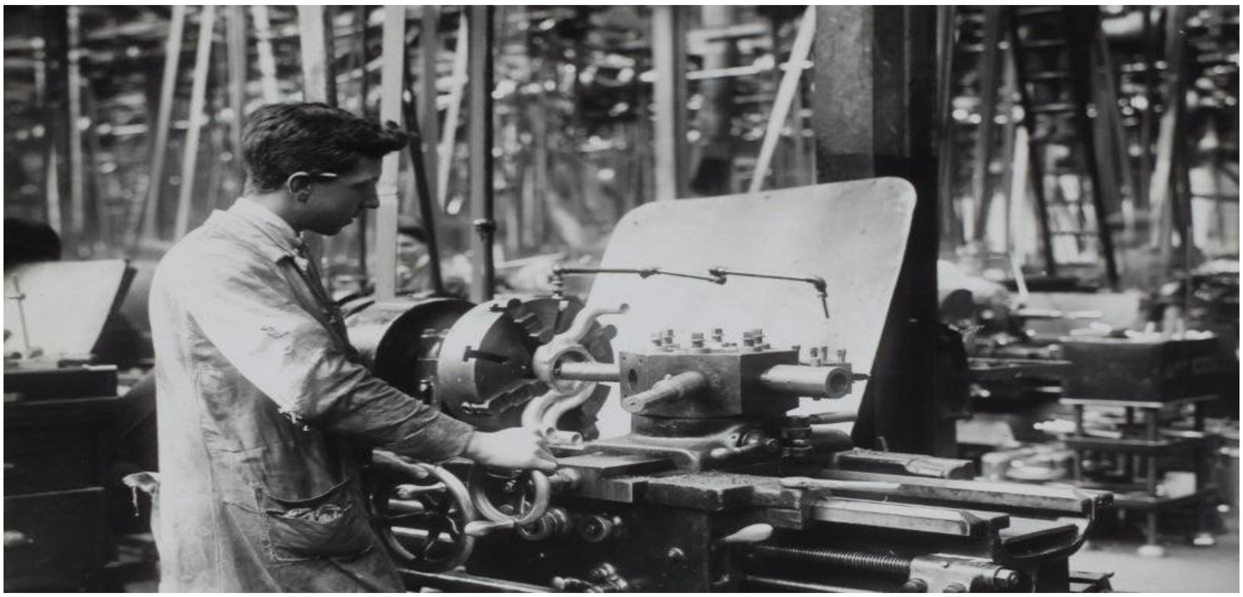
Although watermills can offer more power for its size, windmills were usable in regions which had no flowing water available. Both technologies continued improving and were being adopted across the globe to reduce the manual labor required in:

- Hammermills
- Sawmills
- Paper mills
- Ore-crushing mills
- Tool-sharpening mills

Early windmills

17^{th} to 18^{th} Century: Industrial Revolution

Originating in Western Europe, the 17^{th} century industrial revolution was a major turning point in the evolution of industrial automation. During this era, the invention of steam engines, steam mills and internal combustion engines had mostly replaced the need for watermills and windmills. In 1785, Oliver Evans had also developed an automatic flour mill which was history's first completely automated industrial process by being able to have continuous production without any human intervention.



Early manufacturing factories

In 1867, James Clerk Maxwell published a paper establishing the beginnings of a theoretical basis for understanding control theory. Industrialized factories continued being adopted to mass produce materials such as cotton, paper, plastics, glass, and metals in much higher volumes with greater efficiency. As the technology and processes of the industrial revolution had spread across the globe, the economy, transportation, health, and medicines worldwide were all growing exponentially.

Steam engines for locomotives.

1900 to 1950s: Electrification & Industrial Controllers

Around the 1920s, the evolution of industrial automation accelerated rapidly as factories began making use of relay logic and underwent electrification - the process of powering by electricity. Expanding use of central electric power stations combined with the operation of new high-pressure boilers, electrical substations and steam turbines resulted in a growing demand for instruments and controls.

Electrical power distribution

Early electric motors

Early control stations

20th to 21st Century: Computers & Robotics

In 1971, the invention of microprocessors resulted in large price drops for computer hardware and allowed the rapid growth of digital controls in the manufacturing industry. Our constant advancements in computer technology up till this day continues to advance the evolution of industrial automation. With digital computers, manufacturing facilities were now able to have controllers which can perform more complex tasks at faster speeds and greater efficiency.

Introduction of computers

As technology continued in advancements, the evolution of robotic process automation was becoming more prominent in manufacturing facilities. Victor Scheinman, an American pioneer of the robotics field had invented the “Stanford arm” in 1969. It was designed to permit an arm solution as a 6-axis articulated all-electric robot. This shaped a path for robots to have the potential of performing more complex tasks such as welding and assembly. In 1973, Europe was making huge advancements in industrial robotics by bringing robots to the market through ABB Robotics and KUKA Robotics.

The robots in today’s factories are now used for almost every existing assembly and manufacturing process. Not only do robots remove humans from hazardous environments, but they also help lower costs for business owners to stay competitive by increasing energy efficiency, productivity, accuracy, and precision for better production quality. We can now see the evolution of robotic process automation in processes such as:

- Glass manufacturing
- Pulp and paper mills
- Food and beverage processing
- Automotive assembly
- Natural gas separation
- Electrical power generation
- Electronics manufacturing
- Canning and bottling

Robotics in manufacturing factories

1.2 Need for Industrial automation.

Industrial automation is essential for various reasons, primarily to enhance productivity, quality, safety, and efficiency in manufacturing and other industrial processes. Here are some key reasons why industrial automation is required:

Increased Productivity: Automation allows tasks to be performed consistently and at a faster rate than manual labor, leading to increased output and productivity.

Improved Quality: Automated systems can perform tasks with high precision and accuracy, resulting in products of higher quality and reliability. This consistency reduces errors and defects.

Cost Reduction: While initial investment in automation can be significant, it often leads to reduced labor costs in the long run. Automation can also optimize energy usage and minimize waste, further reducing operational costs.

Enhanced Safety: Automation removes humans from potentially hazardous environments and tasks, reducing the risk of workplace accidents and injuries.

24/7 Operation: Automated systems can operate continuously without breaks, leading to increased uptime and production capacity.

Flexibility and Adaptability: Automation systems can be reprogrammed or reconfigured easily to adapt to changes in production requirements or new product designs.

Data Collection and Analysis: Automation enables real-time monitoring and data collection, providing insights into production processes and enabling predictive maintenance.

Meeting Market Demands: With automation, manufacturers can respond more quickly to changing market demands and produce customized products efficiently.

Conservation of Resources: Automation often leads to optimized use of raw materials, energy, and other resources, contributing to sustainability efforts.

Competitive Advantage: Companies that adopt industrial automation can gain a competitive edge by improving their efficiency, product quality, and responsiveness.

Overall, industrial automation is essential for modern manufacturing and industrial processes to remain competitive, efficient, and sustainable in a rapidly evolving global market.

1.3 Production systems.

The word *manufacturing* derives from two Latin words, *manus* (hand) and *factus* (make), so that the combination means *made by hand*. This was the way manufacturing was accomplished. When the word first appeared in the English language around 1567. Commercial goods of those times were made by hand. The methods were handicraft, accomplished in small shops, and the goods were relatively simple, at least by today's standards. As many years passed, factories came into being, with many workers at a single site, and the work had to be organized using machines rather than handicraft techniques. The products became more complex, and so did the processes to make them. Workers had to specialize in their tasks. Rather than overseeing the fabrication of the entire product, they were responsible for only a small part of the total work. More up-front planning was required, and more coordination of the operations was needed to keep track of the workflow in the factories. Slowly but surely, the systems of production were being developed. The systems of production are essential in modern manufacturing. This book is all about these production systems and how they are sometimes automated and computerized.

A production system is a collection of **people, equipment, and procedures** organized to perform the manufacturing operations of a company. It consists of two major components as indicated in Figure 1.1:

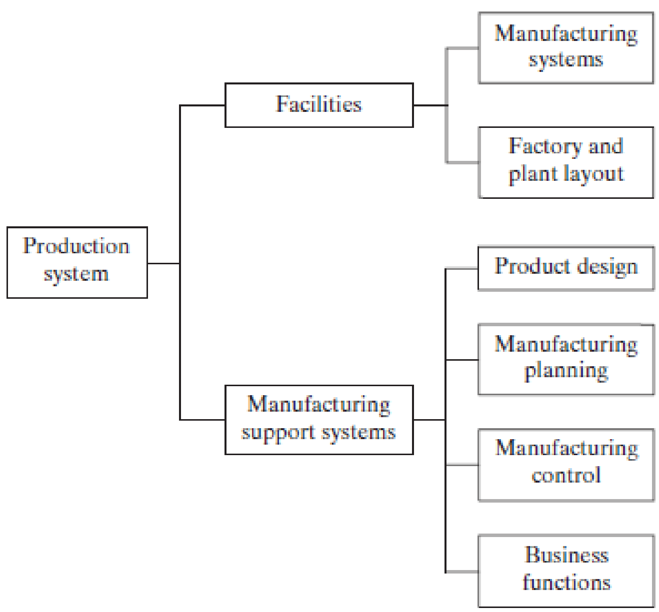


Figure 1.1 The production system consists of facilities and manufacturing support systems.

1. **Facilities:** The physical facilities of the production system include the equipment, the way the equipment is laid out, and the factory in which the equipment is located.

2. **Manufacturing support systems:** These are the procedures used by the company to manage production and to solve the technical and logistics problems encountered in ordering materials, moving the work through the factory, and ensuring that products meet quality standards. Product design and certain business functions are included in the manufacturing support systems. In modern manufacturing operations, portions of the production system are automated and/or computerized. In addition, production systems include people.

   People make these systems work. In general, direct labor people (blue-collar workers) are responsible for operating the facilities, and professional staff people (white-collar workers) are responsible for the manufacturing support systems.

1.3.1 Automation in production systems.

Some components of the firm's production system are likely to be automated, whereas others will be operated manually or clerically. 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 are closely related, because the automated manufacturing systems on the factory floor are themselves usually implemented by computer systems that are integrated with the manufacturing support systems and management information system operating at the plant and enterprise levels. The two categories of automation are shown in Figure 1.2 as an overlay on Figure 1.1.

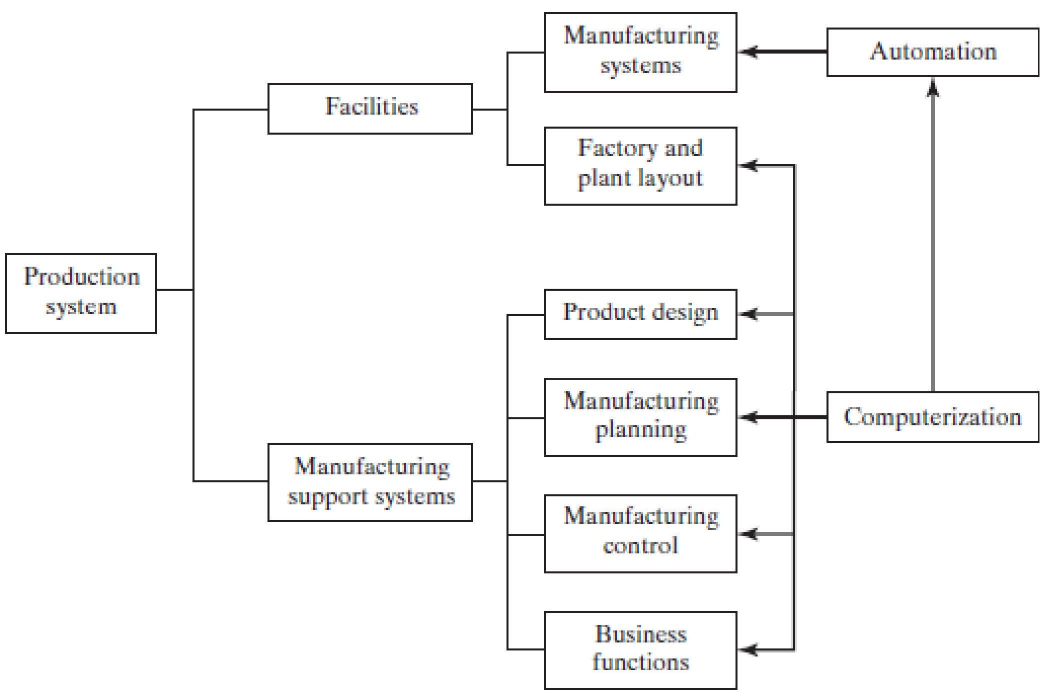


Figure 1.2: Opportunities for automation and computerization in a production system.

Automated Manufacturing Systems:

Automated manufacturing systems operate in the factory for physical products. They perform operations such as processing, assembly, inspection, and material handling, in many 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.

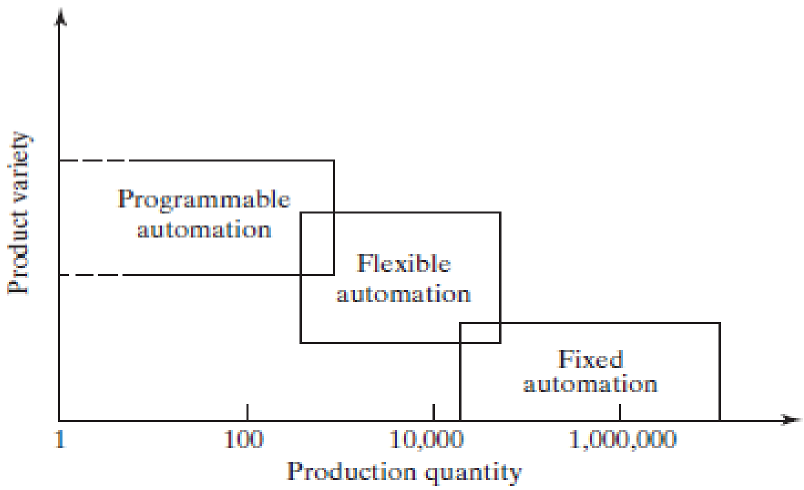


Figure 1.3: Three types of automation relative to production quantity and product variety.

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

Typical features of fixed automation are as follows.

(1) High initial investment for custom-engineered equipment
(2) High production rates, and
(3) Inflexibility of the equipment to accommodate product variety.

The economic justification for fixed automation is found in products that are made 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 minimizing the unit cost relative to 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 the equipment to produce new products. Some of the features that characterize programmable automation include.

(1) High investment in general-purpose equipment
(2) Lower production rates than fixed automation
(3) Flexibility to deal with variations and changes in product configuration
(4) High suitability for batch production.

Programmable automated 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 item, the system must be reprogrammed with the set of machine instructions that correspond to the new item. The physical setup of the machine must also be changed: Tools must be loaded, fixtures must be attached to the machine table, and any required machine settings must be entered. This changeover takes time. Consequently, the typical cycle for a given batch includes a period during which the setup and reprogramming take place, followed by a period in which the parts are 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 can produce a variety of parts or products with virtually no time lost for changeovers from one design to the next. There is no lost production time while reprogramming the system and altering the physical setup (tooling, fixtures, machine settings). Accordingly, the system can produce various mixes 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, so the amount of changeover between designs is minimal. Features of flexible automation include (1) high investment for a custom-engineered system, (2) continuous production of variable mixtures of parts or products, (3) medium production rates, and (4) flexibility to deal with product design variations. Examples of flexible automation are flexible manufacturing systems that perform machining processes.

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 computers. Indeed, computer technology is used to implement automation of the manufacturing systems in the factory as well.
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 information-processing functions needed in a manufacturing firm. True CIM involves integrating all of these functions in one system that operates throughout the enterprise. Other terms
are used to identify specific elements of the CIM system; for example, computer-aided design (CAD) supports the product design function. Computer-aided manufacturing (CAM) is used for functions related to manufacturing engineering, such as process planning 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 involves the information-processing activities that provide the data and knowledge required to successfully produce the product. These 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.

1.4 Automation Principles and Strategies

The preceding section leads one to conclude that automation is not always the right answer for a given production situation. A certain caution and respect must be observed in applying automation technologies. This section offers three approaches for dealing with automation projects:1 (1) the USA Principle, (2) Ten Strategies for Automation and Process Improvement, and (3) an Automation Migration Strategy.

1.4.1 The USA principle

The USA Principle is a commonsense approach to automation and process improvement 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) understanding the existing process, (2) simplify the process, and (3) automate the process. A statement of the USA Principle appeared in an article published by the American Production and Inventory Control Society. The article is concerned with implementing enterprise resource planning, but the USA approach is so general that it is applicable to nearly any automation project. Going through each step of the procedure for an automation project may in fact reveal that simplifying the process is sufficient and automation is not necessary.

Understand the Existing Process

The first step in the USA approach is to comprehend the current process in all its details. What are the inputs? What are the outputs? What exactly happens to the work unit2 between input and output? What is the function of the process? How does it add value to the product? What are the upstream and downstream operations in the production sequence, and can they be combined with the process under consideration? Some of the traditional industrial engineering charting tools used in methods analysis are useful in this regard, such as the operation chart and the flow process chart. Application of these tools to the existing process provides a model of the process that can be analyzed and searched for weaknesses (and strengths). The number of steps in the process, the number and placement of inspections, the number of moves and delays experienced by the work unit, and the time spent in storage can be ascertained by these charting techniques. Mathematical models of the process may also be useful to indicate relationships between input parameters and output variables. What are the important output variables? How are these output variables affected by inputs to the process, such as raw material properties, process settings, operating parameters, and environmental conditions? This information may be valuable in identifying what output variables need to be measured for feedback purposes and in formulating algorithms for automatic process control.

Simplify the Process

Once the existing process is understood, then the search begins for ways to simplify. This often involves a checklist of questions about the existing process. What is the purpose of this step or this transport? Is the step necessary? Can it be eliminated? Does it use the most appropriate technology? How can it be simplified? Are there unnecessary steps in the process that might be eliminated without detracting from function? Some of the ten strategies for automation and process improvement (Section 1.4.2) can help simplify the process. Can steps be combined? Can steps be performed simultaneously? Can steps be integrated into a manually operated production line?

Automate the Process

Once the process has been reduced to its simplest form, then automation can be considered. The possible forms of automation include those listed in the ten strategies discussed in the following section. An automation migration strategy (such as the one in Section 1.4.3) might be implemented for a new product that has not yet proven itself.

1.4.2 Ten Strategies for Automation and Process Improvement

Applying the USA Principle is a good approach in any automation project. As suggested previously, it may turn out that automation of the process is unnecessary or cannot be cost justified after the process has been simplified.

If automation seems a feasible solution to improving productivity, quality, or other measure of performance, then the following ten strategies provide a road map to search for these improvements. These ten strategies were originally published in the author's first book.3 They seem as relevant and appropriate today as they were in 1980. They are referred to as strategies for automation and process improvement because some of them are applicable whether the process is a candidate for automation or just for simplification.

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 specialization of labor, 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. This is accomplished by performing more than one operation at a given machine, thereby reducing the number of separate machines needed. Since each machine typically involves a setup, setup time can usually be saved by this strategy. Material handling effort, nonoperation time, waiting time, and manufacturing lead time are all reduced.

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 work part, thus reducing total processing time.
4. **Integration of operations.** This strategy involves linking 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 work centers 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 shops and medium-volume situations by using the same equipment for a variety of parts or products. It involves the use of programmable or flexible automation. Prime objectives are to reduce setup time and programming time for the production machine. This normally translates into lower manufacturing lead time and less work-in-process.

6. **Improved material handling and storage.** A great opportunity for reducing nonproductive time exists in the use of automated material handling and storage systems. Typical benefits include reduced work-in-process, shorter manufacturing lead times, and lower labor costs.

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 the 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 can be improved.

9. **Plant operations control**. Whereas the previous strategy is concerned with the control of individual manufacturing processes, 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 involves a high level of computer networking within the factory.

10. **Computer-integrated manufacturing (CIM).** Taking the previous strategy one level higher, CIM involves extensive use of computer systems, databases, and networks throughout the enterprise to integrate the factory operations and business functions.

The ten strategies constitute a checklist of possibilities for improving the production system through automation or simplification. They should not be considered mutually exclusive. For most situations, multiple strategies can be implemented in one improvement project.

1.4.3 Automation Migration Strategy

Owing to competitive pressures in the marketplace, a company often needs to introduce a new product in the shortest possible time. As mentioned previously, the easiest and least expensive way to accomplish this objective is to design a manual production method, using a sequence of workstations operating independently. The tooling for a manual method can be fabricated quickly and at low cost. If more than a single set of workstations is required to make the product in sufficient quantities, as is often the case, then the manual cell is replicated as many times as needed to meet demand. If the product turns out to be successful, and high future demand is anticipated, then it makes sense for the company to automate production. The improvements are often carried out in phases. Many companies have an automation migration strategy, that is, a formalized plan for evolving the manufacturing systems used to produce new products as demand grows. A typical automation migration strategy is the following:

Phase 1:

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

Phase 2:

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. Work units are still moved between workstations manually.

Phase 3:

Automated integrated production using a multi-station 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.

This strategy is illustrated in the below figure. Details of the automation migration strategy vary from company to company, depending on the types of products they make and the manufacturing processes they perform. But well-managed manufacturing companies have policies like the automation migration strategy. There are several advantages of such a strategy:

• It allows introduction of the new product in the shortest possible time, since production cells based on manual workstations are the easiest to design and implement.
• It allows automation to be introduced gradually (in planned phases), as demand for the product grows, engineering changes in the product are made, and time is provided to do a thorough design job on the automated manufacturing system.
• It avoids the commitment to a high level of automation from the start because there
is always a risk that demand for the product will not justify it.

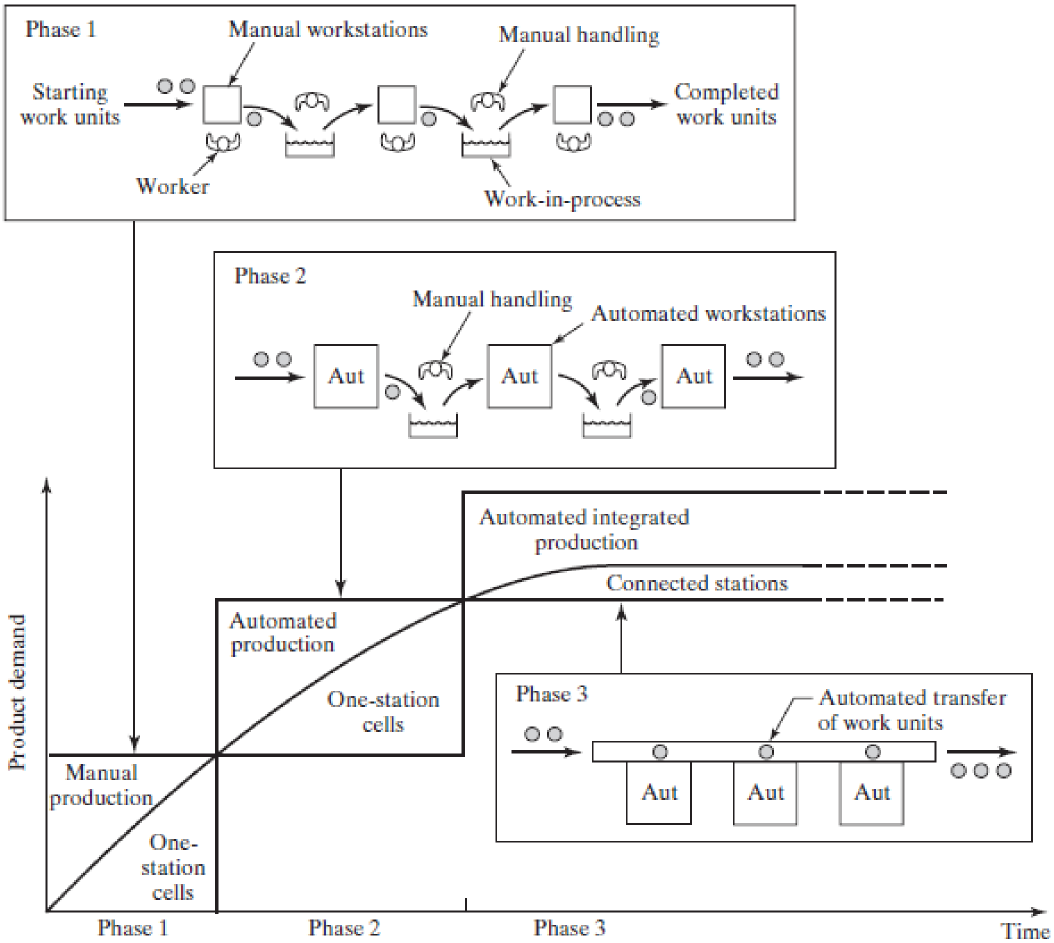


Figure: A typical automation migration strategy. Phase 1: manual production with single independent workstations. Phase 2: automated production stations with manual handling between stations. Phase 3: automated integrated production with automated handling between stations.
Key: Aut = automated workstation.

1.5 Various Kinds of Manufacturing Operations

There are certain basic activities that must be carried out in a factory to convert raw materials into finished products. For 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 ensure high quality. It is sometimes argued that material handling and inspection activities do not add value to the product. However, material handling and inspection may be required to accomplish the necessary processing and assembly operations, for example, loading parts into a production machine and assuring that a starting work unit is of acceptable quality before processing begins.

1.5.1 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. Figure below shows a classification of manufacturing processes and how they divide into various categories.

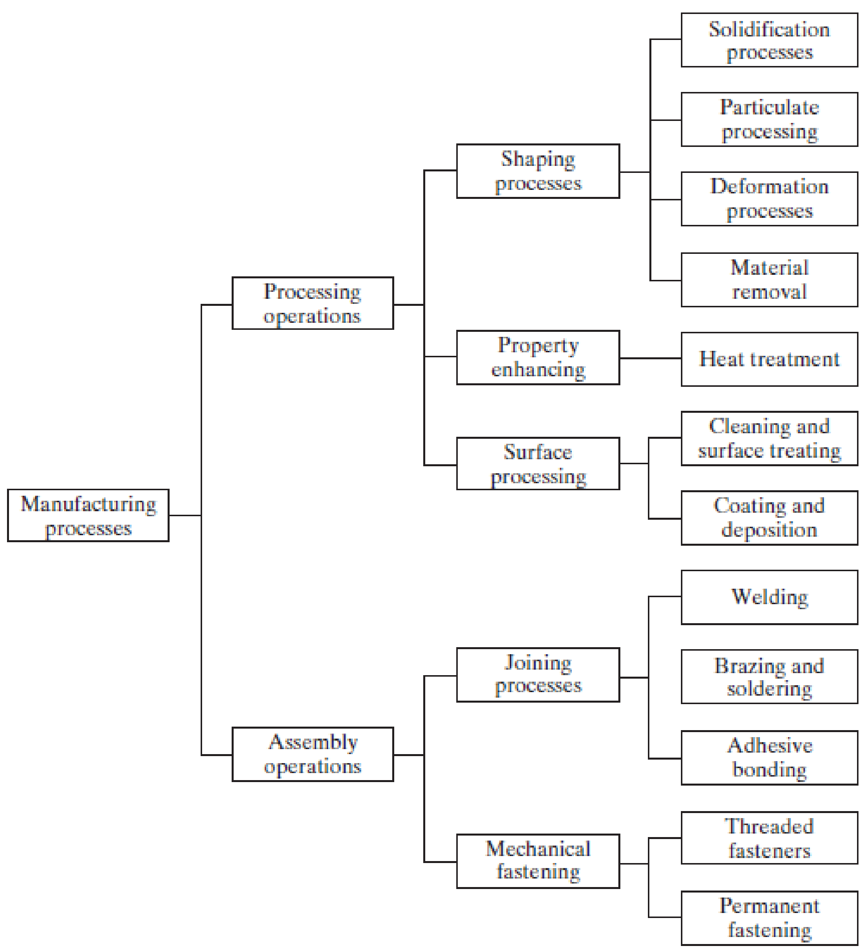


Figure: Classification of manufacturing processes.

1.5.2 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.
Moving and storing materials between processing and/or assembly operations are usually required. In most manufacturing plants, materials spend more time being moved and stored than being processed. In some cases, most 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. Part III of this book considers 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 being processed. 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 non-processing time. These time proportions indicate the significance of material handling and storage in a typical factory.

Inspection and Testing.
Inspection and testing 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. Part V of the text examines inspection and testing.

Coordination and Control.
Coordination and control in manufacturing include both the regulation of individual processing and assembly operations and 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 II of the book. Control at the plant level includes effective use of labor, maintenance of the equipment, moving materials in the factory, controlling inventory, shipping products of good quality on schedule, and keeping plant operating costs to a minimum. 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.

1.6 Manufacturing Economics

Previously, manufacturing was defined as a transformation process that adds value to a starting material. The current topic expands on this definition by considering several metrics. Successful manufacturing companies use metrics to manage their operations. Quantitative metrics allow a company to estimate part and product costs, track performance in successive periods (e.g., months and years), identify problems with performance, and compare alternative methods. Manufacturing metrics can be divided into two basic categories:

(1) Production performance measures
(2) Manufacturing costs.

Metrics that indicate production performance include production rate, plant capacity, equipment availability (a reliability measure), and manufacturing lead time. Manufacturing costs that are important to a company include labor and material costs, overhead costs, the cost of operating a given piece of equipment, and unit part and product costs.

1.6.1 Production performance measures

In this section, various metrics of production performance are defined. The logical starting point is the cycle time for a unit operation, from which the production rate for the operation is derived. These unit operation metrics can be used to develop measures of performance at the factory level: production capacity, utilization, manufacturing lead time, and work-in-process.

Cycle Time and Production Rate

As described in the introduction, manufacturing is almost always carried out as a sequence of unit operations, each of which transforms the part or product closer to its final form as defined by the engineering specifications. Unit operations are usually performed by production machines that are tended by workers, either full time or periodically in the case of automated equipment. In flow-line production (e.g., production lines), unit operations are performed at the workstations that comprise the line.

Cycle Time Analysis. For a unit operation, the cycle time *Tc* is the time that one work unit1 spends being processed or assembled. It is the time interval between when one work unit begins processing (or assembly) and when the next unit begins. *Tc* is the time an individual part spends at the machine, but not all of this is processing time. In a typical processing operation, such as machining, *Tc* consists of (1) actual processing time, (2) work part handling time, and (3) tool handling time per workpiece. As an equation, this can be expressed as:

$$Tc = To + Th + Tt$$

Where *Tc* = cycle time, min/pc.
To = time of the actual processing or assembly operation, min/pc.
Th = handling time, min/pc; and
Tt = average tool handling time, min/pc,

If such an activity is applicable. In a machining operation, tool handling time consists of time spent changing tools when they wear out, time changing from one tool to the next, tool indexing time for indexable inserts or for tools on a turret lathe or turret drill, tool repositioning for a next pass, and so on. Some of these tool handling activities do not occur every cycle; therefore, they must be apportioned over the number of parts between their occurrences to obtain an average time per workpiece.

Each of the terms, *To*, *Th*, and *Tt*, has its counterpart in other types of discrete-item production. There is a portion of the cycle when the part is being processed 1*To*2; there is a portion of the cycle when the part is being handled 1*Th*2; and there is, on average, a portion when the tooling is being adjusted or changed 1*Tt*2. Accordingly, Equation (3.1) can be generalized to cover most processing operations in manufacturing.

Production Rate. The production rate for a unit production operation is usually expressed as an hourly rate, that is, work units completed per hour 1pc/hr2. Consider how the production rate is determined based on the operation cycle time for the three types of production: job shop production, batch production, and mass production.

In job shop production, quantities are low (1to Q *to*100). At the extreme low end of the range, when quantity Q = 1, the production time per work unit is the sum of setup and cycle times:

$$Tp = Tsu + Tc \quad (3.2)$$

where Tp = average production time, min/pc; Tsu = setup time to prepare the machine to produce the part, min/pc; and Tc = cycle time from Equation (3.1). The production rate for the unit operation is simply the reciprocal of production time, usually expressed as an hourly rate:

$$Rp = 60/Tp$$

where Rp = hourly production rate, pc/hr; Tp = production time from Equation (3.2), and the constant 60 converts minutes to hours. When the production quantity is greater than one, the analysis is the same as in batch production.

1.6.2 Manufacturing costs.

Decisions on automation and production systems are usually based on the relative costs of alternatives. This section examines how these costs and cost factors are determined.

Fixed and Variable Costs

Manufacturing costs can be classified into two major categories: (1) fixed costs and (2) variable costs. A ***fixed cost*** is one that remains constant for any level of production output. Examples include the cost of the factory building and production equipment, insurance, and property taxes. All the fixed costs can be expressed as annual amounts. Expenses such as insurance and property taxes occur naturally as annual costs. Capital investments such as buildings and equipment can be converted to their equivalent uniform annual costs using interest rate factors. A ***variable cost*** is one that varies in proportion to production output. As output increases, variable costs increase. Examples include direct labor, raw materials, and electric power to operate the production equipment. The ideal concept of variable cost is that it is directly proportional to output level. Adding fixed and variable costs results in the following total cost equation:

$$TC = Cf + CvQ$$

where TC = total annual cost, \$/yr; Cf = fixed annual cost, \$/yr; Cv = variable cost, \$/pc; and Q = annual quantity produced, pc/yr.

Direct Labor, Material, and Overhead

Fixed versus variable are not the only possible classifications of costs in manufacturing. An alternative classification separates costs into (1) direct labor, (2) material, and (3) overhead. This is often a more convenient way to analyze costs in production.

Direct labor cost is the sum of the wages and benefits paid to the workers who operate the production equipment and perform the processing and assembly tasks.

Material cost is the cost of all raw materials used to make the product. In the case of a stamping plant, the raw material consists of the sheet stock used to make stampings. For the rolling mill that made the sheet stock, the raw material is the starting slab of metal out of which the sheet is rolled. In the case of an assembled product, materials are the component parts, some of which are produced by supplier firms. Thus, the definition of “raw material” depends on the company and the type of production operations in which it is engaged. The final product of one company can be the raw material for another company. In terms of fixed and variable costs, direct labor and material must be considered as variable costs.