Unit 9. Automated Storage Systems

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9.1 Unit Introduction

Storage is an essential function in an automation system. The material storage system allows materials to be stocked for a specified period of time, before they are re-introduced, or are introduced for the first time, into the automation system. The sorts of stored material are related to the product (e.g. raw materials, purchased parts, work-in-process, finished products, and scrap and rework), the process (e.g. process refuse, such as process waste products; and tooling), and the overall support functions in the factory (e.g. maintenance spare parts, office supplies, and plant records). Each of these material types is typically stored under different conditions and controls.

KEYPOINT
A material storage system allows materials to be stocked for a specified period of time, before they are re-introduced, or are introduced for the first time, into the automation system.
END KEYPOINT

In this unit storage equipment is described, alongside appropriate methods in both conventional and automated storage systems. Storage system performance and location strategies examine the operating characteristics associated with storage systems, and where best to place and organise them in the plant layout. Conventional storage methods and equipment turns to an investigation of how storage is regularly accomplished, and the pieces of equipment that is used to achieve storage aims. Automated storage systems, which reduce or eliminate human intervention in the system, are subsequently described. This is followed by an engineering analysis of storage systems, in their various guises. A case study completes the material of the unit, followed by the review of the unit and the self-assessment questions and answers.
9.2 Unit Learning Objectives

After completing this unit you will be able to:

BULLET LIST

- Explain the meaning of a material storage system, and issues that affect its operating characteristics
- Determine performance measures used to assess storage system performance
- List methods and equipment used for storage purposes
- List the types of automated storage categories that can be examined
- Define automated storage/retrieval systems (AS/RS) and their associated equipment
- Define carousel storage systems and their construction
- List the determinants of aisle capacity and system throughput for AS/RS
- List the determinants of size and capacity for carousel systems

ENDLIST

9.3 Storage Systems

Storage systems are used to store materials related to the product (e.g. raw materials, purchased parts, work-in-process, finished products, and scrap and rework), the process (e.g. process refuse, such as process waste products; and tooling), and the overall support functions in the factory (e.g. maintenance spare parts, office supplies, and plant records). Storage systems can be classified into conventional storage systems and automated storage systems (Figure 9.1).
Figure 9.1: Conventional and Automated Storage Systems

We can specify two sets of operating characteristics and issues when it comes to storage systems; these are:

BULLET
Storage system performance

Storage location strategies
END

KEYPOINT
Storage system operating characteristics can be examined on two sets of issues: storage system performance; and storage location strategies.
END KEYPOINT

9.3.1 Storage System Performance

A respective storage system must justify itself in terms of investment and operating expense, by providing an adequate level of performance. Performance measures used to assess this performance are detailed in Table 9.1.

<table>
<thead>
<tr>
<th>Performance measure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity</td>
<td>Defined in two ways: the total volumetric space available; and the total number of storage compartments in the system available for holding items or loads. Use is often made of the unit load principle to standardise storage in the storage system; the number of unit loads that may be stored is a convenient metric that can be quickly captured. The</td>
</tr>
<tr>
<td><strong>Physical capacity of the storage system</strong></td>
<td>physical capacity of the storage system must be greater than the maximum number of loads that can be stored, to allow for additional, emergency, storage requirements, as and when they are necessary.</td>
</tr>
<tr>
<td><strong>Storage density</strong></td>
<td>Defined as the volumetric space available for actual storage relative to the total volumetric space in the storage facility. Aisle space and wasted overhead space are two examples of unutilised storage space; these often take up more space than actual usable storage capacity itself. Often measured by means of the floor area of the storage facility; although volumetric density is a more accurate metric. High densities should be aimed at.</td>
</tr>
<tr>
<td><strong>Accessibility</strong></td>
<td>Defined as the capability to access any desired item or load stored in the system. Density often has an inverse relationship with accessibility to the storage facility, so a trade-off may ensue here.</td>
</tr>
<tr>
<td><strong>System throughput</strong></td>
<td>Defined as the hourly rate at which the storage system either receives and puts loads into storage, and/or retrieves and delivers loads to the output station. Storage system must be design to meet maximum throughput requirements, as variations in the levels of throughput should be expected throughout the working day. Storage throughput is limited by the time to perform a storage or retrieval transaction. Storage consists of: picking up a load at the input station; travel to a storage location; placement of the load in the storage location; and travel back to the input station. Retrieval consists of: travel to the storage location; picking up the item from storage; travel to the output station; and unloading at the output station. The some of each of these element times (for either operation) determines the throughput for the storage system. A dual command cycle reduces throughput by combining storage and retrieval functions. The ability to perform such a cycle is dependent on demand and scheduling issues. It more easily performed by automated storage systems, than manual systems.</td>
</tr>
<tr>
<td><strong>Utilisation</strong></td>
<td>Defined as the proportion of time that the system is actually being used to perform storage/retrieval operations compared with the time it is available. Used in mechanised and automated storage system analysis. Desirable utilisation patterns see ranges between 80-90%. If system utilisation is too low, then it is probably over-designed; if it is too high, then there will be no allowance for rush periods or system breakdowns.</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>Defined as the proportion of time that the system is capable of operating compared with the normal schedule shift hours. System breakdowns cause downtimes in the system. Reasons for downtime include: computer failures, mechanical breakdowns, load jams, improper maintenance, and incorrect operating procedures.</td>
</tr>
</tbody>
</table>

**KEYPOINT**
Performance measures used to assess storage system performance include: storage capacity, storage density, accessibility, system throughput, utilisation, and availability.

**END KEYPOINT**

9.3.2. Storage Location

Storage location strategies try to organise stock in a storage system, with chosen location strategies having a direct impact upon the performance measures outlined in Table 9.1. Two basic strategies that are deployed are: randomised
storage, and dedicated storage; these are outlined further in Table 9.2. It should be noted that both strategies take advantage of stock-keeping-units (SKUs), which uniquely identifies an item type. Inventory records keep a count on the quantities of each type of SKU that has a place in the storage system.

**KEYPOINT**
Storage location strategies organise stock in a storage system, and have a considerable impact upon storage system performance.

**END KEYPOINT**

**Table 9.2: Strategies for storage location**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Randomised storage</td>
<td>Items are stored in any available location in the storage system, typically in the nearest available open location. For retrieval, SKUs are taken from storage on a first-in-first-out policy so that the items held in storage the longest are moved out first. Less storage space is generally required for randomised storage systems, although this affects throughput rates by reducing them, sometimes significantly.</td>
</tr>
<tr>
<td>Dedicated storage</td>
<td>SKUs are assigned to specific locations in the storage facility, so that pre-defined reservation of SKUs can take place, and the system may be designed to accommodate maximum levels of particular SKUs held in inventory. The basis for specifying the storage locations is usually done by: storing items in part number, or product number sequence; storing items as per activity level, with more active SKUs being placed closer to input/output stations; or storing items according to their activity-to-space ratios, with higher ratios being located closer to input/output stations. More storage space is generally required for dedicated storage systems, although with the consequent advantage of higher throughput times being achieved.</td>
</tr>
</tbody>
</table>

**KEYPOINT**
The two basic strategies that may be deployed for storage location are: randomised storage, and dedicated storage.

**END KEYPOINT**

The two strategies may also be mixed; for example, in a system that uses dedicated storage at a general level, but which is further divided into several classes according to activity level, and—within each class—with randomised storage being deployed. This effectively tries to take the benefits of both strategy sets, and to deploy them for the overall advantage of the storage system.
## 9.4 Conventional Storage

Conventional storage methods and equipment to support the various strategies outlined above, are detailed in Table 9.3.

<table>
<thead>
<tr>
<th>Methods and Equipment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk storage using pallet trucks and powered forklifts</td>
<td>Used for the storage of stock in an open floor area, generally in unit loads on pallets or similar containers. Unit loads may be stacked on top of each other to achieve higher storage densities. Highest densities achieved when unit loads placed next to each other, but the formation of rows and blocks in bulk storage can also improve accessibility. Depending on the materials being stacked, there may be restrictions on how high they can be loaded; sometimes materials cannot be stacked owing to physical characteristics or limited compressive strength of the individual loads.</td>
</tr>
<tr>
<td>Rack systems that use pallet trucks and powered forklifts</td>
<td>Rack systems provide bulk storage facilities with adequate support to aid safe stacking, by means of various methods, such as: pallet racks—consisting of a frame to support unit loads stacked one over the other, without the weight of the top-most loads resting on loads lower down; it consists of a frame with horizontal load-supporting beams; cantilever racks—same as pallet racks, except the horizontal beams are cantilevered from the vertical central frame; this provides for unobstructed storage spans; portable racks—consisting of portable box-frames that hold a single pallet load, and can be stacked on top of each other safely; drive-through racks—consisting of a framework with open aisles down the middle of two vertical beam-columns, on each side of which—as we progress in forklifts down the aisle—are supporting horizontal rails for pallet loads, thus providing for unobstructed storage spanning; and flow-through racks—consisting of conveyor tracks capable of supporting a row of unit loads, which replace conventional horizontal rack beams; unit loads are loaded on one side of the rack, and are unloaded on the other side, thus providing first-in-first-out stock rotation.</td>
</tr>
<tr>
<td>Shelving and Bins for manual attendants or powered forklift use</td>
<td>Shelving is one of the most common types of storage equipment. Steel shelving sections are manufactured in standard sizes, and may be fitted as and where they are needed. Bins may be attached to shelves; these consist of compartments or boxes that hold loose items. Shelf storage must be applicable to the storage situation required: sometimes may be improperly placed, or contain material which would be stored more efficiently in other storage equipment.</td>
</tr>
</tbody>
</table>
### Drawer storage for manual attendants

| Drawer storage for manual attendants | Storage drawers solve the problem of shelving, where materials may often be overlooked, by allowing the attendant to pull the drawer out to reveal fully its contents. Modular drawer storage cabinets are available with a variety of drawer depths for different item sizes, and are widely used to store maintenance tools and other items. |

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**KEYPOINT**

Storage methods and equipment include: bulk storage for use by pallet trucks and powered forklifts; rack systems for use by pallet trucks and powered forklifts; shelving and bins for use by manual attendants or powered forklifts; and drawer storage for use by manual attendants.

**END KEYPOINT**

### 9.5 Automated Storage Systems

Automation—when applied to storage systems—tends to minimise human interaction with the storage function; this, in turn, requires an examination of the level of automation that may be required for a particular storage system, and the methods of application that must be used to achieve a successful amalgamation of storage capabilities, coupled to automation processes. Less automated systems, still with a considerable level of human interaction (for example, to handle storage/retrieval transactions), may also be utilised: in such cases, automation must be built around the human element remaining in the system. Highly automated storage systems, meanwhile, usually relegate the operator to the role of data management, whilst automation carries-out the rest of the work-load of the system.

**KEYPOINT**

When automation is applied to storage systems it tends to minimise human interaction with the manual elements of the storage function.

**END KEYPOINT**

Automated storage can be divided into the following headings: automated storage/retrieval systems, and carousel storage systems.
9.6 Automated Storage/Retrieval Systems

An automated storage/retrieval system (AS/RS) is a storage system that performs storage and retrieval operations with speed and accuracy under a defined degree of automation. Different levels of automation may be applied. At one extreme, the AS/RS is completely automated. This can include a full compliment of totally automated, computer-controlled storage functions that are integrated into overall factory or warehouse operations. At the other extreme it may use human workers to control equipment and perform storage/retrieval transactions. Using modular components, available from AS/RS vendors, the AS/RS system is custom-designed to fit the requirements of the plant in which it is installed.

KEYPOINT
An automated storage/retrieval system (AS/RS) is a storage system that performs storage and retrieval operations with speed and accuracy under a defined degree of automation.

END KEYPOINT

The basic equipment of the AS/RS include a rack structure used for storing loads, plus a storage/retrieval (S/R) mechanism with three dimensions of motion (x, y, z). Additionally, the AS/RS maintains one or more storage aisles that are serviced by the S/R mechanism. The S/R mechanism is used to deliver materials to the storage racks and to retrieve materials from the racks. Each aisle has an input/output station where storage deliveries are transferred into the system, or out-of the system; these stations are known as pickup-and-deposit (P&D) stations. P&D stations may be manually operated or connected to an automated transport system, such as a conveyor or an AGVS (see Figure 9.2).
Figure 9.2: Automated Storage and Retrieval System (AS/RS)

**KEYPOINT**

An AS/RS consists of a rack structure and storage/retrieval mechanism that operates to deliver materials into and out-of the storage system, via pickup-and-deposit stations.

**END KEYPOINT**

Different types of AS/RS may be specified as in Table 9.4.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit load AS/RS</td>
<td>A large automated system designed to handle unit loads stored on pallets or other containers. Computer-controlled, with automated S/R customised for unit load handling. Basic form of AS/RS, with all those below being variations of this initial type.</td>
</tr>
<tr>
<td>Deep-lane AS/RS</td>
<td>High-density unit load storage system. Used with large quantities of stock, but where the number of separate stock types (SKUs) is relatively small. Loads are stored one behind another, with up to ten loads in a single rack, in the deep-lane system. Access is ensured by the ‘flow-through’ system, whereby loads are input on one side of the rack by an S/R machine, and retrieved on the other side by another S/R machine.</td>
</tr>
<tr>
<td>Mini-load AS/RS</td>
<td>Used to handle small loads that are contained in bins or drawers in the storage system. The S/R machine retrieves the bin and delivers it to a P&amp;D station at the aisle’s end, so that individual items may be withdrawn. The P&amp;D station is usually operated manually. The bin is then returned to its location in the storage system.</td>
</tr>
<tr>
<td>Man-on-board AS/RS</td>
<td>In this system a human operator rides on the carriage of the S/R machine, so as to allow for the manual retrieval of items directly</td>
</tr>
</tbody>
</table>
Automated item retrieval system | Have the same functionalities as mini-load AS/RS, but the items are stored in lanes rather than bins or drawers. When an item is retrieved, it is pushed from its storage position so that it drops onto a conveyor for delivery to the pickup station. Replenishment of the storage system is accomplished using a first-in/first-out inventory rotation policy.

Vertical lift storage modules (VLSM) | Also known as vertical lift automated storage/retrieval systems (VL-AS/RS). Here the same principles as the above AS/RS types are followed, except that instead of a horizontal aisle, the aisle is vertical.

KEYPOINT
Different types of AS/RS include: unit load AS/RS; deep-lane AS/RS; mini-load AS/RS; man-on-board AS/RS; automated item retrieval system; and vertical lift storage modules.
END KEYPOINT

9.6.1 AS/RS Applications

AS/RS technology has generally been associated with warehousing and distribution operations, although it can also be used for raw material storage, and storage of work-in-process in manufacturing. Three application areas of interest are:

BULLETLIST
Unit load storage and handling
Order picking
Work-in-process storage
ENDLIST

KEYPOINT
The application areas for AS/RS technology are: unit load storage and handling; order picking; and work-in-process storage.
END KEYPOINT

Unit load storage and retrieval applications have been represented above in the discussion on the unit load AS/RS and deep-lane storage system; so here we focus upon work-in-process applications. Work-in-process (WIP) is desirable for balancing work loads throughout the factory and in order to meet the demands for short term fulfilment of customer orders. WIP is inherently inefficient and needs to be minimised. WIP cannot be eliminated entirely: hence the requirement for WIP management, and the use of AS/RS for this application.
For high-production operations large-capacity AS/RS technologies may be used for staging and sequencing the work units as per the production schedule, to achieve increased production efficiencies. General reasons for the implementation of WIP automated storage systems are outlined in Table 9.5.

Table 9.5: Reasons to introduce WIP automated storage systems

<table>
<thead>
<tr>
<th>Reason</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffer storage in production</td>
<td>The automated storage system can be used as a buffer storage zone between two processes whose production rates differ.</td>
</tr>
<tr>
<td>Support of just-in-time delivery</td>
<td>To reduce the chance of stock-out, owing to the failure of deliver by suppliers in the just-in-time system, automated storage systems may be installed as storage buffers for incoming materials.</td>
</tr>
<tr>
<td>Kitting of parts for assembly</td>
<td>The storage system is used to store components for assembly of products or subassemblies. When orders are received from storage they are put together into kits and deliver to production.</td>
</tr>
<tr>
<td>Compatible with automatic identification systems</td>
<td>The systems can be interfaced with other automated systems throughout production, such as automatic identification devices.</td>
</tr>
<tr>
<td>Computer control and tracking of materials</td>
<td>Automated WIP storage system allows the location and status of WIP to be known.</td>
</tr>
<tr>
<td>Support of factory-wide automation</td>
<td>Given the need for some storage of WIP in batch production, an appropriately-sized automated storage system is an important subsystem in a fully automated factory.</td>
</tr>
</tbody>
</table>

**KEYPOINT**

Reasons for the implementation of WIP automated storage systems include: buffer storage in production; support of just-in-time delivery; kitting of parts for assembly; compatibility with automatic identification systems; computer control and tracking of materials; and support of factory-wide automation.

**END KEYPOINT**

### 9.6.2 Components and Operating Features

The components of an AS/RS are illustrated in Figure 9.3 and outlined in Table 9.6.
Figure 9.3: Major Components of an AS/RS

Table 9.6: Components of an AS/RS

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage structure</td>
<td>Consists of the rack framework used to support loads contained in the AS/RS; made from fabricated steel of sufficient strength and toughness to support typical AS/RS loads. May have individual storage compartments to hold storage modules, which hold the stored material. May be built into the plant building itself, as a building support structure. It also supports aisle hardware required to align the S/R machines with the storage compartments of the AS/RS.</td>
</tr>
<tr>
<td>S/R machine</td>
<td>Used to accomplish storage transactions, both delivering loads to storage, and retrieving loads as required. To do this, the S/R machine must be able to move horizontally and vertically with the load along the front of the rack structure. Components consist of a rigid mast on which is mounted an elevator system for vertical motion; all of which is attached to a base with wheels for horizontal motion along a rail system that traverses the storage aisle. A parallel rail at the top of the storage structure ensures alignment of mast and carriage with the rack structure.</td>
</tr>
<tr>
<td>Storage modules</td>
<td>The unit load containers of the stored materials, including pallets, steel wire baskets and containers, plastic tote pans, and special drawers. The storage modules are standardised in size so that can be handled</td>
</tr>
</tbody>
</table>
easily by the carriage shuttle of the S/R machine; it also fits the storage compartments of the rack structure.

| Pickup-and-deposit station | This is where loads are transferred into and out of the AS/RS. It is generally found at the aisle end for convenient access to external handling equipment. The two functions may be divided such that pickup functions occur at one end of the aisle, and deposit functions may happen at the other end; alternatively they may be combined at just one aisle end, depending on the layout of the AS/RS. The pickup-and-deposit station must be compatible with both the S/R machine used, and the external handling system in place. |

**KEYPOINT**

Typical components of an AS/RS include: a storage structure; an S/R machine; storage modules; and one or more pickup-and-deposit stations.

**END KEYPOINT**

Each compartment in the storage structure may be identified by its horizontal and vertical position, and whether it is on the left or right side of the aisle; all of which information can be coded in an alphanumeric coding scheme that is executed by the S/R machine. Using this location reference system, each unit of material in the storage system can be referenced to a particular location in the aisle. The record of these locations is called the item location file.

S/R machine and shuttle positioning is ensured either by means of a counting procedure positioning method in which the number of bays and levels are counted in the direction of travel; or by means of a numerical identification procedure in which each compartment has a unique binary-coded location identification tag. These tags can be read by the S/R machine by deploying an optical scanner that reads the target and positions the shuttle to deliver or retrieve stored material. Computer controls and programmable logic controllers are used to determine the required location and guide the S/R machine to its destination.

**LEARNING ACTIVITY 9.1**

Visit [www.youtube.com](http://www.youtube.com) and look up videos that illustrate the design and operation of various types of AS/RS outlined in Table 9.4. Make a note of the manufacturers names and country of origin.

**END LEARNING ACTIVITY 9.1**

**9.6.3. AS/RS Analysis**

The methods outlined here for AS/RS can also be used for analysis of traditional storage facilities. The total capacity of one storage aisle depends on the number of its storage compartments and their horizontal and vertical arrangement. This is expressed as:
where $n_y$ is the number of load compartments along the length of the aisle; and $n_z$ is the number of load compartments that make up the height of the aisle. This is multiplied by two because there are loads contained on both sides of the aisle.

Assuming a standard size for storage compartments, then compartment size facing the aisle must be larger than the unit load size to be slotted-into it. If $x$ and $y$ are set as the depth and width dimensions of a unit load, respectively, and $z$ is set as the height of the unit load; then the following equations hold for the width ($W$), length ($L$), and height ($H$) of one aisle of the rack structure of the AS/RS:

\[
W = 3(x + a) \\
L = n_y (y + b) \\
H = n_z (z + c)
\]

where $x$, $y$, and $z$ are the dimensions of the unit load; and $a$, $b$, and $c$ are allowances designed into each load compartment to provide clearance for the unit load and to account for the size of the supporting beams in the rack structure.

**KEYPOINT**
Aisle capacity depends on the number of its storage compartments and their horizontal and vertical arrangement.

**END KEYPOINT**

**EXAMPLE 9.1**
A unit load AS/RS is being designed to store 1000 pallet loads in a distribution center located next to the factory. Pallet dimensions are: $x = 1000$ mm, $y = 1200$ mm; and the maximum height of a unit load = 1300 mm. The following is specified:
(1) the AS/RS will consist of two aisles with one S/R machine per aisle, (2) length of the structure should be approximately five times its height, and (3) the rack structure will be built 500 mm above floor level. Using the allowances $a = 150$ mm, $b = 200$ mm, and $c = 250$ mm, determine the width, length, and height of the AS/RS rack structure.

**Solution**: Assumption: the $L/H$ ratio does not include the 500 mm foundation.
1000 pallets/2 aisles = 500 pallets/aisle. 500 pallets/aisle → 250 pallets per aisle side.
Thus $n_y n_z = 250$ Eq. (1)
$L = n_y (y + b) = n_y (1200 + 200) = 1400 n_y (n_y \text{ in mm}) = 1.4 n_y (n_y \text{ in m})$
$H = n_z (z + c) = n_z (1300 + 250) = 1550 n_z (n_z \text{ in mm}) = 1.55 n_z (n_z \text{ in m})$
Given the specification $L/H = 5$
Combining Eqs. (1) and (2):

\[ n_y \times n_z = \frac{5.536 \times n_z}{n_z} = 250 \]

\[ n_y = \frac{250}{5.536} = 45.161 \quad n_z = 6.72 \rightarrow \text{use } n_z = 7 \]

\[ W = 3(1000 + 150) = 3450 \text{ mm} = 3.45 \text{ m/aisle.} \]

With 2 aisles, \( W = 2(3.45) = 6.9 \text{ m} \)

\[ L = 1.4 \times n_y = 1.4(36) = 50.4 \text{ m} \]

\[ H = 1.55 \times n_z = 1.55(7) = 10.85 \text{ m} \]

Given that the rack structure is built 500 mm above floor level, \( H = 10.85 + 0.5 = 11.35 \text{ m} \)

Check on specifications: Capacity = 2 x 2 x 36 x 7 = 1008 pallets.

\[ L/H = 50.4/10.85 = 4.645 \]

END EXAMPLE

LEARNING ACTIVITY 9.1

Given the rack structure dimensions computed in Example 9.1. Assuming that only 80% of the storage compartments are occupied on average, and that the average volume of a unit load per pallet in storage = 0.75 m³, compute the ratio of the total volume of unit loads in storage relative to the total volume occupied by the storage rack structure.

END LEARNING ACTIVITY 9.1

System throughput is defined as the hourly rate of S/R transactions that the automated storage system can perform. A transaction involves depositing a load into storage, or retrieving a load from storage. These two separate transactions may be combined into a dual command cycle, which accomplishes both transaction types in one cycle. There are, in fact, several methods for the computation of AS/RS cycle times, for the estimation of throughput performance; only one of which is outlined here.

The method makes these assumptions:

BULLETLIST

- There is randomised storage of loads in the AS/RS
- There are storage compartments of equal size
- The pick-up and deposit station is located at the aisle’s end
- The S/R machine travels at constant horizontal and vertical speeds
- There is simultaneous horizontal and vertical travel
For a single command cycle the load to be deposited/retrieved is assumed to be in the centre of the rack structure

From these assumptions we can show that the S/R machine must travel half the length and height of the AS/RS, and it must return the same distance. The single command cycle time is, therefore:

\[
T_{cs} = 2\text{Max} \left\{ \frac{0.5L}{v_y}, \frac{0.5H}{v_z} \right\} + 2T_{pd} = \text{Max} \left\{ \frac{L}{v_y}, \frac{H}{v_z} \right\} + 2T_{pd}
\]

where \( T_{cs} \) is the cycle time of a single command cycle; \( L \) is the length of the AS/RS rack structure; \( v_y \) is the velocity of the S/R machine along the length of the AS/RS; \( H \) is the height of the rack structure; \( v_z \) is the velocity of the S/R machine in the vertical direction of the AS/RS; and \( T_{pd} \) is the pickup-and-deposit time. Two pickup-and-deposit times are required per cycle, representing load transfers to and from the S/R machine.

For dual command cycles, the S/R machine is assumed to travel to the centre of the rack structure to deposit a load, and then to three quarters the length and height of the AS/RS to retrieve a load. The total distance travelled by the S/R machine is \( \frac{3}{4} \) the length and \( \frac{3}{4} \) the height of the rack structure, and back. Cycle time is:

\[
T_{cd} = 2\text{Max} \left\{ \frac{0.75L}{v_y}, \frac{0.75H}{v_z} \right\} + 4T_{pd} = \text{Max} \left\{ \frac{1.5L}{v_y}, \frac{1.5H}{v_z} \right\} + 4T_{pd}
\]

where terms as defined above; and \( T_{cd} \) is the cycle time for a dual command cycle.

System throughput depends upon the above analysis of single and dual command cycles; so that \( R_{cs} \) may be set as the number of single command cycles performed per hour, while \( R_{cd} \) may be set as the number of dual command cycles per hour at a specified or assumed utilisation level. Thus, the amounts of time spent in performing single command and dual command cycles each hour, is:

\[
R_{cs} T_{cs} + R_{cd} T_{cd} = 60U
\]

where \( U \) is the system utilisation during the hour; and all other terms as defined above. For this equation we need to determine the relative proportions of both \( R_{cs} \) and \( R_{cd} \); once known, the total hourly cycle rate is given by:
where $R_c$ is the total S/R cycle rate. The total number of storage and retrieval transactions per hour will be greater than this value unless $R_{cd}$ is zero, since there are two transactions accomplished in each dual command cycle. If $R_t$ is the total number of transactions performed per hour, then:

$$R_t = R_{cs} + 2R_{cd}$$

EXAMPLE 9.2

An AS/RS is used for work-in-process storage in a manufacturing facility. The AS/RS has five aisles, each aisle being 120 ft long and 40 ft high. The horizontal and vertical speeds of the S/R machine are 400 ft/min and 50 ft/min, respectively. The S/R machine requires 12 sec to accomplish a pick and deposit operation. The number of single command cycles equals the number of dual command cycles. If the requirement is that the AS/RS must have a throughput rate of 200 S/R transactions per hour during periods of peak activity, will the AS/RS satisfy this requirement? If so, what is the utilization of the AS/RS during peak hours.

Solution:

$$T_{cs} = 2 \left( \frac{0.5(120)}{400}, \frac{0.5(40)}{50} \right) + 2(12/60) = 1.2 \text{ min/cycle}$$

$$T_{cd} = 2 \left( \frac{0.75(120)}{400}, \frac{0.75(40)}{50} \right) + 4(12/60) = 2.0 \text{ min/cycle}$$

$1.2R_{cs} + 2.0R_{cd} = 60$

Given $R_{cs} = R_{cd}$,

$1.2R_{cs} + 2.0R_{cs} = 3.2R_{cs} = 60$

$R_{cs} = 18.75 \text{ cycles/hr.}$

$R_{cd} = R_{cs} = 18.75 \text{ cycles/hr.}$

$R_t = 5(R_{cs} + 2R_{cd}) = 5(3 \times 18.75) = 281.25 \text{ S/R transactions/hr}$

$U = 200/281.25 = 0.711 = 71.1\%$

END EXAMPLE

LEARNING ACTIVITY 9.3

An automated storage/retrieval system installed in a warehouse has five aisles. The storage racks in each aisle are 10m high and 50m long. The S/R machine for each aisle travels at a horizontal speed of 100 m/min and a vertical speed of 30 m/min. The pick and deposit time = 0.25 min. Assume that the number of single command cycles per hour is equal to the number of dual command cycles per hour and that the system operates at 75% utilization. Determine the throughput rate (loads moved/hour) of the AS/RS.

END LEARNING ACTIVITY 9.3
9.7 Carousel Storage Systems

A carousel storage system is one with a series of bins or baskets suspended from an overhead chain conveyor that revolves around a long oval rail system. The chain conveyor positions the bins/baskets at load/unload stations at each end of the oval, the whole system being operated by human workers positioned at the load/unload stations (See Figure 9.4). The worker activates the system, and the powered carousel delivers the desired bin to its desired station; one or more parts are removed, or added-to, the bin at this station; and then the bin is moved by the powered carousel from the station to another location. Once completed, the process cycle can be repeated. Transfer mechanisms from load/unload stations to carousel bins may also be automated.

Figure 9.4: Carousel Systems

9.7.1 Carousel Technology
Carousels are classified as horizontal or vertical, with the former being more common in practice. Horizontal carousels consist of a welded steel framework for the oval rail system, which can be either mounted overhead (a top-driven unit), or from below (a bottom-driven unit). In the top-driven structure, a motorised pulley system drives the overhead trolley system, attached to which are suspended bins. In the bottom-driven structure, the pulley drive system is mounted at the base of the frame, and the trolley system rides on a rail in the base. Carousel bins and baskets are designed to be consistent with the loads they are to carry. Standard bins are made of steel wire to increase operator visibility.

**KEYPOINT**
Carousels are either horizontal or vertical in construction.
**END KEYPOINT**

Vertical carousels operate around a vertical conveyor loop. They operate in less floor space than horizontal carousel designs, but take up as much space again in the vertical plane, which means that they can be limited by the size of the building that houses them. Because of this, storage capacity is generally lower for vertical carousels than for horizontal carousel designs.

**KEYPOINT**
Vertical carousels operate around a vertical conveyor loop that may be limited by the height of the building in which they are implemented.
**END KEYPOINT**

Various control structures used in carousel systems are outlined in Table 9.7.

<table>
<thead>
<tr>
<th>Control mechanism</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual controls</td>
<td>Human-operated controls include foot pedals, hand switches, and</td>
</tr>
<tr>
<td></td>
<td>specialised keyboards. Foot control allows the carousel to be rotated in</td>
</tr>
<tr>
<td></td>
<td>either direction as the operator requires; similarly for hand control,</td>
</tr>
<tr>
<td></td>
<td>which is facilitated by a hand-operated switch that projects from the</td>
</tr>
<tr>
<td></td>
<td>frame of the carousel to within easy reach of the operator. Keyboard</td>
</tr>
<tr>
<td></td>
<td>control is even more flexible: it allows a greater amount of control</td>
</tr>
<tr>
<td></td>
<td>features to be implemented on the bins in the carousel system; for</td>
</tr>
<tr>
<td></td>
<td>example, keyboard control can allow the system to be programmed to</td>
</tr>
<tr>
<td></td>
<td>take the shortest route for the delivery of bins to stations.</td>
</tr>
<tr>
<td>Computer controls</td>
<td>These increase the opportunities for automation of the mechanical</td>
</tr>
<tr>
<td></td>
<td>carousel and for management of the inventory records. For example,</td>
</tr>
<tr>
<td></td>
<td>automatic loading and unloading is available on modern carousel storage</td>
</tr>
<tr>
<td></td>
<td>systems, which allows the carousel to be interfaced with automated</td>
</tr>
<tr>
<td></td>
<td>handling systems without the need for human intervention. Additionally,</td>
</tr>
<tr>
<td></td>
<td>data management facilities provide computer control over bin locations,</td>
</tr>
<tr>
<td></td>
<td>bin inventories, and inventory control records.</td>
</tr>
</tbody>
</table>

**KEYPOINT**
Both manual and computer control mechanisms may be used in conjunction with horizontal and vertical carousel systems.

9.7.2 Carousel Applications

Carousels are sometimes seen as an attractive alternative to AS/RS, especially mini-load systems, in some manufacturing contexts. Typical applications include:

- **Storage and retrieval operations**—particularly where individual items must be selected from groups of items in storage
- **Transport and accumulation**—whereby the carousel is used to transport and/or sort materials as they are stored
- **Work-in-process**—whereby carousels may compete with automated storage and retrieval systems for applications where work-in-process is to be temporarily stored
- **Specialised uses**—for example, the use of carousels during the electrical testing of products, such that the carousel is used to store the item during the test for a specified period of time

Typical applications of carousels include their use in: storage and retrieval operations; transport and accumulation functions; work-in-process storage; and other specialised use areas.

9.7.3. Carousel Systems Analysis

Similar relationships can be developed for carousel systems. The size and capacity of a carousel consists of individual bins suspended in columns from carriers that revolve around an oval rail with a circumference given by:

\[
C = 2(L - W) + \pi W
\]

where \( C \) is the circumference; \( L \) is the length; and \( W \) is the width of the track oval. Capacity of the system depends on the number and size of the bins in the system (See Figure 9.5). Assuming standard-sized bins are used, each with a fixed volumetric capacity, then the number of bins can be used as our measure of capacity. The number of bins that may hang in a column, one below another,
from each carrier may be set as $n_b$, and $n_c$ may be set as the number of carriers supported by the rail; then the total number of bins is given by:

$$\text{Tot.} = n_c n_b$$

Each carrier is separated by a distance from the preceding carrier, and the next carrier, to avoid interference as it operates. If $s_c$ is the centre-to-centre spacing from one carrier to the next carrier, then:

$$s_c n_c = C$$

with terms as defined above.

**KEYPOINT**
The size and capacity of a carousel system depends upon the number individual bins that revolve around an oval rail with a given circumference, and by a set centre-to-centre spacing from one carrier to the next.

**END KEYPOINT**

![Figure 9.5: Major Components of Carousel](image-url)
Carousel systems have higher throughput rates than an AS/RS. The following set of assumptions must be made when calculating storage/retrieval cycle times for carousel systems:

**BULLET LIST**

- Only single command cycles are performed—a bin is accessed in the carousel either to put items into storage or to retrieve one or more items from storage.

- The carousel operates at constant speed—acceleration and deceleration effects are ignored.

- Random storage is assumed—any location around the carousel is equally likely to be selected for an S/R transaction.

- The carousel can move in either direction.

**END LIST**

Upon the last assumption, the mean travel distance between the load/unload station and a bin randomly located in the carousel is $C/4$. Thus, the S/R cycle time is given by:

$$T_c = \frac{C}{4v_c} + T_{pd}$$

where $T_c$ is the S/R cycle time; $C$ is the carousel circumference; $v_c$ is the carousel velocity; and $T_{pd}$ is the average time required to pick or deposit items each cycle by the operator at the load/unload station. The number of transactions accomplished per hour is the same as the number of cycles and is given by the following:

$$R_t = R_c = \frac{60}{T_c}$$

**KEYPOINT**

Carousel systems have higher throughput rates than an AS/RS.

**END KEYPOINT**

**EXAMPLE 9.2**
A single carousel storage system is located in a factory making small assemblies. It is 20 m long and 1.0 m wide. The pick and deposit time is 0.25 min. The speed at which the carousel operates is 0.5 m/s. The storage system has a 90% utilization. Determine the hourly throughput rate.

**Solution:**

\[ C = 2(L - W) + \pi W = 2(20 - 1) + 1\pi = 41.14 \text{ m} \]

\[ T_c = \frac{C}{4v_c} + T_{pd} = \frac{41.14}{4(0.5)} + 0.25(60) = 35.57 \text{ sec} = 0.593 \text{ min}, \]

\[ R_t = \frac{60}{0.593} = 101.2 \text{ transaction/hr} \]

**END EXAMPLE**

**LEARNING ACTIVITY 9.3**

A carousel storage system is to be designed to serve a mechanical assembly plant. The specifications on the system are that it must have a total of 400 storage bins and a throughput of at least 125 storage and retrieval transactions per hour. Two alternative configurations are being considered: (1) a one-carousel system and (2) a two-carousel system. In either case, the width of the carousel is to be 1.2m and the spacing between carriers = 0.8m. One picker-operator will be required for the one-carousel system and two picker-operators will be required for the two-carousel system. In either case, the height of the carousel is to be limited to 5 bins. The standard time for a pick and deposit operation at the load/unload station = 0.4 min if one part is picked or stored per bin and 0.6 min if more than one part is picked or stored. Assume that 50% of the transactions will involve more than one component. Determine (a) the required length of the one-carousel system and (b) the corresponding throughput rate; (c) the required length of the two-carousel and (d) the corresponding throughput rate. (e) Which system better satisfies the design specifications?

**END LEARNING ACTIVITY**

**9.8 Unit Review**

**BULLETLIST**

A material storage system allows materials to be stocked for a specified period of time, before they are re-introduced, or are introduced for the first time, into the automation system.

Storage systems’ operating characteristics can be examined on two sets of issues: storage system performance; and storage location strategies.

Performance measures used to assess storage system performance include: storage capacity, storage density, accessibility, system throughput, utilisation, and availability.
Storage location strategies organise stock in a storage system, and have a considerable impact upon storage system performance.

The two basic strategies that may be deployed for storage location are: randomised storage, and dedicated storage.

Storage methods and equipment include: bulk storage for use by pallet trucks and powered forklifts; rack systems for use by pallet trucks and powered forklifts; shelving and bins for use by manual attendants or powered forklifts; and drawer storage for use by manual attendants.

When automation is applied to storage systems it tends to minimise human interaction with the storage function.

Depending on particular requirements and individual circumstances, storage system automation can be set to different levels, so that human interaction is included to a higher or lower degree.

Automated storage can be examined as either automated storage/retrieval systems, or carousel storage systems.

An automated storage/retrieval system (AS/RS) is a storage system that performs storage and retrieval operations with speed and accurate under a defined degree of automation.

An AS/RS consists of a rack structure and storage/retrieval mechanism that operates to deliver materials into and out-of the storage system, via pickup-and-deposit stations.

Different types of AS/RS include: unit load AS/RS; deep-lane AS/RS; mini-load AS/RS; man-on-board AS/RS; automated item retrieval system; and vertical lift storage modules.

The application areas for AS/RS technology are: unit load storage and handling; order picking; and work-in-process storage.

Work-in-process may be managed by either AS/RS systems or carousel systems, for batch and job shop production.

Reasons for the implementation of WIP automated storage systems include: buffer storage in production; support of just-in-time delivery; kitting of parts for assembly; compatibility with automatic identification systems; computer control and tracking of materials; and support of factory-wide automation.
Typical components of an AS/RS include: a storage structure; an S/R machine; storage modules; and one or more pickup-and-deposit stations.

The item location file is the locational record of a particular material stored in the storage system. The item location file is used as the basis for the retrieval and deposit of materials in the storage system by the S/R machine.

A carousel storage system is one with a series of bins or baskets suspended from an overhead chain conveyor that revolves around a long oval rail system.

Carousels are either horizontal or vertical in construction.

Horizontal carousels consist of a welded steel framework for the oval rail system, which can be either mounted overhead (a top-driven unit), or from below (a bottom-driven unit).

Vertical carousels operate around a vertical conveyor loop that may be limited by the height of the building in which they are implemented.

Both manual and computer control mechanisms may be used in conjunction with horizontal and vertical carousel systems.

Typical applications of carousels include their use in: storage and retrieval operations; transport and accumulation functions; work-in-process storage; and other specialised use areas.

Aisle capacity depends on the number of its storage compartments and their horizontal and vertical arrangement.

System throughput depends upon an analysis of single and dual command cycles in the AS/RS.

The size and capacity of a carousel system depends upon the number of individual bins that revolve around an oval rail with a given circumference, and by a set centre-to-centre spacing from one carrier to the next.

Carousel systems have higher throughput rates than an AS/RS.

**9.9 Self-Assessment Questions**

What do we mean by the phrase material storage system? What issues affect its operating characteristics?
List performance measures that may be used to assess storage system performance.

What methods and equipment are typically used for storage purposes?

What are the effects of automation on human intervention in storage systems?

What are the types of automated storage categories that can be examined?

What are automated storage/retrieval systems (AS/RS)? What is their associated equipment?

What types of AS/RS construction are possible?

Why are WIP automated storage systems typically deployed?

What are carousel storage systems? Briefly describe their overall construction.

What are the typical applications of carousel storage systems?

What are the determinants of aisle capacity and system throughput for AS/RS?

What are the determinants of size and capacity for carousel systems?

9.10 Answers to Self-Assessment Questions

A material storage system allows materials to be stocked for a specified period of time, before they are re-introduced, or are introduced for the first time, into the automation system. Storage systems' operating characteristics can be examined on two sets of issues: storage system performance; and storage location strategies.

Performance measures that may be used to assess storage system performance include: storage capacity, storage density, accessibility, system throughput, utilisation, and availability.

Methods and equipment that is typically used for storage purposes include: bulk storage for use by pallet trucks and powered forklifts; rack systems for use by pallet trucks and powered forklifts; shelving and bins for use by manual attendants or powered forklifts; and drawer storage for use by manual attendants.
When automation is applied to storage systems it tends to minimise human interaction with the storage function. Depending on particular requirements and individual circumstances, storage system automation can be set to different levels, so that human interaction is included to a higher or lower degree.

Automated storage can be examined as either automated storage/retrieval systems, or carousel storage systems.

An automated storage/retrieval system (AS/RS) is a storage system that performs storage and retrieval operations with speed and accurate under a defined degree of automation. An AS/RS consists of a rack structure and storage/retrieval mechanism that operates to deliver materials into and out-of the storage system, via pickup-and-deposit stations.

Different types of AS/RS construction include: unit load AS/RS; deep-lane AS/RS; mini-load AS/RS; man-on-board AS/RS; automated item retrieval system; and vertical lift storage modules.

Reasons for the implementation of WIP automated storage systems include: to provide buffer storage in production; to support of just-in-time delivery; to allow for the kitting of parts for assembly; to ensure the compatibility with automatic identification systems; to enable computer control and tracking of materials; and to support of factory-wide automation.

A carousel storage system is one with a series of bins or baskets suspended from an overhead chain conveyor that revolves around a long oval rail system. Carousels are either horizontal or vertical in construction.

Typical applications of carousels include their use in: storage and retrieval operations; transport and accumulation functions; work-in-process storage; and other specialised use areas.

The determinants of aisle capacity are the number of its storage compartments and their horizontal and vertical arrangement. The determinants of system throughput depend upon an analysis of single and dual command cycles in the AS/RS.

The determinants of size and capacity for carousel systems are the number of individual bins that revolve around an oval rail with a given circumference, and by a set centre-to-centre spacing from one carrier to the next.

END LIST