12. Automated Manufacturing Systems

12.1 Introduction

Manufacturing systems consist of human workers, automation, and various material handling technologies, configured in ways that create specific manufacturing system typologies. More specifically, a manufacturing system is 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. Our focus in this unit is upon manufacturing systems that are said to be automated, and so concentration will be put upon the types of integrated equipment that is used and arranged in a manufacturing cell. This can range from production machines and tools, material handling and work positioning devices, to the use of various computer systems that facilitate automation in the production environment.

KEYPOINT
A manufacturing system is 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.

END KEYPOINT

The manufacturing system is where value-added work is performed to parts and/or products, and this activity gives manufacturing a central place in the overall scheme of the system of production, where it is supported by systems of manufacturing support, quality control, material handling, and automation control. Different types of manufacturing systems may be identified. These include:

BULLETLIST
Single station cell—one worker tends one production machine that operates on semi-automatic cycle
Machine cluster—one worker tends a group of semi-automated machines

Manual assembly line—consists of a series of workstations at which assembly operations are performed to build gradually a product, such as an automobile

Automated transfer line—production line consisting of a series of automated workstations that perform processing operations such as machining, with transfer of parts between workstation also being automated

Automated assembly system—performs a sequence of automated or mechanized assembly operations

Machine cell—a series of manually-operated production machines and workstations, often in a U-shaped configuration, which performs a sequence of operations on a family of parts or products that are similar but not identical; also known as cellular manufacturing (See Figure 12.1).

Flexible manufacturing system (FMS)—a highly automated machine cell that produces part or product families; often consists of workstations comprising CNC machine tools

Figure 12.1: Machine Cluster (Robotic Spot Welding Line)

KEYPOINT
Different types of manufacturing systems may be identified; these include: single station cells; machine clusters; manual assembly lines; automated transfer lines; automated assembly systems; machine cells (cellular manufacturing); and flexible manufacturing systems (FMS).

END KEYPOINT
In this unit a general overview of these manufacturing types is offered by describing their common components and features, plus by supplying a classification scheme. Single-station manufacturing cells, which are the most common manufacturing system in industry, are described. This leads to an analysis of single-station manned workstations and automated cells; as well as a consideration of single-station cell applications, and an in-depth analysis of single-station systems.

12.2 Learning Objectives

After completing this unit you should be able to:

BULLET LIST
Define what is meant by a manufacturing system
Specify the general material handling processes that may be distinguished
List the types of work transport to be encountered, and the equipment used to carry it out
Explain what computer functions are utilised in automated manufacturing
Describe why the number of workstations has an impact upon the type of manufacturing system implemented
Explain why workstation layout is an important consideration in the manufacturing system
Define what is meant by the manning level of a workstation, and list the levels themselves for single and multi-station systems
Specify the importance of part or product variety for manufacturing systems
Describe single- and multi-station systems
List the enablers for unattended cell operation
Calculate the length of time that the automated cell can theoretically operate unattended
Determine the number of workstations that are required in a system
Define a machine cluster
ENDLIST
### 12.3 Components of a Manufacturing System

A manufacturing system consists of the following components: production machines (plus tools, fixtures, and other related hardware); a material handling system; a computer system to co-ordinate and/or control the preceding components; and human workers to operate and manage the system.

**KEYPOINT**
A manufacturing system consists of the following components: production machines (plus associated tooling); a material handling system; a computer system for co-ordination and/or control; and human workers.

**END KEYPOINT**

#### 12.3.1 Production Machines

Most manufacturing in modern-day manufacturing systems is done by machines of one form or another. Machines can be classified according to worker participation in the task, as: manually-operated; semi-automated; or fully automated. These three types are outlined in Table 12.1.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manually operated machines</td>
<td>Controlled or supervised by a worker or operator, there is a clear division of labour, whereby the machine provides the power for the operation and the worker provides the control. Conventional machine tools (such as lathes, milling machines, drill presses etc.) fit this category. The worker must attend the machine continuously during the work cycle.</td>
</tr>
<tr>
<td>Semi-automated machines</td>
<td>This performs a portion of the work cycle under programme control, and then a worker assumes control for the remainder of the cycle. An example of a machine in this capacity is a CNC lathe, where the CNC machine performs its processing operation as per the programme, and then the worker unloads and reloads the machine for the next work cycle. The worker must attend the machine every cycle, but need not be continuously present.</td>
</tr>
<tr>
<td>Fully automated machines</td>
<td>This has the capability to operate with no human attention for periods of time that are longer than one work cycle. Some form of machine tending will be required periodically, however; for example, to replenish the machine with raw material etc.</td>
</tr>
</tbody>
</table>
Machines can be classified according to worker participation in the task, as: manually-operated; semi-automated; or fully automated.

A workstation refers to the 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 power tools. A particular manufacturing system may consist of one or more workstations.

12.3.2 Material Handling System

For most processing and assembly operations the following material handling actions can be distinguished: loading work units at each station; positioning work units at the station; unloading work units from the station after processing; transporting work units between stations; and performing temporary storage, if necessary, also. Some of these actions are linked so that the same machinery may be used to perform the actions (for example, many load and unload actions); whereas other actions are specialised and require their own equipment. These specialities are discussed later; here we focus upon more general material handling issues.

The following material handling actions may be distinguished: loading work units at each station; positioning work units at the station; unloading work units from the station after processing; transporting work units between stations; and performing temporary storage, if necessary, also.

Loading, positioning, and unloading work units are a group of actions that are regularly performed together at individual workstations. These groups of actions may be manual, semi-automated (where the operator is assisted by some material handling devices), or fully-automated (where the material handling system takes full control of material handling, without operator assistance). In loading the workstation is supplied with the correct type and amount of work units so that the processing operation can be performed; positioning requires the work unit to be oriented or located correctly within the processing machine, so that the
processing action can be performed upon the work unit accurately; while unloading involves the removal of the processed work units from the workstation, often for further material handling processes to occur.

For loading, work units are often held in containers near the workstation, such as pallets, totes, or bins, which can be accessed according to requirements. Positioning requires the use of a work-holder (such as a jig, fixture, or chuck), a device which helps to support the positioning operation in the processing machine; it accurately locates, orients, and clamps the part so that the processing operation may proceed. In unloading work units are either placed in containers or transported away from the workstation to other processing workstations, or to storage. In some cases, a conveyor system may be used to transport work units between workstations.

**KEYPOINT**
Loading, positioning, and unloading work units are a group of material handling actions that are regularly performed together at individual workstations, and, as such, may be considered together.

**END KEYPOINT**

Work units may be passed between workstations by hand or in batches, by means of manual techniques or by using appropriate material transport systems. The movement of work units in batches is generally considered to be the most efficient method, according to the Unit Load Principle; but manual material transport may be favoured in situations where work units are small and light, and where manual transport is considered to be ergonomically acceptable. When work units exceed certain weight standards, manual transport with assistance from material handling devices (such as lift equipment) may be deployed; and, beyond these categories, manufacturers may favour fully-automating the whole material transport system.

**KEYPOINT**
Material transport systems involve passing work units between workstations by hand or in batches, by means of manual techniques or by using appropriate material transport systems.

**END KEYPOINT**

There are, in general, two types of work transport: fixed routing, and variable routing (see Figure 12.2). Fixed routing uses the same sequence of workstations to process identical work units as they passed through the system; whereas, with variable routing, work units are transported through a variety of different station sequences to allow for variable processing to be performed on transported work units. Both work types emphasise different types of automated material handling equipment. Fixed routing typically deploys conveyors of powered roller, belt, drag chain, or overhead trolley type, and can use rotary index mechanisms, and walking beam transfer equipment. For variable routing an automated guided
vehicle system is favoured, together with power-and-free overhead conveyors, or cart-on-track conveyors, or monorail systems.

![Diagram of work transport system](image)

**KEYPOINT**

There are two types of work transport, fixed routing and variable routing.

**END KEYPOINT**

Pallets may also be used in the material transport system, if it is designed in such a way that it can accommodate a pallet fixture—a specialised work-holder explicitly designed for positioning and clamping pallets to the material transport system. The work unit is positioned and attached to the pallet’s upper-side, while the pallet’s lower portion is moved and positioned at each workstation as required. Since the work unit is carefully positioned on the pallet, and the pallet fixture is designed accurately to present the pallet at all workstations, the resultant movement will see the work unit correctly positioned at each workstation for processing.

Alternative methods may or may not use work carriers such as pallet fixtures. A work carrier is some sort of container that holds one or more work units and can be moved in the system. Unlike pallet fixtures, their main function is work unit transport, not work unit orientation; that is, work units are carried loosely and are not clamped into exact positions by positioning devices in work carriers. Positioning is generally done when the work unit reaches a particular workstation.

Direct transport may also be used. This involves designing the transport system to move the work unit itself. This has obvious advantages over work carriers and
pallet fixtures, which have to be specially-designed and are expensive, and it is an option that is available both for manual and automated material handling systems. For manual systems direct transport simply involves the use of operators to move work units from one workstation to another, and to position the work units for processing once there. For automated systems, issues of workpart geometry and processing accuracy must be considered, as—generally—the more precise the work transport system must be, the more difficult it is to design, and the more expensive the resultant design turns out to be. The automated material method must be capable of moving, locating, and clamping the workpart with sufficient precision and accuracy. Not all part shapes allow these actions to occur easily, and so in some cases automated direct transport will not be feasible.

KEYPOINT
Workpart transport can be accomplished by means of pallet fixtures, work carriers, or direct transport.
END KEYPOINT

12.3.3 Computer Control System

Computer systems are an integral part of automated manufacturing, as they are required to control fully-automated and semi-automated equipment and participate in overall co-ordination and management of the manufacturing system. Typical computer functions are outlined in Table 12.2.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communicate instructions to workers</td>
<td>Operators must receive the appropriate work instructions for work units that they are processing at manual workstations</td>
</tr>
<tr>
<td>Download workpart programmes</td>
<td>All computer-controlled machines are operated by programmes that are sent to it by the computing system</td>
</tr>
<tr>
<td>Control material handling system</td>
<td>Workstation availability and material handling system status must be co-ordinated in order to ensure efficient processing of work units in transit</td>
</tr>
<tr>
<td>Schedule production</td>
<td>Certain production scheduling functions may be accomplished at the site of the manufacturing system</td>
</tr>
<tr>
<td>Diagnose failures</td>
<td>Diagnostics of equipment, the preparation of preventative maintenance schedules, and the maintenance of the spare parts inventory</td>
</tr>
<tr>
<td>Monitor safety</td>
<td>The maintenance of the system to ensure it only operates in a safe manner</td>
</tr>
<tr>
<td>Maintain quality control</td>
<td>This involves the detection and rejection of work units that are effective in the work system</td>
</tr>
<tr>
<td>Manage operations</td>
<td>Managing the overall operations of the manufacturing system, either directly via supervisory control, or indirectly via the production of periodic reports</td>
</tr>
</tbody>
</table>

KEYPOINT
Computer functions utilised in automated manufacturing include: the communication of instructions to workers; the downloading of workpart programmes; the control of the material handling system; the scheduling of production; the diagnosis of failures; the monitoring of safety; the maintenance of quality control; and the management of operations.

**END KEYPOINT**

### 12.3.4 Human Resources

Humans also have a role to play, even if it is only in a supervisory capacity. In cases where humans perform some value-added work on work units, the work done is called direct labour—that is, physical labour that results in an increase in value of the processed work unit. This generally includes direct work done on work units or work done to control the machines that are processing the workpart. Human workers are also required to: manage and support the system as computer programmers; operate and direct computer activities; maintain and repair the automated manufacturing system, as required; and the performance of other, similar, indirect labour roles.

**KEYPOINT**
Humans supply direct and indirect labour to automated manufacturing systems.

**END KEYPOINT**

### 12.4 Classification of Manufacturing Systems

Various types of manufacturing systems can be created from a consideration of different entities that have an impact upon manufacturing system design. These considerations include: types of operations performed; number of workstations; system layout; automation and manning level; and product or part variety. These considerations are outlined in detail in the following sub-sections.

#### 12.4.1 Types of operations performed

At the highest level operational types include processing operations on individual work units, and assembly operations to combine individual work parts into sub-assemblies, or full assemblies. Additional parameters include:

- **BULLETLIST**
  - Type of material processed—different materials require different methods to process them
  - Size or weight of the part or product—this has a significant influence on the type, scope, and scale of manufacturing equipment chosen to process the item
Part or product complexity—part complexity correlates with the number of processing operations required, while product complexity refers to the number of components that must be assembled.

Part geometry—machined parts are rotational or non-rotational, which has a significant effect on the processing machine operations that can be performed on the parts, plus the material handling system must be designed in an appropriate fashion for rotational and non-rotational parts.

**KEYPONT**
Operational types include processing operations on individual work units, and assembly operations to combine individual work parts into sub-assemblies, or full assemblies.

**END KEYPOINT**

### 12.4.2 Number of Workstations

The number of workstations in a manufacturing system exerts a strong influence on the performance of the manufacturing system, in terms of its workload capacity, production rate, and reliability. The number of workstations is a good measure of the size of the manufacturing system; the more workstations it has, the bigger it is generally found to be. As the number of workstations increases, the more work can be performed by the system, which may translate into a higher production rate than if a number of single workstation systems were deployed concurrently. The use of multiple workstations can also produce a synergistic benefit, when compared against single workstation systems, as the total amount of work performed on the part or product is too complex to accomplish at a single workstation; instead the task is divided among a multiple of stations, thus simplifying the complexity of the task into simpler work elements.

However, the more workstations developed in a system generally means that the system itself becomes more complex, and harder to manage and maintain. The system consists of more workers, machines, and parts to be handed. Material handling also increases in complexity and problems of logistics and system coordination begin to be felt. Reliability and maintenance problems also begin to surface on a more frequent basis.

**KEYPOINT**
The number of workstations in a manufacturing system exerts a strong influence on the performance of the manufacturing system, in terms of its workload capacity, production rate, and reliability.

**END KEYPOINT**
12.4.3 System Layout

System configuration, or the layout of the manufacturing system’s workstations, is also an important factor. This applies mainly, of course, to systems with multiple workstations. Workstation layouts for fixed routing are usually arranged linearly, as in a production line, while variable routing layouts can have multiple configurations. System layout is an important factor for the design of the material handling system.

If we consider the number workstations (where number of workstations may be depicted by \( n \)) against system layout, we can determine the workload of the system, which is defined as 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. The workload capacity of a manufacturing system increases in proportion to the number of workstations in it.

Since the overall work to be done is divided into a number of simplified work tasks, each performed at a different workstation, this explains why a multi-system manufacturing system with \( n \) workstations has the workload advantage over \( n \) single stations that operate concurrently. Generally the single workstation would find the total work content to be done to be too complex to be performed with the same efficiency as the multiple workstation system, which has divided the work into tasks. This is the synergistic benefit referred-to in §12.4.2 earlier.

KEYPOINT
System configuration, or the layout of the manufacturing system’s workstations, is also an important factor. Workstation layouts for fixed routing are usually arranged linearly, as in a production line, while variable routing layouts can have multiple configurations.
END KEYPOINT

12.4.4 Automation and Manning Levels

The level of automation deployed is an important characteristic of the manufacturing system. Workstation machines may be manually-operated, semi-automated, or fully-automated. This factor allows us to define the amount of time that a human operator is required to be in attendance at a workstation as the manning level \( (M_i) \) of the workstation (where \( i \) denotes a particular workstation in the system). The average manning level of a multi-station manufacturing system is given by:
where \( M \) is the average manning level for the system; \( w_u \) is the number of utility workers assigned to the system; \( w_i \) is the number of workers assigned specifically to station \( i \), for \( i = 1, 2, 3, \ldots, n \); and \( w \) is the total number of workers assigned to the system.

By including the manning level scenario into the classification, we can see that there are two levels for single station systems (manned and fully automated), and three levels for multi-station systems (manned, fully automated, and hybrid—that is where some stations are manned and others are fully automated).

**KEYPOINT**

In manufacturing systems the manning level produces two levels for single station systems (manned and fully automated), and three levels for multi-station systems (manned, fully automated, and hybrid).

**END KEYPOINT**

### 12.4.5 Part or Product Variety

This factor examines the manufacturing system’s flexibility for dealing with variations in the parts or products it produces. Part or product variations that could occur in manufacturing systems include: variations in type, or colour of plastic or moulded parts; variations in electronic components placed on circuit boards; variations in the size of printed circuit boards handled; variations in part geometry; and variations in parts and options in an assembled product. The cases of part or product variety in manufacturing systems are single model, batch model, or mixed model—the details of which are outlined in Table 12.3, and in Figure 12.3.

**Table 12.3: The cases of part/product variety in manufacturing systems**

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single model</td>
<td>All parts/products produced are identical, which means that the production system is dedicated to the production of the item in question. Equipment is specialised and designed for maximum efficiency. Fixed automation is also common.</td>
</tr>
<tr>
<td>Batch model</td>
<td>Different parts or products are made, but in batches, as changeover in physical set-up (tooling and programming) is required and/or equipment re-programming is required between models (hard product variety).</td>
</tr>
<tr>
<td>Mixed model</td>
<td>Different parts/products produced by the manufacturing system, but differences between part/product styles produced are not significant (soft product variety). The system is able to handle the changes without changeovers in physical set-up or equipment re-programming. The mixture is</td>
</tr>
</tbody>
</table>
thus produced continuously and not in batches.

**KEYPOINT**
Part or product variety examines the manufacturing system’s flexibility for dealing with variations in the parts or products it produces. The cases of part or product variety in manufacturing systems are single model, batch model, or mixed model.

END KEYPOINT

![Diagram showing cases of part or product variety in manufacturing systems: (a) single model, (b) batch model, and (c) mixed model.](image)

Figure 12.3: Cases of part or product variety in manufacturing systems: (a) single model, (b) batch model, and (c) mixed model

The creation and management of flexibility for the mixed model is also an issue. Flexibility can refer to a number of entities within the manufacturing system, including the following capabilities, which can be difficult to design concurrently: being able to identify and adapt to the requirements of different work units; being able to perform quick changeovers of operating instructions, as necessary; and being able to perform quick changeovers of physical set-ups, as required.

Single-station manned cells typically offer the greatest amount of flexibility as they possess relatively low levels of complexity, and are staffed by adaptable human personnel. However they are limited in terms of the amount of work they can perform, especially upon highly complex work units. With multi-station set-ups, routing becomes an important determinant on flexibility: fixed routing is favoured in those situations where the product is made in large quantities, with little or no product variety; alternatively, variable routing becomes favourable in situations where product variety is increased, for medium production range. The greatest amount of flexibility can probably be achieved in job shop scenarios, but these organizations offer the least amount of efficiency, and the lowest production rates of the manufacturing systems under consideration.

**KEYPOINT**
The flexible capability of the mixed model of manufacturing is an important determinant of the success of the manufacturing scheme that is adopted.

END KEYPOINT

12.5 Overview of the Classification Scheme

Here we provide an overview of the classification scheme for the three basic types of manufacturing system: (1) single-station cells; (2) multi-station systems with fixed routing; and (3) multi-station systems with variable routing. The unit then concludes with an in-depth focus upon single-station manufacturing cells, which is only perfunctorily described here.

12.5.1 Single-station Cells

Single workstations are widespread, but typically come in one of two forms: manned workstations—where a worker is in attendance continuously or for a portion of each work cycle; and automated stations—where worker attention is required less frequently than the set work cycle. Both systems are used for assembly and processing operations, and their applications fit single, batch and mixed model cases. Single-station cell systems are popular because they are relatively inexpensive to implement (especially manned versions), they are highly flexible, and they are easy to convert to automation when required. See Figure 12.4.

KEYPOINT
Single workstations come in two forms: manned workstations, and automated stations.
END EYPOINT

Figure 12.4: Single Station Cell
12.5.2 Multi-station Systems with Fixed Routing

A multi-station system with fixed routing is essentially a production line, which consists of a series of workstations laid-out so that the part/product moves from one station to the next, while a value-adding work element is performed at each workstation along the way. Material transference between workstations is usually accomplished by means of a conveyor system, or other mechanical transport system, although there are cases where material may be transferred by hand. See Figure 12.5. Conditions that favour the use of production lines include:

BULLETLIST
Part/product quantity is very high (up to millions of units)
Work units are identical, or very similar
Total work content can easily be divided into work tasks that may be performed at separate workstations
ENDLIST

Production lines are used for both processing and assembly operations, and they can be either manually operated or automated.

KEYPOINT
A multi-station system with fixed routing is a production line.
END KEYPOINT

12.5.3 Multi-station Systems with Variable Routing

A multiple-station system with variable routing is a group of workstations organised to achieve some special purpose. It usually handles medium-sized
production quantities, although it has been used for production quantities beyond this, in certain situations, such as:

**BULLETLIST**

Production of a family of parts having similar processing requirements

Assembly of a family of parts having similar assembly requirements

Production of a complete set of components that are used in the assembly of one unit of final product

**ENDLIST**

Machines may be manual, semi-automated, or fully-automated. The first two types—i.e. manually-operated and semi-automated—may be arranged into machine groups called machine cells; and it is the emergence of numbers of these cells that gives rise to cellular manufacturing. Fully-automated machines, on the other hand, may be arranged into flexible manufacturing systems. See Figure 12.6.

**KEYPOINT**

A multiple-station system with variable routing is a group of workstations organised to achieve some special purpose.

**END KEYPOINT**

![Figure 12.6: Multi-station System with Variable Routing](image)

**12.6 Single Station Manned Workstations**
As single stations are the most used type of manufacturing system in contemporary industry, we shall focus upon their features and operations in the following sections and sub-sections.

Single-station manufacturing cells can be manual or automated, and can be used for either processing or assembly; they can be designed for single model production, batch production, or mixed model production. The most common type of single-station manufacturing cell is the single-station manned cell, consisting of one worker tending one machine; it is found throughout job shop and batch production environments, and is found even in high production scenarios. Its popularity is owing to:

BULLETPROBE
Quick set-up and maintenance requirements

Its relative inexpensiveness

It often represents the lowest cost set-up per unit produced

Its flexibility in the face of changeovers from one part style to another

ENDPROBE

KEYPOINT
The single-station manned cell is the most popular type of single-station manufacturing cell owing to its flexibility, cost-effectiveness, and relatively quick set-up and maintenance characteristics.

END KEYPOINT

In the single-station manufacturing cell the machine is usually manually or semi-operated. In the manually operated station the operator controls the machine, loads and unloads the work, and monitors the work cycle either continuously or for most of the cycle time. It may also require the operator to use a variety of work tools, such as screwdrivers, wrenches, or portable powered tools etc., to perform additional processes in the cell. All work tasks are performed at one station (one location) in the factory. In the semi-automated station the machine is controlled by a part programme, leaving the operator free to perform additional tasks, such as loading and unloading the machine, performing tool maintenance, and controlling changeovers. Typically operators’ attention would be required at the end of every work cycle, and not necessarily on a continual basis.

KEYPOINT
The machines in single-station manufacturing cells are usually manually or semi-operated.

END KEYPOINT

Variations from the standard single-station manufacturing cell include:
Where two or more workers are required to operate the machine fulltime to accomplish the work task.

Where the principal production machinery is augmented by auxiliary machines in the manufacturing cell.

### 12.7 Single-Station Automated Cells

The single-station automated cell consists of a fully automated machine that can operate unattended for a time period longer than one machine cycle. The operator must load and unload the machine, and otherwise tend it, but is not required to be at the machine except periodically. See Figure 12.7. Advantages of single-station automated cells include:

- **Reduced labour costs**
- Relatively inexpensive to implement and maintain compared to other automated manufacturing system types
- Production rates are higher than manned machines
- It can represent the first step towards implementing an integrated multi-station automated system

Auxiliary equipment and supporting machines may also be found in single-station automated cells.

**KEYPOINT**

The single-station automated cell consists of a fully automated machine that can operate unattended for a time period longer than one machine cycle.

**END KEYPOINT**
12.7.1 Enablers for Unattended Cell Operation

Two categories of enablers can be deduced, one for unattended single model and batch model production, and one for mixed model production. The enablers for single model and batch model production are given in Table 12.4.

Table 12.4: Enablers of unattended cell operation in single model and batch model production

<table>
<thead>
<tr>
<th>Enabler</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Programmed cycle</td>
<td>This allows the machine to operate automatically</td>
</tr>
<tr>
<td>Parts storage subsystem</td>
<td>This allows for a continuous supply of parts beyond the operation of one machine cycle.</td>
</tr>
<tr>
<td>Automatic transfer of work parts</td>
<td>This occurs between the storage system and the machine, and must be in place to ensure an automatic and regular feed of parts as necessary</td>
</tr>
<tr>
<td>Periodic attention of worker</td>
<td>This is required to load/unload machine, change tools as they wear, and performs supporting maintenance and service operations</td>
</tr>
<tr>
<td>Built-in safeguards</td>
<td>These protect the system from operating conditions that are unsafe for workers, self-destructive, or destructive to the work units being processed</td>
</tr>
</tbody>
</table>

The enablers for mixed model production are recounted in Table 12.5; these are additional enablers required because of the unique traits of mixed model production.

Table 12.5: Enablers of unattended cell operation in mixed model production

<table>
<thead>
<tr>
<th>Enabler</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work identification subsystem</td>
<td>Required so that the system can distinguish the part style currently being processed. Usually in sensor form, so that they can distinguish part features on work units.</td>
</tr>
<tr>
<td>Programme downloading</td>
<td>This is needed so that the machine can change to the</td>
</tr>
<tr>
<td>capability</td>
<td>machine cycle programme that corresponds to the part or product currently being processed.</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Quick set-up changeover capability</td>
<td>This is required so the system can change to processing different part styles, as necessary</td>
</tr>
</tbody>
</table>

**KEYPOINT**

Enablers for unattended cell operation include (for all models): a programmed cycle, a parts storage subsystem, the automatic transfer of work parts, periodic attention of worker, and built-in safeguards; and (for mixed models): a work identification subsystem; a programme downloading capability; and a quick set-up changeover capability.

**END KEYPOINT**

### 12.7.2 Parts Storage Subsystem and Automatic Parts Transfer

The automated cell can theoretically operate unattended for a length of time given by:

$$ UT = \sum_{j=1}^{n_p} T_{cj} $$

where $UT$ is the unattended time of the operation of the manufacturing cell; $T_{cj}$ is the cycle time for part $j$ that is held in the parts storage subsystem, for $j = 1, 2, 3, \ldots, n_p$, where $n_p$ is the parts storage capacity of the storage subsystem, pc. This equation assumes that a work unit is processed each work cycle, and—if all of the parts are identical and require the same machine cycle—we can further simplify the equation to:

$$ UT = n_p T_c $$

In reality the unattended time will be less than this amount; this is because the worker will need time to completely unload and to reload the machine for the start of the next work cycle.

**KEYPOINT**

The length of time that the automated cell can theoretically operate unattended can be calculated by considering storage capacity and the cycle time of the automated cell in question.

**END KEYPOINT**
Generally, the time of unattended operation increases directly with storage capacity, so this should be taken into consideration in automated cell design. The objectives of designing sufficient storage capacity include:

**BULLETLIST**
- Allowing a fixed time interval for an operator to tend a number of machines
- Scheduling time to allow for multiple tool changes during the same machine downtime
- Allowing a time period of one complete shift to occur
- To allow for unattended, over-night operation

**ENDLIST**

The minimum storage capacity of a parts storage system is one workpart. When the storage capacity is only one workpart, this usually means that the operator must be in full-time attendance. The overall cycle time of the single station with no storage is:

\[
T_c = T_m + T_s
\]

where \(T_c\) is the overall cycle time; \(T_m\) is the machine processing time; and \(T_s\) is the worker service time, typically required to load/unload the machine, or other tending duties. The overall cycle time of the single station with one part storage is:

\[
T_c = \text{Max}\{T_m, T_s\} + T_r
\]

where \(T_r\) is the repositioning time to (1) move the completed workpart away from the machine workhead, and (2) to replace and position the next workpart in its stead. Machine utilization is high if the worker service time is less than the machine processing time; if, on the other hand, the machine processing time is less than the worker service time, then the machine will go through periods of forced idleness. This should be avoided.

**KEYPOINT**
The time of unattended operation increases directly with storage capacity.

**END KEYPOINT**

In scenarios where the storage capacity is greater than one workpart, unattended operation is feasible when load/unload tasks are accomplished in less time than the machine processing time. Table 12.6 depicts several possible designs of parts storage subsystems for CNC machining centres.


<table>
<thead>
<tr>
<th>Type</th>
<th>Depiction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic pallet changer with pallet</td>
<td><img src="image1.png" alt="Diagram" /></td>
</tr>
<tr>
<td>holders arranged radially, and parts</td>
<td></td>
</tr>
<tr>
<td>storage capacity equal to five</td>
<td></td>
</tr>
<tr>
<td>In-line shuttle cart system with pallet</td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td>holders along its length, and parts</td>
<td></td>
</tr>
<tr>
<td>storage capacity equal to sixteen</td>
<td></td>
</tr>
<tr>
<td>Pallets held on indexing table, and parts</td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td>storage capacity equal to six</td>
<td></td>
</tr>
<tr>
<td>Parts storage carousel with parts</td>
<td><img src="image4.png" alt="Diagram" /></td>
</tr>
<tr>
<td>storage capacity equal to twelve</td>
<td></td>
</tr>
</tbody>
</table>

**KEYPOINT**

If storage capacity is greater than one workpart, unattended operation is feasible when load/unload tasks are accomplished in less time than the machine processing time. This often requires innovative parts storage system design.
12.8 Applications of Single-Station Cells

Examples of manned single station cells include:

BULLETLIST
A CNC centre producing identical parts, with an operator required to load and unload parts as the processing programme is completed by the machine

A CNC centre producing non-identical parts, with an operator required to load new part programmes as necessary

A cluster of two CNC turning centres, each producing the same part, but operating independently. A single worker attends to both machines.

An assembly workstation where an operator performs mechanical assembly of a simple product (or sub-assembly) from components located in tote bins at the station

Examples of single-station automated cells include:

BULLETLIST
A CNC machining centre complete with parts carousel and automatic pallet changer producing identical parts

A CNC machining centre complete with parts carousel and automatic pallet changer producing non-identical parts. In this case the appropriate part programme is downloaded automatically as necessary

An automated insertion machine assembling electronic components onto printed circuit boards in a batch operation

A robotic assembly cell with one robot assembling a simple product or sub-assembly

Numerous examples of both manned and automated single-station cells can be given, right across the manufacturing environmental spectrum.
12.9 Analysis of Single-Station Systems

In our analysis here we can determine:

NUMLIST

The number of single stations required to satisfy specified production requirements

The number of machines to assign to a worker in a machine cluster

ENDLIST

12.9.1 Number of Workstations Required

We must determine how many workstations are required, given a certain production rate, or a given quantity of work units. This is generally done by determining the total workload that must be accomplished over a certain period, and dividing that by the hours available on one workstation during the same period. Workload is determined thus:

\[ WL = QT_c \]

where \( WL \) is the workload scheduled for a given period; \( Q \) is the quantity to be produced during the same period; and \( T_c \) is the cycle time required per piece. If the workload includes multiple part or product styles that can all be produced on the same workstation, then:

\[ WL = \sum_j Q_j T_{cj} \]

where \( Q_j \) is the quantity of part or product style \( j \) produced during the period; and \( T_{cj} \) is the cycle time of part or product style \( j \).

We must now divide the result by the number of hours available on one workstation, thus:

\[ n = \frac{WL}{AT} \]

where \( n \) is the number of workstations; and \( AT \) is the available time on one station in the period under consideration. These equations do not take into account a number of potential complicating factors, which makes it more difficult to assess the number of workstations required; these include:

BULLETLIST
Set-up time in batch production

Availability of machines

Utilization of machines

Defect rates from various machines

ENDLIST

Example

800 parts are to be produced. Cycle time is 11.5min. Determine number of machines given 40hrs availability.

\[ WL = 800(11.5) = 9,200 \text{min} = 153.33 \text{hrs} \]
\[ AT = 40 \text{hrs} \]
\[ n = 153.33/40 = 3.83 \text{ or } 4 \text{ machines} \]

End Example

Availability time may be measured as follows, with the available time becoming the actual shift time in the period multiplied by availability and utilization:

\[ AT = H_{sh} AU \]

where \( AT \) is available time; \( H_{sh} \) is the shift hours during the period; \( A \) is availability; and \( U \) is utilization. The defect rate—that is, the fraction of parts produced that are defective—must be assessed so that it can be factored-in to the starting batch size, so that the output can compensate for defective parts produced.

Example

800 shafts are in 20 different types. Average batch size is 40. Set-up time between batches is 3.5hr.

\[ WL = 20(3.5) + 20(40)(11.5/60) \]
\[ = 70 + 153.33 = 223.33 \text{hrs} \]
\[ n = 223.33/40 = 5.58 \text{ or } 6 \text{ machines} \]

End Example

The relationship between starting quantity and actual quantity produced is:

\[ Q = Q_o(1 - q) \]
where $Q$ is the quantity of good units made in the process; $Q_o$ is the original or starting quantity; and $q$ is the fraction defect rate. This formula can be rearranged to give us the amount of starting units we require, thus:

$$Q_o = \frac{Q}{1 - q}$$

Taking these factors into consideration, we can now amend our original formula, thus:

$$WL = \frac{QT_c}{1 - q}$$

Example
Using previous data and Availability is 100% during set-up and 92% during running. Utilisation is 100%. Fraction defect rate is 5%. Determine number of machines.

For set-up:
$WL = 20(3.5) = 70.0$hrs
$AT = 40 \times (1.0)(1.0) = 40$
$n_{su} = 70/40 = 1.75$ machines

For production runs:
$WL = ((20)(40)(11.5/60)) / (1-0.05) = 161.4$hrs
$AT = 40(0.92) = 36.8$hrs per machine
$n_{pr} = 161.4 / 36.8 = 4.39$ machines
Total Machines = $1.75 + 4.39 = 6.14$ or $7$ machines
End Example

**KEYPOINT**
The number of workstations that are required is determined by the total workload that must be accomplished over a certain period, divided that by the hours available on one workstation during the same period; together with a consideration of any mitigating factors.

**END KEYPOINT**

**12.9.2 Analysis of Machine Clusters**

Sometimes opportunities exist to allow a worker to oversee more than one machine at a time, owing to the semi-automatic machine cycle of individual machines. Worker attention remains important; however not as regularly as every work cycle; instead, the worker will be required on the basis of a manning level of less than one for each workstation. This type of organisation is referred to as a
machine cell, or machine cluster, which is defined as a collection of two or more machines producing parts or products with identical cycle times and serviced by one worker. A machine cluster must satisfy several conditions in order to exist:

NUMLIST
The semi-automatic machine cycle must be long relative to the service portion of the cycle that requires the worker’s attention

The semi-automatic machine cycle time must be the same for all machines

The machines that the worker would service must be located in close enough proximity to allow time to walk between them

The work rules of the plant must permit a worker to service more than one machine
ENDLIST

If we consider a situation where we have a collection of single workstations, all producing the same parts and operating under the conditions outlined above, then we can say:

BULLETLIST
Each machine operates for a certain portion of the total cycle under its own control $T_m$ (machine time), before requiring servicing from an operator $T_s$ (service time)

The total cycle time ($T_c$) of the machine is therefore machine time plus service time; or, in equation form:

$$T_c = T_m + T_s$$

If we add another machine to the operator’s purview, then the operator will lose some time walking to this machine, called the repositioning time ($T_r$)

The total time that an operator needs to service one machine must be adjusted from simply $T_s$, to: $T_s + T_r$

We must also factor-in the time to service $n$ machines, which is: $n(T_s + T_r)$

Thus, the original equation takes the form:

$$n(T_s + T_r) = T_m + T_s$$

Further, we can determine the number of machines that should be assigned to one worker by solving:
\[ n = \frac{T_m + T_s}{T_s + T_r} \]

ENDLIST

Note that the result for \( n \) is unlikely to be an integer, so worker time in the cycle cannot be perfectly balanced with the cycle time of the machines. In reality, either the machines or the workers will experience some idle time. There arise two potential cases from this consideration:

NUMLIST
Case 1: the number of machines will be an integer greater than the value of \( n \) (call this \( n_1 \)); or

Case 2: the number of machines will be an integer less than the value of \( n \) (call this \( n_2 \)).

ENDLIST

Example
Machine shop contains number of machines with cycle time for one particular part of 2.75 min. One worker can load and unload machines in 25 sec. It takes 20 sec to walk between machines. How many machines can one worker manage if no machine idle time is allowed.

\[ T_m = 2.75 \text{min}; T_s = 25 \text{sec} = 0.4167 \text{min}; T_r = 20 \text{sec} = 0.33 \text{min} \]

\[ n_1 = \text{max integer} \leq \frac{2.75 + 0.4167}{0.4167 + 0.33} = 4.22 = 4 \text{machines} \]

End Example

The most favourable case is dependent on other factors, such as the labour cost rate \( (C_L) \) and the machine cost rate \( (C_m) \). For case 1 (where \( n_1 \leq n \)) the worker will have idle time, and the cycle time of the machine cluster will be:

\[ T_c = T_m + T_s \]

If we assume that one work unit is produced by each machine during a cycle, we have:

\[ C_{pc}(n_1) = \left( \frac{C_L}{n_1} + C_m \right) \left( T_m + T_s \right) \]
For case 2 (where $n_2 > n$) the machines will have idle time, and the cycle time of the machine cluster will be the time it takes for the worker to service the $n_2$ machines, which is:

$$n_2(T_s + T_r)$$

The corresponding cost per piece is given by:

$$C_{pc}(n_2) = \left( C_L + C_m n_2 \right) (T_s + T_r)$$

The selection of either $n_1$ or $n_2$ is based upon whichever results in the lowest cost per work unit. In the absence of precise cost data, the layout should be arranged so that any idle time is taken by the workers, and not the machines. This is because the total hourly cost rate of operating $n$ machines is larger than the labour rate of one worker. The corresponding number of machines to assign the worker is given by:

$$n_1 = \text{max int} \leq \frac{T_m + T_s}{T_s + T_r}$$

**KEYPOINT**

A machine cluster is defined as a collection of two or more machines producing parts or products with identical cycle times and serviced by one worker.

**END KEYPOINT**

### 12.10 Unit Review

**BULLETLIST**

A manufacturing system is 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.

Different types of manufacturing systems may be identified; these include: single station cells; machine clusters; manual assembly lines; automated transfer lines; automated assembly systems; machine cells (cellular manufacturing); and flexible manufacturing systems (FMS).

A manufacturing system consists of the following components: production machines (plus associated tooling); a material handling system; a computer system for co-ordination and/or control; and human workers.

Machines can be classified according to worker participation in the task, as: manually-operated; semi-automated; or fully automated.
The following material handling actions may be distinguished: loading work units at each station; positioning work units at the station; unloading work units from the station after processing; transporting work units between stations; and performing temporary storage, if necessary, also.

Loading, positioning, and unloading work units are a group of material handling actions that are regularly performed together at individual workstations, and, as such, may be considered together.

Material transport systems involve passing work units between workstations by hand or in batches, by means of manual techniques or by using appropriate material transport systems.

There are two types of work transport, fixed routing and variable routing.

Workpart transport can be accomplished by means of pallet fixtures, work carriers, or direct transport.

Computer functions utilised in automated manufacturing include: the communication of instructions to workers; the downloading of workpart programmes; the control of the material handling system; the scheduling of production; the diagnosis of failures; the monitoring of safety; the maintenance of quality control; and the management of operations.

Humans supply direct and indirect labour to automated manufacturing systems.

Operational types include processing operations on individual work units, and assembly operations to combine individual workparts into sub-assemblies, or full assemblies.

The number of workstations in a manufacturing system exerts a strong influence on the performance of the manufacturing system, in terms of its workload capacity, production rate, and reliability.

System configuration, or the layout of the manufacturing system's workstations, is also an important factor. Workstation layouts for fixed routing are usually arranged linearly, as in a production line, while variable routing layouts can have multiple configurations.

The level of automation deployed is an important characteristic of the manufacturing system.

The manning level of a workstation is the amount of time that a human operator is required to be in attendance at the workstation in question.
In manufacturing systems the manning level produces two levels for single station systems (manned and fully automated), and three levels for multi-station systems (manned, fully automated, and hybrid).

Part or product variety examines the manufacturing system’s flexibility for dealing with variations in the parts or products it produces. The cases of part or product variety in manufacturing systems are single model, batch model, or mixed model.

The flexible capability of the mixed model of manufacturing is an important determinant of the success of the manufacturing scheme that is adopted.

Single workstations come in two forms: manned workstations, and automated stations.

A multi-station system with fixed routing is a production line.

A multiple-station system with variable routing is a group of workstations organised to achieve some special purpose.

The single-station manned cell is the most popular type of single-station manufacturing cell owing to its flexibility, cost-effectiveness, and relatively quick set-up and maintenance characteristics.

The machines in single-station manufacturing cells are usually manually or semi-operated.

The single-station automated cell consists of a fully automated machine that can operate unattended for a time period longer than one machine cycle.

Enablers for unattended cell operation include (for all models): a programmed cycle, a parts storage subsystem, the automatic transfer of work parts, periodic attention of worker, and built-in safeguards; and (for mixed models): a work identification subsystem; a programme downloading capability; and a quick set-up changeover capability.

The length of time that the automated cell can theoretically operate unattended can be calculated by considering storage capacity and the cycle time of the automated cell in question.

The time of unattended operation increases directly with storage capacity.

If storage capacity is greater than one workpart, unattended operation is feasible when load/unload tasks are accomplished in less time than the machine processing time. This often requires innovative parts storage system design.
Numerous examples of both manned and automated single-station cells can be given, right across the manufacturing environmental spectrum.

The number of workstations that are required is determined by the total workload that must be accomplished over a certain period, divided by the hours available on one workstation during the same period; together with a consideration of any mitigating factors.

A machine cluster is defined as a collection of two or more machines producing parts or products with identical cycle times and serviced by one worker.

**12.11 Self-Assessment Questions**

**NUMLIST**

- What is a manufacturing system?
- What are the general material handling processes that may be distinguished in an automated manufacturing system?
- What are the types of work transport that may be encountered? What equipment is used in the operation?
- What computer functions are typically utilised in automated manufacturing?
- Why does the number of workstations in a system have an impact upon the type of manufacturing system that is finally implemented?
- Why is workstation layout an important consideration in the manufacturing system?
- What is meant by the manning level of a workstation? List the levels for single and multi-station systems.
- What is the importance of part or product variety for manufacturing systems?
- What are single- and multi-station systems? What are the differences between the two?
- List the enablers for unattended cell operation.
- How can we calculate the length of time that the automated cell can theoretically operate unattended?
- How do we determine the number of workstations that are required in a system?
What is a machine cluster?

12.12 Answers to Self-Assessment Questions

A manufacturing system is 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.

For automated manufacturing systems the following material handling actions may be distinguished: loading work units at each station; positioning work units at the station; unloading work units from the station after processing; transporting work units between stations; and performing temporary storage, if necessary, also.

There are two types of work transport that may be encountered; these are fixed routing and variable routing. Workpart transport is usually accomplished by means of equipment such as pallet fixtures, work carriers, or direct transport.

Computer functions utilised in automated manufacturing include: the communication of instructions to workers; the downloading of workpart programmes; the control of the material handling system; the scheduling of production; the diagnosis of failures; the monitoring of safety; the maintenance of quality control; and the management of operations.

The number of workstations in a manufacturing system exerts a strong influence on the performance of the manufacturing system, in terms of its workload capacity, production rate, and reliability. These are all important considerations in the final manufacturing system design.

System configuration, or the layout of the manufacturing system’s workstations, is also an important factor because workstation layouts for fixed routing are usually arranged linearly, as in a production line, while variable routing layouts can have multiple configurations. Decisions on the type of layout to proceed with has consequences for all other physical elements in the manufacturing system, from the layout of material handling systems and storage, as well as impacts upon the performance and management of the system at higher levels.

The manning level of a workstation is the amount of time that a human operator is required to be in attendance at the workstation in question. In manufacturing systems the manning level produces two levels for single station systems (manned and fully automated), and three levels for multi-station systems (manned, fully automated, and hybrid).
Part or product variety examines the manufacturing system’s flexibility for dealing with variations in the parts or products it produces. The cases of part or product variety in manufacturing systems are single model, batch model, or mixed model.

Single workstations come in two forms: manned workstations, and automated stations; whereas, multi-station systems with fixed routing are essentially production lines. A multiple-station system with variable routing is a group of workstations that is usually organised to achieve some special purpose; whereas the single-station manned cell remains the most popular type of single-station manufacturing cell owing to its flexibility, cost-effectiveness, and relatively quick set-up and maintenance characteristics.

Enablers for unattended cell operation include (for all models): a programmed cycle, a parts storage subsystem, the automatic transfer of work parts, periodic attention of worker, and built-in safeguards; and (for mixed models): a work identification subsystem; a programme downloading capability; and a quick set-up changeover capability.

The length of time that the automated cell can theoretically operate unattended can be calculated by considering storage capacity and the cycle time of the automated cell in question.

The number of workstations that are required is determined by the total workload that must be accomplished over a certain period, divided by the hours available on one workstation during the same period; together with a consideration of any mitigating factors.

A machine cluster is defined as a collection of two or more machines producing parts or products with identical cycle times and serviced by one worker.

END LIST