Chapter 11

Storage Systems

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The function of a material storage system is to store materials for a period of time and to permit access to those materials when required. Materials stored by manufacturing firms include a variety of types, as indicated in Table 11.1. Categories (1)–(5) relate directly to the product, (6)–(8) relate to the process, and (9) and (10) relate to overall support of factory operations. The different categories of materials require different storage methods and controls. Many production plants use manual methods for storing and retrieving items. The storage function is often accomplished inefficiently, in terms of human resources, factory floor space, and material control. Automated methods are available to improve the efficiency of the storage function.

In this chapter, we describe the types of storage equipment and methods, dividing them into conventional and automated types. The final section presents a quantitative analysis of automated storage systems, with emphasis on two important performance measures: storage capacity and throughput.
TABLE 11.1 Types of Materials Typically Stored in a Factory

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Raw materials</td>
<td>Raw stock to be processed (e.g., bar stock, sheet metal, plastic molding compound)</td>
</tr>
<tr>
<td>2. Purchased parts</td>
<td>Parts from vendors to be processed or assembled (e.g., castings, purchased components)</td>
</tr>
<tr>
<td>3. Work-in-process</td>
<td>Partially completed parts between processing operations or parts awaiting assembly</td>
</tr>
<tr>
<td>4. Finished product</td>
<td>Completed product ready for shipment</td>
</tr>
<tr>
<td>5. Rework and scrap</td>
<td>Parts that do not meet specifications, either to be reworked or scrapped</td>
</tr>
<tr>
<td>6. Refuse</td>
<td>Chips, swarf, oils, other waste products left over after processing; these materials must be disposed of, sometimes using special precautions</td>
</tr>
<tr>
<td>7. Tooling</td>
<td>Cutting tools, jigs, fixtures, molds, dies, welding wire, and other tooling used in manufacturing and assembly; supplies such as helmets, gloves, etc.</td>
</tr>
<tr>
<td>8. Spare parts</td>
<td>Parts needed for maintenance and repair of factory equipment</td>
</tr>
<tr>
<td>9. Office supplies</td>
<td>Paper, paper forms, writing instruments, and other items used in support of plant office</td>
</tr>
<tr>
<td>10. Plant records</td>
<td>Records on product, equipment, and personnel</td>
</tr>
</tbody>
</table>

11.1 STORAGE SYSTEM PERFORMANCE AND LOCATION STRATEGIES

Before describing the storage methods and equipment, let us describe certain terms and operating characteristics related to storage systems. Our coverage is organized into the following topics: (1) storage system performance and (2) storage location strategies.

11.1.1 Storage System Performance

The performance of a storage system in accomplishing its function must be sufficient to justify its investment and operating expense. Various measures used to assess the performance of a storage system include (1) storage capacity, (2) storage density, (3) accessibility, and (4) throughput. In addition, standard measures used for mechanized and automated systems include (5) utilization and (6) reliability.

Storage capacity can be defined and measured in two ways: (1) as the total volumetric space available or (2) as the total number of storage compartments in the system available to hold items or loads. In many storage systems, materials are stored in unit loads that are held in standard size containers (pallets, tote pans, or other containers). The standard container can readily be handled, transported, and stored by the storage system and by the material transport system that may be connected to it. Hence, storage capacity is conveniently measured as the number of unit loads that can be stored in the system. The physical capacity of the storage system should be greater than the maximum number of loads anticipated to be stored, to provide available empty spaces for materials entering the system and to allow for variations in maximum storage requirements.

Storage density is defined as the volumetric space available for actual storage relative to the total volumetric space in the storage facility. In many warehouses, aisle space and wasted overhead space account for more volume than the volume available for actual
storage of materials. Floor area is sometimes used to assess storage density, because it is convenient to measure this on a floor plan of the facility. However, volumetric density is usually a more appropriate measure than area density.

For efficient use of space, the storage system should be designed to achieve a high density. However, as storage density is increased, accessibility, another important measure of storage performance, is adversely affected. Accessibility refers to the capability to access any desired item or load stored in the system. In the design of a given storage system, appropriate tradeoffs must be made between storage density and accessibility.

System throughput is defined as the hourly rate at which the storage system (1) receives and puts loads into storage and/or (2) retrieves and delivers loads to the output station. In many factory and warehouse operations, there are certain periods of the day when the required rate of storage and/or retrieval transactions is greater than at other times. The storage system must be designed for the maximum throughput that will be required during the day.

System throughput is limited by the time to perform a storage or retrieval (S/R) transaction. A typical storage transaction consists of the following elements: (1) pick up load at input station, (2) travel to storage location, (3) place load in storage location, and (4) travel back to input station. A retrieval transaction consists of: (1) travel to storage location, (2) pick up item from storage, (3) travel to output station, and (4) unload at output station. Each element takes time. The sum of the element times is the transaction time that determines throughput of the storage system. Throughput can sometimes be increased by combining storage and retrieval transactions in one cycle, thus reducing travel time; this is called a dual command cycle. When either a storage or a retrieval transaction alone is performed in the cycle, it is called a single command cycle. The ability to perform dual command cycles rather than single command cycles depends on demand and scheduling issues. If, during a certain portion of the day, there is demand for only storage transactions and no retrievals, then it is not possible to include both types of transactions in the same cycle. If both transaction types are required, then greater throughput will be achieved by scheduling dual command cycles. This scheduling is more readily done by a computerized (automated) storage system than by one controlled manually.

There are variations in the way a storage/retrieval cycle is performed, depending on the type of storage system. In manually operated systems, time is often lost looking up the storage location of the item being stored or retrieved. On the other hand, manual systems can achieve greater efficiency by combining multiple storage and/or retrieval transactions in one cycle, thus reducing time traveling to and from the input/output station. Element times are subject to the variations and motivations of human workers, and there is a lack of control over the operations.

Two additional performance measures applicable to mechanized and automated storage systems are utilization and availability. Utilization is defined as the proportion of time that the system is actually being used for performing S/R operations compared with the time it is available. Utilization varies throughout the day, as requirements change from hour to hour. It is desirable to design an automated storage system for relatively high utilization, in the range 80–90%. If utilization is too low, then the system is probably oversized. If utilization is too high, then there is no allowance for rush periods or system breakdowns.

Availability is a measure of system reliability, defined as the proportion of time that the system is capable of operating (not broken down) compared with the normally scheduled shift hours (Section 3.1.3). Malfunctions and failures of the equipment cause
downtime. Reasons for downtime include computer failures, mechanical breakdowns, load jams, improper maintenance, and incorrect procedures by personnel using the system. The reliability of an existing system can be improved by following good preventive maintenance procedures and by having repair parts on hand for critical components. Backup procedures should be devised to mitigate the effects of system downtime.

11.1.2 Storage Location Strategies

Several strategies can be used to organize stock in a storage system. These storage location strategies affect the performance measures discussed above. The two basic strategies are (1) randomized storage and (2) dedicated storage. Let us explain these strategies as they are commonly applied in warehousing operations. Each item type stored in a warehouse is known as a stock-keeping-unit (SKU). The SKU uniquely identifies that item type. The inventory records of the storage facility maintain a count of the quantities of each SKU that are in storage.

In randomized storage, items are stored in any available location in the storage system. In the usual implementation of randomized storage, incoming items are placed into storage in the nearest available open location. When an order is received for a given SKU, the stock is retrieved from storage according to a first-in-first-out policy so that the items held in storage the longest are used to make-up the order.

In dedicated storage, SKUs are assigned to specific locations in the storage facility. This means that locations are reserved for all SKUs stored in the system, and so the number of storage locations for each SKU must be sufficient to accommodate its maximum inventory level. The basis for specifying the storage locations is usually one of the following: (1) items are stored in part number or product number sequence; (2) items are stored according to activity level, the more active SKUs being located closer to the input/output station; or (3) items are stored according to their activity-to-space ratios, the higher ratios being located closer to the input/output station.

When comparing the benefits of the two strategies, it is generally found that less total space is required in a storage system that uses randomized storage, but higher throughput rates can usually be achieved when a dedicated storage strategy is implemented based on activity level. Example 11.1 illustrates the storage density advantage of randomized storage.

EXAMPLE 11.1 Comparison of Storage Strategies

Suppose that a total of 50 SKUs must be stored in a storage system. For each SKU, average order quantity = 100 cartons, average depletion rate = 2 cartons/day, and safety stock level = 10 cartons. Each carton requires one storage location in the system. Based on this data, each SKU has an inventory cycle that lasts 30 days. Since there are 50 SKUs in all, management has scheduled incoming orders so that a different SKU arrives each day. Determine the number of storage locations required in the system under two alternative strategies: (a) randomized storage and (b) dedicated storage.

Solution: Our estimates of space requirements are based on average order quantities and other values in the problem statement. Let us first calculate the maximum inventory level and average inventory level for each SKU. The inventory for each SKU varies over time as shown in Figure 11.1. The maximum inventory
level, which occurs just after an order has been received, is the sum of the order quantity and safety stock level:

\[
\text{Maximum inventory level} = 100 + 10 = 110 \text{ cartons}
\]

The average inventory is the average of the maximum and minimum inventory levels under the assumption of uniform depletion rate. The minimum value occurs just before an order is received when the inventory is depleted to the safety stock level:

\[
\text{Minimum inventory level} = 10 \text{ cartons}
\]

\[
\text{Average inventory level} = \frac{(110 + 10)}{2} = 60 \text{ cartons}
\]

(a) Under a randomized storage strategy, the number of locations required for each SKU is equal to the average inventory level of the item, since incoming orders are scheduled each day throughout the 50-day cycle. This means that when the inventory level of one SKU near the beginning of its cycle is high, the level for another SKU near the end of its cycle is low. Thus, the number of storage locations required in the system is

\[
\text{Number of storage locations} = (50 \text{ SKUs})(60 \text{ cartons}) = 3,000 \text{ locations}
\]

(b) Under a dedicated storage strategy, the number of locations required for each SKU must equal its maximum inventory level. Thus, the number of storage locations required in the system is

\[
\text{Number of storage locations} = (50 \text{ SKUs})(110 \text{ cartons}) = 5,500 \text{ locations}
\]

Some of the advantages of both storage strategies can be obtained in a class-based dedicated storage allocation, in which the storage system is divided into several classes according to activity level, and a randomized storage strategy is used within each class. The classes containing more active SKUs are located closer to the input/output point of the storage system for increased throughput, and the randomized locations within the classes reduce the total number of storage compartments required. We examine the effect of class-based dedicated storage on throughput in Example 11.4 and several of our end-of-chapter problems.
11.2 CONVENTIONAL STORAGE METHODS AND EQUIPMENT

A variety of storage methods and equipment are available to store the various materials listed in Table 11.1. The choice of method and equipment depends largely on the material to be stored, the operating philosophy of the personnel managing the storage facility, and budgetary limitations. In this section, we discuss the traditional (nonautomated) methods and equipment types. Automated storage systems are discussed in the following section. Application characteristics for the different equipment types are summarized in Table 11.2.

**Bulk Storage.** Bulk storage is the storage of stock in an open floor area. The stock is generally contained in unit loads on pallets or similar containers, and unit loads are stacked on top of each other to increase storage density. The highest density is achieved when unit loads are placed next to each other in both floor directions, as in Figure 11.2(a). However, this provides very poor access to internal loads. To increase accessibility, bulk storage loads can be organized into rows and blocks, so that natural aisles are created between pallet loads, as in Figure 11.2(b). The block widths can be designed to provide an appropriate balance between density and accessibility. Depending on the shape and physical support provided by the items stored, there may be a restriction on how high the unit loads can be stacked. In some cases, loads cannot be stacked on top of each other, either because of the physical shape or limited compressive strength of the individual loads. The inability to stack loads in bulk storage reduces storage density, removing one of its principal benefits.

Although bulk storage is characterized by the absence of specific storage equipment, material handling equipment must be used to put materials into storage and to retrieve them. Industrial trucks such as pallet trucks and powered forklifts (Section 10.2.1) are typically used for this purpose.

**Rack Systems.** Rack systems provide a method of stacking unit loads vertically without the need for the loads themselves to provide support. One of the most common rack systems is the pallet rack, consisting of a frame that includes horizontal load-supporting beams, as illustrated in Figure 11.3. Pallet loads are stored on these horizontal beams. Alternative storage rack systems include

<table>
<thead>
<tr>
<th>Storage Equipment</th>
<th>Advantages and Disadvantages</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk storage</td>
<td>Highest density is possible</td>
<td>Storage of low turnover, large stock, or large unit loads</td>
</tr>
<tr>
<td></td>
<td>Low accessibility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low possible cost per square foot</td>
<td></td>
</tr>
<tr>
<td>Rack systems</td>
<td>Low cost</td>
<td>Palletized loads in warehouses</td>
</tr>
<tr>
<td></td>
<td>Good storage density</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Good accessibility</td>
<td></td>
</tr>
<tr>
<td>Shelves and bins</td>
<td>Some stock items not clearly visible</td>
<td>Storage of individual items on shelves</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Storage of commodity items in bins</td>
</tr>
<tr>
<td>Drawer storage</td>
<td>Contents of drawer easily visible</td>
<td>Small tools</td>
</tr>
<tr>
<td></td>
<td>Good accessibility</td>
<td>Small stock items</td>
</tr>
<tr>
<td></td>
<td>Relatively high cost</td>
<td>Repair parts</td>
</tr>
<tr>
<td>Automated storage systems</td>
<td>High throughput rates</td>
<td>Work-in-process storage</td>
</tr>
<tr>
<td></td>
<td>Facilitate use of computerized inventory control system</td>
<td>Final product warehousing and distribution center</td>
</tr>
<tr>
<td></td>
<td>Highest cost equipment</td>
<td>Order picking</td>
</tr>
<tr>
<td></td>
<td>Facilitate interface to automated material handling systems</td>
<td>Kitting of parts for electronic assembly</td>
</tr>
</tbody>
</table>

**TABLE 11.2 Application Characteristics of the Types of Storage Equipment and Methods**
Figure 11.2 Various bulk storage arrangements: (a) high-density bulk storage provides low accessibility; (b) bulk storage with loads arranged to form rows and blocks for improved accessibility.

Figure 11.3 Pallet rack system for storage of unit loads on pallets.
• **Cantilever racks**, similar to pallet racks except the supporting horizontal beams are cantilevered from the vertical central frame. Elimination of the vertical beams at the front of the frame provides unobstructed spans, which facilitates storage of long materials such as rods, bars, and pipes.

• **Portable racks**, which consist of portable box-frames that hold a single pallet load and can be stacked on top of each other, thus preventing load crushing that might occur in bulk vertical storage.

• **Drive-through racks.** These consist of aisles, open at each end, having two vertical columns with supporting rails for pallet loads on either side but no obstructing beams spanning the aisle. The rails are designed to support pallets of specific widths (Table 10.3). Forklift trucks are driven into the aisle to place the pallets onto the supporting rails. A related rack system is the *drive-in rack*, which is open at one end, permitting forklifts to access loads from one direction only.

• **Flow-through racks.** In place of the horizontal load-supporting beams in a conventional rack system, the flow-through rack uses long conveyor tracks capable of supporting a row of unit loads. The unit loads are loaded from one side of the rack and unloaded from the other side, thus providing first-in-first-out stock rotation. The conveyor tracks are inclined at a slight angle to allow gravity to move the loads toward the outside of the rack system.

**Shelving and Bins.** Shelves represent one of the most common storage equipment types. A *shelf* is a horizontal platform, supported by a wall or frame, on which materials are stored. Steel shelving sections are manufactured in standard sizes, typically ranging from about 0.9 to 1.2 m (3 to 4 ft) long (in the aisle direction), from 0.3 to 0.6 m (12 to 24 in) wide, and up to 3.0 m (10 ft) tall. Shelving often includes *bins*, which are containers or boxes that hold loose items.

**Drawer Storage.** Finding items in shelving can sometimes be difficult, especially if the shelf is either far above or far below eye level for the storage attendant. Storage drawers, Figure 11.4, can alleviate this problem because each drawer pulls out to allow its entire contents to be readily seen. Modular drawer storage cabinets are available with a variety of drawer depths for different item sizes and are widely used for storage of tools and maintenance items.

![Cabinet](image)

**Figure 11.4** Drawer storage.
Figure 11.5 A unit load automated storage/retrieval system.

around an oval track loop to deliver the baskets to a load/unload station, as pictured in Figure 11.6. The differences between an AS/RS and a carousel storage system are summarized in Table 11.4.

An AS/RS consists of one or more storage aisles that are each serviced by a storage/retrieval (S/R) machine. (The S/R machines are sometimes referred to as cranes.) The aisles have storage racks for holding the stored materials. The S/R machines are used to deliver materials to the storage racks and to retrieve materials from the racks. Each AS/RS aisle has one or more input/output stations where materials are delivered into the storage system or moved out of the system. The input/output stations are called pickup-and-deposit (P&D) stations in AS/RS terminology. P&D stations can be manually operated or interfaced to some form of automated transport system such as a conveyor or an AGVS.

**AS/RS Types.** Several important categories of automated storage/retrieval system can be distinguished. The following are the principal types:

- **Unit load AS/RS.** The unit load AS/RS is typically a large automated system designed to handle unit loads stored on pallets or in other standard containers. The
11.3 AUTOMATED STORAGE SYSTEMS

The storage equipment described in the preceding section requires a human worker to access the items in storage. The storage system itself is static. Mechanized and automated storage systems are available that reduce or eliminate the amount of human intervention required to operate the system. The level of automation varies. In less automated systems, a human operator is required to handle each storage/retrieval transaction. In highly automated systems, loads are entered or retrieved under computer control, with no human participation except to input data to the computer. Table 11.2 lists the advantages and disadvantages as well as typical applications of automated storage systems.

An automated storage system represents a significant investment, and it often requires a new and different way of doing business. Companies have different reasons for automating the storage function. Table 11.3 provides a list of possible objectives and reasons behind company decisions to automate their storage operations. Automated storage systems divide into two general types: (1) automated storage/retrieval systems and (2) carousel storage systems. These two types are discussed in the following sections.

11.3.1 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. Figure 11.5 shows one aisle of an AS/RS that handles and stores unit loads on pallets. A wide range of automation is found in commercially available AS/RSs. At the most sophisticated level, the operations are totally automated, computer controlled, and fully integrated with factory and/or warehouse operations. At the other extreme, human workers control the equipment and perform the storage/retrieval transactions. Automated storage/retrieval systems are custom designed for each application, although the designs are based on standard modular components available from each respective AS/RS supplier.

Our definition of AS/RS might be interpreted to include carousel storage systems. However, in the material handling industry, carousel-based systems are distinguished from AS/RSs. The biggest difference is in the construction of the equipment. The basic AS/RS consists of a rack structure for storing loads and a storage/retrieval mechanism whose motions are linear (x-y-z motions), as pictured in Figure 11.5. By contrast, the carousel system uses storage baskets suspended from an overhead conveyor that revolves

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**TABLE 11.3** Possible Objectives and Reasons for Automating a Company's Storage Operations

- To increase storage capacity
- To increase storage density
- To recover factory floor space presently used for storing work-in-process
- To improve security and reduce pilferage
- To improve safety in the storage function
- To reduce labor cost and/or increase labor productivity in storage operations
- To improve control over inventories
- To improve stock rotation
- To improve customer service
- To increase throughput
system is computer controlled, and the S/R machines are automated and designed to handle the unit load containers. The AS/RS pictured in Figure 11.5 is a unit load system. Other systems described below represent variations of the unit load AS/RS.

- **Deep-lane AS/RS.** The deep-lane AS/RS is a high-density unit load storage system that is appropriate when large quantities of stock are stored, but the number of separate stock types (SKUs) is relatively small. Instead of storing each unit load so that it can be accessed directly from the aisle (as in a conventional unit load system), the deep-lane system stores ten or more loads in a single rack, one load behind the next.

### Table 11.4 Differences Between an AS/RS and a Carousel Storage System

<table>
<thead>
<tr>
<th>Feature</th>
<th>Basic AS/RS</th>
<th>Basic Carousel Storage System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage structure</td>
<td>Rack system to support pallets or shelf system to support tote bins</td>
<td>Baskets suspended from overhead convey or trolleys</td>
</tr>
<tr>
<td>Motions</td>
<td>Linear motions of S/R machine</td>
<td>Revolution of overhead conveyor trolleys around oval track</td>
</tr>
<tr>
<td>Storage/retrieval operation</td>
<td>S/R machine travels to compartments in rack structure</td>
<td>Conveyor revolves to bring baskets to load/unload station</td>
</tr>
<tr>
<td>Replication of storage capacity</td>
<td>Multiple aisles, each consisting of rack structure and S/R machine</td>
<td>Multiple carousels, each consisting of oval track and suspended bins</td>
</tr>
</tbody>
</table>
Each rack is designed for "flow-through," with input on one side and output on the other side. Loads are picked up from one side of the rack by an S/R-type machine designed for retrieval, and another machine inputs loads on the entry side of the rack.

- **Miniload AS/RS.** This storage system is used to handle small loads (individual parts or supplies) that are contained in bins or drawers in the storage system. The S/R machine is designed to retrieve the bin and deliver it to a P&D station at the end of the aisle so that individual items can be withdrawn from the bins. The P&D station is usually operated by a human worker. The bin or drawer must then be returned to its location in the system. A miniload AS/RS is generally smaller than a unit load AS/RS and is often enclosed for security of the items stored.

- **Man-on-board AS/RS.** A man-on-board (also called man-aboard) storage/retrieval system represents an alternative approach to the problem of retrieving individual items from storage. In this system, a human operator rides on the carriage of the S/R machine. Whereas the miniload system delivers an entire bin to the end-of-aisle pick station and must return it subsequently to its proper storage compartment, with the man-on-board system the worker picks individual items directly at their storage locations. This offers an opportunity to increase system throughput.

- **Automated item retrieval system.** These storage systems are also designed for retrieval of individual items of small product cartons; however, the items are stored in lanes rather than bins or drawers. When an item is retrieved, it is pushed from its lane and drops onto a conveyor for delivery to the pickup station. The operation is somewhat similar to a candy vending machine, except that an item retrieval system has more storage lanes and a conveyor to transport items to a central location. The supply of items in each lane is periodically replenished, usually from the rear of the system so that there is flow-through of items, thus permitting first-in/first-out inventory rotation.

- **Vertical lift storage modules (VLSM) [10].** These are also called vertical lift automated storage/retrieval systems (VL-AS/RS) [7]. All of the preceding AS/RS types are designed around a horizontal aisle. The same principle of using a center aisle to access loads is used except that the aisle is vertical. Vertical lift storage modules, some with heights of 10 m (30 ft) or more, are capable of holding large inventories while saving valuable floor space in the factory.

**AS/RS Applications.** Most applications of AS/RS technology have been associated with warehousing and distribution operations. An AS/RS can also be used to store raw materials and work-in-process in manufacturing. Three application areas can be distinguished for automated storage/retrieval systems: (1) unit load storage and handling, (2) order picking, and (3) work-in-process storage. Unit load storage and retrieval applications are represented by the unit load AS/RS and deep-lane storage systems. These kinds of applications are commonly found in warehousing for finished goods in a distribution center, rarely in manufacturing. Deep-lane systems are used in the food industry. As described above, order picking involves retrieving materials in less than full unit load quantities. Miniload, man-on-board, and item retrieval systems are used for this second application area.

Work-in-process (WIP) storage is a more recent application of automated storage technology. While it is desirable to minimize the amount of work-in-process, WIP is unavoidable and must be effectively managed. Automated storage systems, either automated storage/retrieval systems or carousel systems, represent an efficient way to store materials
between processing steps, particularly in batch and job shop production. In high production, work-in-process is often carried between operations by conveyor systems, which thus serve both storage and transport functions.

The merits of an automated WIP storage system for batch and job shop production can best be seen by comparing it with the traditional way of dealing with work-in-process. The typical factory contains multiple work cells, each performing its own processing operations on different parts. At each cell, orders consisting of one or more parts are waiting on the plant floor to be processed, while other completed orders are waiting to be moved to the next cell in the sequence. It is not unusual for a plant engaged in batch production to have hundreds of orders in progress simultaneously, all of which represent work-in-process. The disadvantages of keeping all of this inventory in the plant include (1) time spent searching for orders, (2) parts or even entire orders becoming temporarily or permanently lost, sometimes resulting in repeat orders to reproduce the lost parts, (3) orders not being processed according to their relative priorities at each cell, and (4) orders spending too much time in the factory, causing customer deliveries to be late. These problems indicate poor control of work-in-process.

Automated storage/retrieval systems are also used in high-production operations. In the automobile industry, some final assembly plants use large capacity AS/RSs to temporarily store car and small truck bodies between major assembly steps. The AS/RS can be used for staging and sequencing the work units according to the most efficient production schedule [1].

Automated storage systems help to regain control over WIP. Reasons that justify the installation of automated storage systems for work-in-process include

- **Buffer storage in production.** A storage system can be used as a buffer storage zone between two processes whose production rates are significantly different. A simple example is a two-process sequence in which the first processing operation feeds a second process, which operates at a slower production rate. The first operation requires only one shift to meet production requirements, while the second step requires two shifts to produce the same number of units. An in-process buffer is needed between these operations to temporarily store the output of the first process.

- **Support of just-in-time delivery.** Just-in-time (JIT) is a manufacturing strategy in which parts required in production and/or assembly are received immediately before they are needed in the plant (Section 26.2). This results in a significant dependency of the factory on its suppliers to deliver the parts on time for use in production. To reduce the chance of stock-outs due to late supplier deliveries, some plants have installed automated storage systems as storage buffers for incoming materials. Although this approach subverts the objectives of JIT, it also reduces some of its risks.

- **Kitting of parts for assembly.** The storage system is used to store components for assembly of products or subassemblies. When an order is received, the required components are retrieved, collected into kits (tote pans), and delivered to the production floor for assembly.

- **Compatible with automatic identification systems.** Automated storage systems can be readily interfaced with automatic identification devices such as bar code readers. This allows loads to be stored and retrieved without needing human operators to identify the loads.
• **Computer control and tracking of materials.** Combined with automatic identification, an automated WIP storage system permits the location and status of work-in-process to be known.

• **Support of factory-wide automation.** Given the need for some storage of work-in-process in batch production, an appropriately sized automated storage system is an important subsystem in a fully automated factory.

**Components and Operating Features of an AS/RS.** Virtually all of the automated storage/retrieval systems described above consist of the following components, shown in Figure 11.5: (1) storage structure, (2) S/R machine, (3) storage modules (e.g., pallets for unit loads), and (4) one or more pickup-and-deposit stations. In addition, a control system is required to operate the AS/RS.

The storage structure is the rack framework, made of fabricated steel, which supports the loads contained in the AS/RS. The rack structure must possess sufficient strength and rigidity that it does not deflect significantly due to the loads in storage or other forces on the framework. The individual storage compartments in the structure must be designed to hold the storage modules used to contain the stored materials. The rack structure may also be used to support the roof and siding of the building in which the AS/RS resides. Another function of the storage structure is to support the aisle hardware required to align the S/R machines with respect to the storage compartments of the AS/RS. This hardware includes guide rails at the top and bottom of the structure as well as end stops and other features required to provide safe operation.

The S/R machine is used to accomplish storage transactions, delivering loads from the input station into storage, and retrieving loads from storage and delivering them to the output station. To perform these transactions, the storage/retrieval machine must be capable of horizontal and vertical travel to align its carriage (which carries the load) with the storage compartment in the rack structure. The S/R machine consists of a rigid mast on which is mounted an elevator system for vertical motion of the carriage. Wheels are attached at the base of the mast to permit horizontal travel along a rail system that runs the length of the aisle. A parallel rail at the top of the storage structure is used to maintain alignment of the mast and carriage with respect to the rack structure.

The carriage includes a shuttle mechanism to move loads into and from their storage compartments. The design of the shuttle system must also permit loads to be transferred from the S/R machine to the P&D station or other material-handling interface with the AS/RS. The carriage and shuttle are positioned and actuated automatically in the usual AS/RS. On-board S/R machines are equipped for a human operator to ride on the carriage.

To accomplish the desired motions of the S/R machine, three drive systems are required: horizontal movement of the mast, vertical movement of the carriage, and shuttle transfer between the carriage and a storage compartment. Modern S/R machines are available with horizontal speeds up to 200 m/min (600 ft/min) along the aisle and vertical or lift speeds up to around 50 m/min (150 ft/min). These speeds determine the time required for the carriage to travel from the P&D station to a particular location in the storage aisle. Acceleration and deceleration have a more significant effect on travel time over short distances. The shuttle transfer is accomplished by any of several mechanisms, including forks (for pallet loads) and friction devices for flat bottom tote pans.

The storage modules are the unit load containers of the stored material. These include pallets, steel wire baskets and containers, plastic tote pans, and special drawers (used in miniload systems). The storage modules are generally made to a standard base
size that can be handled automatically by the carriage shuttle of the S/R machine. The standard size is also designed to fit in the storage compartments of the rack structure.

The pickup-and-deposit station is where loads are transferred into and out of the AS/RS. It is generally located at the end of the aisle for access by the external handling system that brings loads to the AS/RS and takes loads away. Pickup stations and deposit stations may be located at opposite ends of the storage aisle or combined at the same location. This depends on the origin of incoming loads and the destination of output loads. A P&D station must be compatible with both the S/R machine shuttle and the external handling system. Common methods to handle loads at the P&D station include manual load/unload, forklift truck, conveyor (e.g., roller), and AGVS.

The principal AS/RS controls problem is positioning the S/R machine within an acceptable tolerance at a storage compartment in the rack structure to deposit or retrieve a load. The locations of materials stored in the system must be determined to direct the S/R machine to a particular storage compartment. Within a given aisle in the AS/RS, each compartment is identified by its horizontal and vertical positions and whether it is on the right side or left side of the aisle. A scheme based on alphanumeric codes can be used for this purpose. Using this location identification scheme, each unit of material stored in the system can be referenced to a particular location in the aisle. The record of these locations is called the “item location file.” Each time a storage transaction is completed, the transaction must be recorded in the item location file.

Given a specified storage compartment to go to, the S/R machine must be controlled to move to that location and position the shuttle for load transfer. One positioning method uses a counting procedure in which the number of bays and levels are counted in the direction of travel (horizontally and vertically) to determine position. An alternative method is a numerical identification procedure in which each compartment has a reflective target with binary-coded location identifications on its face. The S/R machine uses optical scanners to read the target and position the shuttle for depositing or retrieving a load.

Computer controls and programmable logic controllers are used to determine the required location and guide the S/R machine to its destination. Computer control permits the physical operation of the AS/RS to be integrated with the supporting information and record-keeping system. It allows storage transactions to be entered in real-time, inventory records to be accurately maintained, system performance to be monitored, and communications to be facilitated with other factory computer systems. These automatic controls can be superseded or supplemented by manual controls when required under emergency conditions or for man-on-board operation of the machine.

11.3.2 Carousel Storage Systems

A carousel storage system consists of a series of bins or baskets suspended from an overhead chain conveyor that revolves around a long oval rail system, as depicted in Figure 11.6. The purpose of the chain conveyor is to position bins at a load/unload station at the end of the oval. The operation is similar to the powered overhead rack system used by dry cleaners to deliver finished garments to the front of the store. Most carousels are operated by a human worker at the load/unload station. The worker activates the powered carousel to deliver a desired bin to the station. One or more parts are removed from or added to the bin, and then the cycle is repeated. Some carousels are automated by using transfer mechanisms at the load/unload station to move loads into and from the carousel.
Carousel Technology. Carousels can be classified as horizontal or vertical. The more common horizontal configuration, shown in Figure 11.6, comes in a variety of sizes, ranging between 3 m (10 ft) and 30 m (100 ft) in length. Carousels at the upper end of the range have higher storage density, but the average access cycle time is greater. Accordingly, most carousels are 10-16 m (30-50 ft) long to achieve a proper balance between these competing factors.

A horizontal carousel storage system consists of welded steel framework that supports the oval rail system. The carousel can be either an overhead system (called a top-driven unit) or a floor-mounted system (called a bottom-driven unit). In the top-driven unit, a motorized pulley system is mounted at the top of the framework and drives an overhead trolley system. The bins are suspended from the trolleys. In the bottom-driven unit, the pulley drive system is mounted at the base of the frame, and the trolley system rides on a rail in the base. This provides more load-carrying capacity for the carousel storage system. It also eliminates the problem of dirt and oil dripping from the overhead trolley system onto the storage contents in top-driven systems.

The design of the individual bins and baskets of the carousel must be consistent with the loads to be stored. Bin widths range from about 50 to 75 cm (20 to 30 in), and depths are up to about 55 cm (22 in). Heights of horizontal carousels are typically 1.8–2.4 m (6–8 ft). Standard bins are made of steel wire to increase operator visibility.

Vertical carousels are constructed to operate around a vertical conveyor loop. They occupy much less floor space than the horizontal configuration, but require sufficient overhead space. The ceiling of the building limits the height of vertical carousels, and therefore their storage capacity is typically lower than for the average horizontal carousel.

Controls for carousel storage systems range from manual call controls to computer control. Manual controls include foot pedals, hand switches, and specialized keyboards. Foot pedal control allows the operator at the pick station to rotate the carousel in either direction to the desired bin position. Hand control involves use of a hand-operated switch that is mounted on an arm projecting from the carousel frame within easy reach of the operator. Again, bidirectional control is the usual mode of operation. Keyboard control permits a greater variety of control features than the previous control types. When the operator enters the desired bin position, the carousel is programmed to deliver the bin to the pick station by the shortest route (i.e., clockwise or counterclockwise motion of the carousel).

Computer control increases opportunities for automation of the mechanical carousel and for management of the inventory records. On the mechanical side, automatic loading and unloading is available on modern carousel storage systems. This allows the carousel to be interfaced with automated handling systems without the need for human participation in the load/unload operations. Data management features provided by computer control include the capability to maintain data on bin locations, items in each bin, and other inventory control records.

Carousel Applications. Carousel storage systems provide a relatively high throughput and are often an attractive alternative to a miniload AS/RS in manufacturing operations where their relatively low cost, versatility, and high reliability are recognized. Typical applications of carousel storage systems include (1) storage and retrieval operations, (2) transport and accumulation, (3) work-in-process, and (4) specialized uses.

Storage and retrieval operations can be efficiently accomplished using carousels when individual items must be selected from groups of items in storage. Sometimes called "pick and load" operations, these procedures are common in order-picking of tools in a toolroom, raw materials in a stockroom, service parts or other items in a wholesale firm, and work-in-process in a factory. In small electronics assembly, carousels are used for kitting of parts to be transported to assembly workstations.
In transport and accumulation applications, the carousel is used to transport and/or sort materials as they are stored. One example of this is in progressive assembly operations where the workstations are located around the periphery of a continuously moving carousel, and the workers have access to the individual storage bins of the carousel. They remove work from the bins to complete their own respective assembly tasks, then place their work into another bin for the next operation at some other workstation. Another example of transport and accumulation applications is sorting and consolidation of items. Each bin is defined for collecting the items of a particular type or customer. When the bin is full, the collected load is removed for shipment or other disposition.

Carousel storage systems often compete with automated storage and retrieval systems for applications where work-in-process is to be temporarily stored. Applications of carousel systems in the electronics industry are common.

One example of specialized use of carousel systems is electrical testing of products or components, where the carousel is used to store the item during testing for a specified period of time. The carousel is programmed to deliver the items to the load/unload station at the conclusion of the test period.

11.4 ENGINEERING ANALYSIS OF STORAGE SYSTEMS

Several aspects of the design and operation of a storage system are susceptible to quantitative engineering analysis. In this section, we examine capacity sizing and throughput performance for the two types of automated storage systems.

11.4.1 Automated Storage/Retrival Systems

While the methods developed here are specifically for automated storage/retrieval systems, similar approaches can be used for analyzing traditional storage facilities, such as warehouses consisting of pallet racks and bulk storage.

Sizing the AS/RS Rack Structure. The total storage capacity of one storage aisle depends on how many storage compartments are arranged horizontally and vertically in the aisle, as indicated in our diagram in Figure 11.7. This can be expressed as

\[
\text{Capacity per aisle} = 2n_y n_z
\]  

(11.1)

where \( n_y \) = number of load compartments along the length of the aisle, and \( n_z \) = number of load compartments that make up the height of the aisle. The constant, 2, accounts for the fact that loads are contained on both sides of the aisle.

If we assume a standard size compartment (to accept a standard size unit load), then the compartment dimensions facing the aisle must be larger than the unit load dimensions. Let \( x \) and \( y \) = the depth and width dimensions of a unit load (e.g., a standard pallet size as given in Table 10.3), and \( z \) = the height of the unit load. The width, length, and height of the rack structure of the AS/RS aisle are related to the unit load dimensions and number of compartments as follows [6]:

\[
W = 3(x + a) \quad (11.2a)
\]

\[
L = n_y(y + b) \quad (11.2b)
\]

\[
H = n_z(z + c) \quad (11.2c)
\]
where $W$, $L$, and $H$ are the width, length, and height of one aisle of the AS/RS rack structure (mm, in); $x$, $y$, and $z$ are the dimensions of the unit load (mm, in); and $a$, $b$, and $c$ are allowances designed into each storage compartment to provide clearance for the unit load and to account for the size of the supporting beams in the rack structure (mm, in). For the case of unit loads contained on standard pallets, recommended values for the allowances [6] are: $a = 150$ mm (6 in), $b = 200$ mm (8 in), and $c = 250$ mm (10 in). For an AS/RS with multiple aisles, $W$ is simply multiplied by the number of aisles to obtain the overall width of the storage system. The rack structure is built above floor level by 300–600 mm (12–24 in), and the length of the AS/RS extends beyond the rack structure to provide space for the P&D station.

**EXAMPLE 11.2 Sizing an AS/RS System**

Each aisle of a four-aisle AS/RS contains 60 storage compartments in the length direction and 12 compartments vertically. All storage compartments are the same size to accommodate standard size pallets of dimensions: $x = 42$ in and $y = 48$ in. The height of a unit load $z = 36$ in. Using the allowances, $a = 6$ in, $b = 8$ in, and $c = 10$ in, determine (a) how many unit loads can be stored in the AS/RS and (b) the width, length, and height of the AS/RS.
**Solution:** (a) The storage capacity is given by Eq. (11.1):

Capacity per aisle = \(2(60)(12) = 1,440\) unit loads. With four aisles, the total capacity is

\[
\text{AS/RS capacity} = 4(1440) = 5760 \text{ unit loads}
\]

(b) From Eqs. (11.2), we can compute the dimensions of the storage rack structure:

\[
W = 3(42 + 6) = 144 \text{ in} = 12 \text{ ft/aisle}
\]

Overall width of the AS/RS = \(4(12) = 48 \text{ ft}\)

\[
L = 60(48 + 8) = 3,360 \text{ in} = 280 \text{ ft}
\]

\[
H = 12(36 + 10) = 552 \text{ in} = 46 \text{ ft}
\]

**AS/RS Throughput.** System throughput is defined as the hourly rate of S/R transactions that the automated storage system can perform (Section 11.1). A transaction involves depositing a load into storage or retrieving a load from storage. Either of these transactions alone is accomplished in a single command cycle. A dual command cycle accomplishes both transaction types in one cycle; since this reduces travel time per transaction, throughput is increased by using dual command cycles.

Several methods are available to compute AS/RS cycle times to estimate throughput performance. The method presented here is recommended by the Material Handling Institute [2]. It assumes (1) randomized storage of loads in the AS/RS (i.e., any compartment in the storage aisle is equally likely to be selected for a transaction), (2) storage compartments of equal size, (3) the P&D station located at the base and end of the aisle, (4) constant horizontal and vertical speeds of the S/R machine, and (5) simultaneous horizontal and vertical travel. For a single command cycle, the load to be entered or retrieved is assumed to be located at the center of the rack structure, as in Figure 11.8(a). Thus, the S/R machine must travel half the length and half the height of the AS/RS, and it must return the same distance. The single command cycle time can therefore be expressed by

\[
T_{cs} = 2 \text{ Max} \left\{ \frac{0.5L}{v_y}, \frac{0.5H}{v_z} \right\} + 2T_{pd} = \text{Max} \left\{ \frac{L}{v_y}, \frac{H}{v_z} \right\} + 2T_{pd} \quad (11.3a)
\]

![Diagram](image)

**Figure 11.8** Assumed travel trajectory of the S/R machine for (a) single command cycle and (b) dual command cycle.
where \( T_{cs} \) = cycle time of a single command cycle (min/cycle), \( L \) = length of the AS/RS rack structure (m, ft), \( v_y \) = velocity of the S/R machine along the length of the AS/RS (m/min, ft/min), \( H \) = height of the rack structure (m, ft), \( v_z \) = velocity of the S/R machine in the vertical direction of the AS/RS (m/min, ft/min), and \( T_{pd} \) = pickup-and-deposit time (min). Two P&D times are required per cycle, representing load transfers to and from the S/R machine.

For a dual command cycle, the S/R machine is assumed to travel to the center of the rack structure to deposit a load, and then it travels to 3/4 the length and height of the AS/RS to retrieve a load, as in Figure 11.8(b). Thus, the total distance traveled by the S/R machine is 3/4 the length and 3/4 the height of the rack structure, and back. In this case, cycle time is given by

\[
T_{cd} = 2 \max\left\{0.75L \over v_y, 0.75H \over v_z\right\} + 4T_{pd} = \max\left\{1.5L \over v_y, 1.5H \over v_z\right\} + 4T_{pd} \tag{11.3b}
\]

where \( T_{cd} \) = cycle time for a dual command cycle (min/cycle), and the other terms are defined above.

System throughput depends on the relative numbers of single and dual command cycles performed by the system. Let \( R_{cs} \) = number of single command cycles performed per hour, and \( R_{cd} \) = number of dual command cycles per hour at a specified or assumed utilization level. We can formulate the following equation for the amounts of time spent in performing single command and dual command cycles each hour:

\[
R_{cs}T_{cs} + R_{cd}T_{cd} = 60U \tag{11.4}
\]

where \( U \) = system utilization during the hour. The right-hand side of the equation gives the total number of minutes of operation per hour. To solve Eq. (11.4), the relative proportions of \( R_{cs} \) and \( R_{cd} \) must be determined, or assumptions about these proportions must be made. When solved, the total hourly cycle rate is given by

\[
R_c = R_{cs} + R_{cd} \tag{11.5}
\]

where \( R_c \) = total S/R cycle rate (cycles/hr). Note that the total number of storage and retrieval transactions per hour will be greater than this value unless \( R_{cd} = 0 \), since there are two transactions accomplished in each dual command cycle. Let \( R_t \) = the total number of transactions performed per hour; then

\[
R_t = R_{cs} + 2R_{cd} \tag{11.6}
\]

**EXAMPLE 11.3 AS/RS Throughput Analysis**

Consider the AS/RS from previous Example 11.2, in which an S/R machine is used for each aisle. The length of the storage aisle = 280 ft and its height = 46 ft. Suppose horizontal and vertical speeds of the S/R machine are 200 ft/min and 75 ft/min, respectively. The S/R machine requires 20 sec to accomplish a P&D operation. Determine (a) the single command and dual command cycle times per aisle and (b) throughput per aisle under the assumptions that storage system utilization = 90% and the number of single command and dual command cycles are equal.

**Solution:**  (a) We first compute the single and dual command cycle times by Eqs. (11.3):

\[
T_{cs} = \max\{280/200, 46/75\} + 2(20/60) = 2.066 \text{ min/cycle}
\]

\[
T_{cd} = \max\{1.5 \times 280/200, 1.5 \times 46/75\} + 4(20/60) = 3.432 \text{ min/cycle}
\]
(b) From Eq. (11.4), we can establish the single command and dual command activity levels each hour as follows:

\[ 2.066R_{cs} + 3.432R_{cd} = 60(0.90) = 54.0 \text{ min} \]

According to the problem statement, the number of single command cycles is equal to the number of dual command cycles. Thus, \( R_{cs} = R_{cd} \).

Substituting this relation into the above equation, we have

\[ 2.066R_{cs} + 3.432R_{cs} = 54 \]

\[ 5.498R_{cs} = 54 \]

\[ R_{cs} = 9.822 \text{ single command cycles/hr} \]

\[ R_{cd} = R_{cs} = 9.822 \text{ dual command cycles/hr} \]

System throughput is equal to the total number of S/R transactions per hour from Eq. (11.6):

\[ R_t = R_{cs} + 2R_{cd} = 29.46 \text{ transactions/hr} \]

With four aisle, \( R_t \) for the AS/RS = 117.84 transactions/hr

---

**EXAMPLE 11.4 AS/RS Throughput Using a Class-Based Dedicated Storage Strategy**

The aisles in the AS/RS of the previous example will be organized following a class-based dedicated storage strategy. There will be two classes, according to activity level. The more active stock is stored in the half of the rack system that is located closest to the input/output station, and the less active stock is stored in the other half of the rack system farther away from the input/output station. Within each half of the rack system, random storage is used. The more active stock accounts for 80% of the transactions, and the less active stock accounts for the remaining 20%. As before, assume that system utilization = 90%, and the number of single command cycles = the number of dual command cycles. Determine the throughput of the AS/RS, basing the computation of cycle times on the same kinds of assumptions used in the MHI method.

**Solution:** With a total length of 280 ft, each half of the rack system will be 140 ft long and 46 ft high. Let us identify the stock nearest the input/output station (accounting for 80% of the transactions) as Class A, and the other half of the stock (accounting for 20% of the transactions) as Class B. The cycle times are computed as follows:

For Class A stock:

\[ T_{scA} = \text{Max}\left\{ \frac{140}{200}, \frac{46}{75} \right\} + 2(0.333) = 1.366 \text{ min} \]

\[ T_{dcA} = \text{Max}\left\{ \frac{1.5 \times 140}{200}, \frac{1.5 \times 46}{75} \right\} + 4(0.333) = 2.382 \text{ min} \]

For Class B stock:

\[ T_{scB} = 2 \text{ Max}\left\{ \frac{140 + 0.5(140)}{200}, \frac{0.5(46)}{75} \right\} + 2(0.333) = 2.766 \text{ min} \]
\[ T_{dB} = 2 \max \left\{ \frac{140 + 0.75(140)}{200}, \frac{0.75(46)}{75} \right\} + 4(0.333) = 3.782 \text{ min} \]

Consistent with the previous problem, let us conclude that

\[ R_{cxA} = R_{cDA} \text{ and } R_{cxB} = R_{cDB} \quad (a) \]

We are also given that 80% of the transactions are Class A and 20% are Class B. Accordingly,

\[ R_{cxA} = 4R_{cxB} \text{ and } R_{cDA} = 4R_{cDB} \quad (b) \]

We can establish the following equation for how each aisle spends its time during 1 hr:

\[ R_{cxA} T_{cxA} + R_{cDA} T_{cDA} + R_{cxB} T_{cxB} + R_{cDB} T_{cDB} = 60(.90) \]

Based on Eqs. (a),

\[ R_{cxA} T_{cxA} + R_{cDA} T_{cDA} + R_{cxB} T_{cxB} + R_{cDB} T_{cDB} = 60(.90) \]

Based on Eqs. (b),

\[ 4R_{cxB} T_{cxA} + 4R_{cxB} T_{cDA} + R_{cxB} T_{cxA} + R_{cDB} T_{cDB} = 60(.90) \]

\[ 4(1.366)R_{cxB} + 4(2.382)R_{cxB} + 2.766R_{cxB} + 3.782R_{cxB} = 54 \]

\[ 21.54R_{cxB} = 54 \]

\[ R_{cxB} = 2.507 \]

\[ R_{cxA} = 4R_{cxB} = 10.028 \]

\[ R_{cDA} = R_{cDB} = 2.507 \]

\[ R_{cDB} = 4R_{cDB} = 10.028 \]

For one aisle,

\[ R_t = R_{cxA} + R_{cxB} + 2(R_{cDA} + R_{cDB}) \]

\[ = 10.028 + 2.507 + 2(10.028 + 2.507) = 37.605 \text{ transactions/hr} \]

For four aisles, \( R_t = 150.42 \text{ transactions/hr} \)

This represents almost a 28% improvement over the randomized storage strategy in Example 11.3.

### 11.4.2 Carousel Storage Systems

Let us develop the corresponding capacity and throughput relationships for a carousel storage system. Because of their construction, carousel systems do not possess nearly the volumetric capacity of an AS/RS. However, according to our calculations, a typical carousel system is likely to have higher throughput rates than an AS/RS.
**Storage Capacity.** The size and capacity of a carousel can be determined with reference to Figure 11.9. Individual bins or baskets are suspended from carriers that revolve around an oval rail with circumference given by

\[
C = 2(L - W) + \pi W \tag{11.7}
\]

where \(C\) = circumference of oval conveyor track (m, ft), and \(L\) and \(W\) are the length and width of the track oval (m, ft).

The capacity of the carousel system depends on the number and size of the bins (or baskets) in the system. Assuming standard size bins are used, each of a certain volumetric capacity, then the number of bins can be used as our measure of capacity. As illustrated in Figure 11.9, the number of bins hanging vertically from each carrier is \(n_b\), and \(n_c\) = the number of carriers around the periphery of the rail. Thus,

\[
\text{Total number of bins} = n_c n_b \tag{11.8}
\]

The carriers are separated by a certain distance so that they do not interfere with each other while traveling around the ends of the carousel. Let \(s_c\) = the center-to-center spacing of carriers along the oval track. Then the following relationship must be satisfied by the values of \(s_c\) and \(n_c\):

\[
s_c n_c = C \tag{11.9}
\]

where \(C\) = circumference (m, ft), \(s_c\) = carrier spacing (m/carerrier, ft/carerrier), and \(n_c\) = number of carriers, which must be an integer value.

**Throughput Analysis.** The storage/retrieval cycle time can be derived based on the following assumptions. First, 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. Second, the carousel operates with a constant speed \(v_c\); acceleration and deceleration effects are ignored. Third, random storage is assumed; that is, any location
around the carousel is equally likely to be selected for an S/R transaction. And fourth, the carousel can move in either direction. Under this last assumption of bidirectional travel, it can be shown that 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

\[ T_c = \frac{C}{4v_c} + T_{pd} \tag{11.10} \]

where \( T_c = \text{S/R cycle time (min)} \), \( C = \text{carousel circumference as given by Eq. (11.7) (m, ft)} \), \( v_c = \text{carousel velocity (m/min, ft/min)} \), and \( T_{pd} = \text{the average time required to pick or deposit items each cycle by the operator at the load/unload station (min)} \). The number of transactions accomplished per hour is the same as the number of cycles and is given by the following:

\[ R_t = R_c = \frac{60}{T_c} \tag{11.11} \]

**EXAMPLE 11.5 Carousel Operation**

The oval rail of a carousel storage system has length = 12 m and width = 1 m. There are 75 carriers equally spaced around the oval. Suspended from each carrier are six bins. Each bin has volumetric capacity = 0.026 m\(^3\). Carousel speed = 20 m/min. Average P&D time for a retrieval = 20 sec. Determine (a) volumetric capacity of the storage system and (b) hourly retrieval rate of the storage system.

**Solution:**

(a) Total number of bins in the carousel is

\[ n_c n_b = 75 \times 6 = 450 \text{ bins} \]

Total volumetric capacity = 450(0.026) = 11.7 m\(^3\)

(b) The circumference of the carousel rail is determined by Eq. (11.7):

\[ C = 2(12 - 1) + 1\pi = 25.14 \text{ m} \]

Cycle time per retrieval is given by Eq. (11.10):

\[ T_c = \frac{25.14}{4(20)} + 20/60 = 0.647 \text{ min} \]

Expressing throughput as an hourly rate, we have

\[ R_t = 60/0.647 = 92.7 \text{ retrieval transactions/hr} \]

**REFERENCES**

