WAREHOUSE AUTOMATION

From a product life cycle perspective, warehousing activities have a tremendous impact on the quality, cost, and lead time of product delivery to the customer. Typically, these activities include receiving, prepackaging, put-away, storing, order picking (pallets, cases, loose items), packaging, sorting, accumulating, packing and shipping, cross docking, and replenishing (1). Each product and its manufacturing/distribution situation is different and demands different considerations for the design of wareshousing systems. However, systems such as automated storage and retrieval systems (AS/RS) are a convenient way of integrating with other material handling, manufacturing, and distribution systems. For example, automated manufacturing systems such as flexible manufacturing systems (FMS) can provide the kind of flexibility of quick changeovers to different part types and their cost-effective production only if we can get the right parts, pallets, fixtures, and tools to the right place at the right time. For this purpose an efficient system for their storage and retrieval, together with a material transportation system, is required. An integrated system of FMS, AGVS, and AS/RS) provides an efficient production system to manufacture low-to-medium volume and mid-to-high variety products. In this article, we focus on automated storage and retrieval systems. The issues of design, analysis, and integration with other systems are covered. The majority of material adapted from Singh (2).

ARCHITECTURE FOR AUTOMATED COMPUTER CONTROL

There are two prominent computer control architectures that can be used to control the flow of materials and information: central control and distributed control. The bottom line in the design of a control system is to ensure that the automated systems keep running even if a control component fails. In a manufacturing environment that requires integration of various components such as AGVS, AS/RS, and FMS, distributed control is the logical choice. Distributed control allows debugging of the system level by level, does not need large central computer, and permits easy addition of components and expansion to integrate other systems. A generic distributed control system architecture is given in Fig. 1. Starting from the lowest level, the programmable logic controllers (PLCs) control and execute movements of AGVs, storage and retrieval (S/R) machines, other carriers, and equipment such as conveyors, monorails, and robots. The PLCs receive instructions from a group of microcomputers at the middle level (sometimes called system directors), which oversee the operations of systems such as AGVS, AS/RS, conveyors, and monorail systems. In turn, the microcomputers receive instructions at the top level from a minicomputer, called a *system manager,* which schedules material movement through the system. Back-up units are maintained at each level to ensure reliable system operation. This control system is only one of the modules of a complete manufacturing control system. The other modules are machine-tool control, management control, part control, tool control, and service control.

A computerized control system can be used to monitor the AS/RS system constantly. The system normally operates in a real-time mode; however, manual data input is also permitted. The locations of machines and movement of loads are

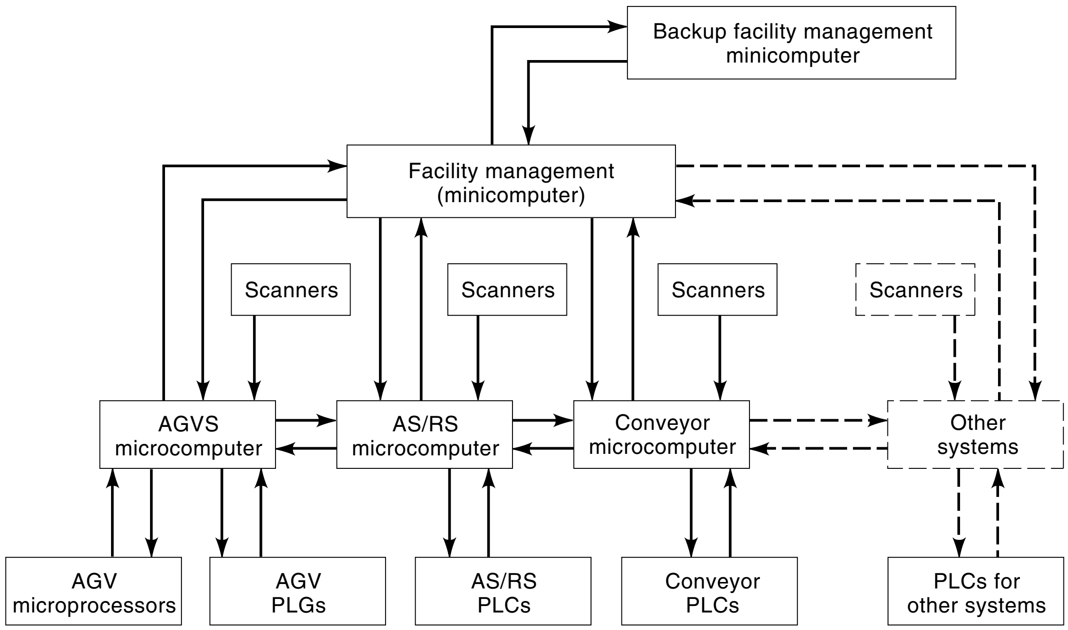


Figure 1. A distributed control architecture for AS/RS and AGVS (Source: Nanua Singh, *Systems Approach to Computer Integrated Design and Manufacturing,* New York: Wiley, 1996)

continuously monitored through a system of manual key pads, bar code scanners, and photoelectric sensors. Such a system increases the speed of storage and retrieval by reducing to a minimum the number of moves and distances moved required to locate a load. Full/empty bin detectors are used by S/R machines to determine the presence or absence of a load in the storage area. This increases the S/R machine productivity by preventing it from making any unnecessary or damaging actions such as inserting a load into a location that is already occupied.

FUNCTIONS OF STORAGE SYSTEMS AND DEFINITION OF AS/RS

The receiving, identified and sorting, dispatching to storage, placing in storage, storage, retrieving from storage, packing, shipping, and the like have traditionally been considered the functions of storage systems. An AS/RS attempts to achieve these functions by automating most of the procedures in a cost-effective and efficient manner.

An automated storage/retrieval system is defined by the Materials Handling Institute as "A combination of equipment and controls which handles, stores and retrieves materials with precision, accuracy and speed under a defined degree of automation." In general, it is a system that performs a basic set of operations without human intervention, regardless of the specific type of system that is employed. These operations are:

- automatic removal of an item from a storage location
- transportation of this item to a specific processing or interface point,
- automatic storage of an item in a predetermined location having received an item from a processing or interface point

Furthermore, operational control of all actions performed is automated by using a microprocessor or computer with appropriate software. However, in practice, the term AS/RS has come to mean a specific type of system using multitiered racks and a vehicle that stores and retrieves loads from a rack position in an aisle. A computerized system is used to regulate its performance.

AS/RS COMPONENTS AND TERMINOLOGY

An automated storage and retrieval system is made up of the following:

- a series of storage aisles having storage racks
- the S/R machines, normally one machine per aisle to store and retrieve materials
- one or more pick-up and delivery stations where materials are delivered for entry to the system and where materials are picked up from the system

Some of the components are indicated in Fig. 2. A brief explanation follows:

Storage Space. Storage space is the three-dimensional space in the storage racks that is normally required to store a single load unit of material.

Bay. Vertical stack of storage locations from the floor to the ceiling.

Row. A series of bays placed side by side.

Aisle. The space between two rows for the AS/RS machine operations.

Aisle Unit. Aisle space and racks adjacent to an aisle constitutes an aisle unit.

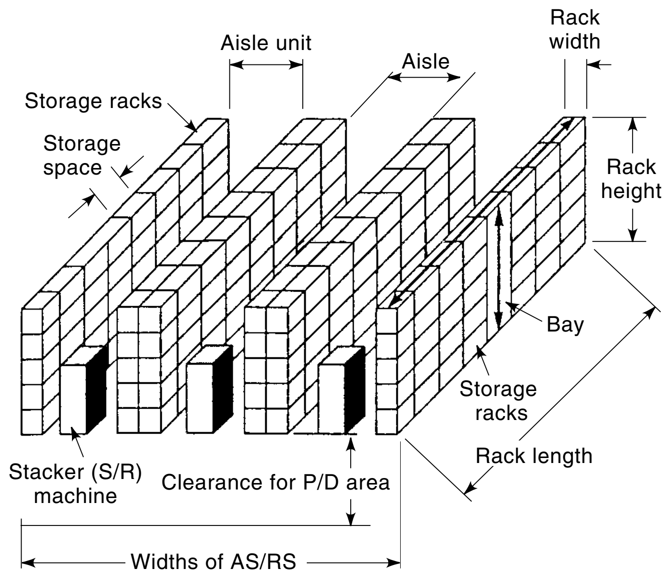


Figure 2. A generic structure of an AS/RS. (Source: Nanua Singh, *Systems Approach to Computer Integrated Design and Manufacturing,* New York: Wiley, 1996)

Storage Racks. A structural entity comprising storage locations, bays, and rows.

Storage Structure. A storage structure is composed of storage racks and is used to store inventory items. Usually, it is a steel frame structure designed to handle the expected size and weight of the stored items.

Storage and Retrieval Machine. In order to move the items in and out of inventory, it is necessary to have an S/R machine to perform this function. The S/R machine must be capable of both vertical and horizontal movements and must be able to place and remove items from storage, as well as to interface to entry and exit points of the AS/RS system. The entry and exit stations are sometimes referred to as input/output stations and also as pick-up-and-deposit (P/D) stations. There is a rail system along the floor to guide the machine and an overhead rail that is used to maintain the alignment of the machine.

Storage Modules. Modules are used to hold the inventory items. These may be pallets, bins, wire baskets, pans or other containers. The storage modules must be designed so that they are of a standard size capable of being stored in the structure and moved by the S/R machines.

Pick-up and Deposit Station. To allow inventory into the system, it is necessary to have P/D stations. These are generally located at the end of aisles so that they can be accessed by the S/R machines from the external material handling system. The actual location and number of P/D stations will depend on the quantity and type of inventory that flows through the AS/RS system. These are also be known as input/output (I/O) stations.

WHY AN AS/RS?

Some of the reasons that a company would choose to use an AS/RS system follow:

- AS/RS is highly space efficient. Space now occupied by raw stock, work-in-process, or finished parts and assemblies can be released for valuable manufacturing space.
- AS/RS increases storage capacity to meet long-range plans.
- AS/RS has improved inventory management and control.
- AS/RS has quick response time to locate, store and retrieve items.
- AS/RS has reduced shortages of inventory items as a result of real-time information and control.
- AS/RS has reduced labor costs as a result of automation.
- AS/RS has improved stock rotation.
- AS/RS has improved security and reduced pilferage because of closed storage area.
- AS/RS has flexible design to accommodate a wide variety of loads.
- AS/RS has a flexible interface with other systems such as AGVS and FMS and inspection systems such as coordinate machines.
- AS/RS reduces scrap and rework caused by automatic handling of parts.
- AS/RS reduces operating expenses on light, power, and heat requirements.
- AS/RS helps implement JIT concepts by getting the right parts, tools, pallets, and fixtures to the right place at the right time because of automatic control of storage and retrieval functions.

THE TYPES OF AS/RS

Several types of AS/RSs can be distinguished based on certain features and applications. Some of the important categories include

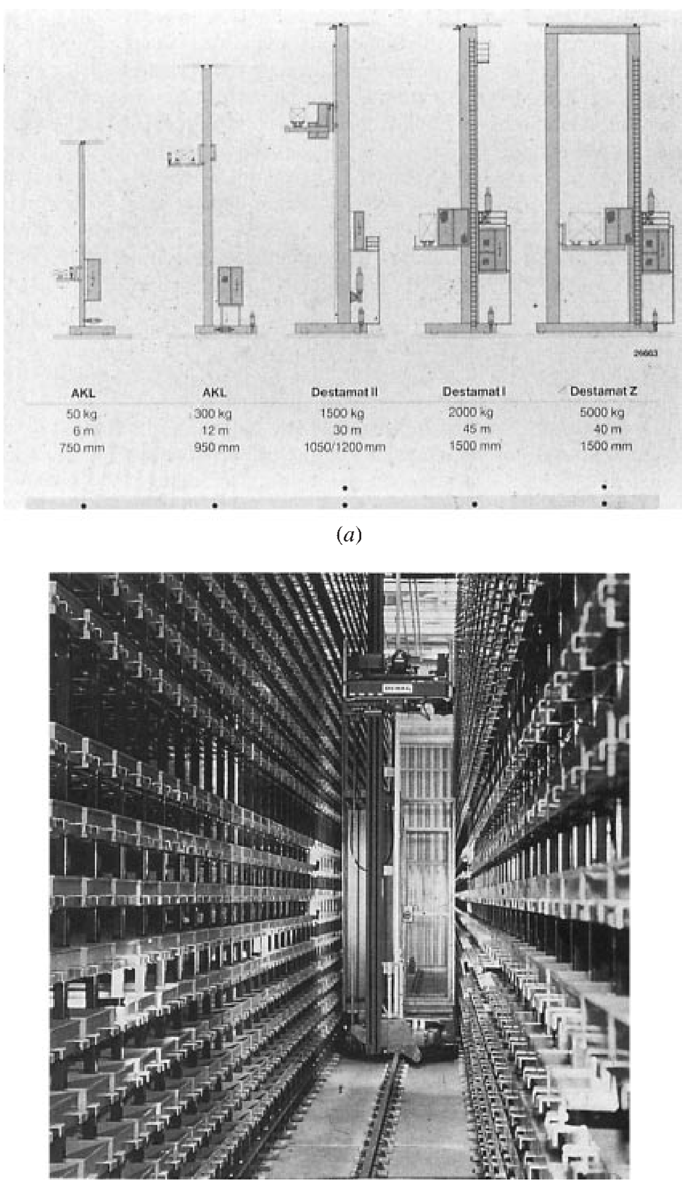
- Unit load AS/RS
- Miniload AS/RS
- Person-on-board AS/RS
- Automated item retrieval system
- Deep-lane AS/RS

Unit Load AS/RS

The unit load AS/RS system is used to store and retrieve loads that are palletized or stored in standard-sized containers. The loads are generally over 500 lb per unit. In general, a unit load system is computer-controlled having automated S/R machines designed to handle unit load containers. Each S/R machine is guided by rails in the floor of the structure, which is supported by the frame of the storage structure at the top of the frame. On the frame of the S/R machine itself is a shuttle, which is the load-supporting mechanism that moves loads to and from storage locations and the P/D stations. Usually, a mechanical clamp mechanism on the S/R machine handles the load. However, other mechanisms can be used such as a vacuum- or magnet-based mechanism for handling sheet metal. Typical R/S machines are shown in Fig. 3(a) and a typical unit load AS/RS in Fig. 3(b).

Miniload AS/RS

A miniload system is designed to handle small loads such as individual parts, tools, and supplies. The system is suitable for use in cases where there is a limit on the amount of space that can be used and where the volume is too low for a full-scale unit load system and too high for a manual system. A smaller investment and flexibility of handling small items makes it a popular choice in industry.



(*b*)

Figure 3. (a) S/R machines and (b) unit load AS/RS. (Courtesy: Rapistan Demag Corporation) (Source: Nanua Singh, *Systems Approach to Computer Integrated Design and Manufacturing,* New York: Wiley, 1996)

Person-on-Board System

The person-on-board system allows for storage of items in less than unit load quantities. A person rides on a platform with the S/R machine to pick up individual items from a bin or drawer. This provides an in-aisle order-picking ability that can reduce the time it takes to fill an order. The operator can select the items and place them into a tote or module, which is then carried by the S/R machine to the end of the aisle or to a conveyor to reach its destination. The platform (the operator is on) may contain additional devices, some automatic, to facilitate lifting of heavy items.

Deep Lane AS/RS

The deep lane AS/RS is another variation of the unit load system. The items are stored in multideep storage up to ten items per row rather than single or double-deep. This leads to a high density of stored items thus permitting high usage of the unit. Each rack permits a flow-through of items (i.e., an item is deposited on one side of the storage rack and removed from the other side). The S/R vehicle operates in the aisle loads and loads the rack-entry vehicle. It is typically a moving platform that carries the load into the storage rack, deposits it there, and returns to the S/R machine for the next load. The S/R machine is similar to the unit load S/R machine, except that S/R machines have specialized functions such as controlling rack-entry vehicles.

Automated Item Retrieval Systems

This system is designed for the automatic retrieval of individual items or cases for storage. The storage system consists of items stored individually in a flow-through system, which can be automatically released from storage and automatically brought to a required point. The items are stored from the rear, similar to the deep lane system and are only retrieved from the front by a rear-mounted pusher bar, usually onto a conveyor. The picking head moves to the correct lane, activates the pusher mechanism to the correct position, and pushes to release only the required number of units from storage.

DESIGN OF AS/RS

There are a large number of user and supplier related decisions that must be made in the design of an automated storage and retrieval system. Bozer and White (3) and the Material Handling Institute provide a list of a number of user and supplier related issues that must be considered. In this section we discuss the following important issues related to the layout and design of AS/RS:

- Determining load sizes
- Determining dimensions of an individual storage space
- Determining the number of storage spaces
- Determining the number of storage spaces considering dedicated storage policy
- Determining the number of storage spaces considering randomized storage policy
- Determining the system throughput and number of S/R machines

- Determining size parameters of storage and retrieval systems
- Determining the number of rows and the number of bays in each row in a system
- Determining bay width, rack length, system length, bay depth, aisle unit, and system width
- Determining single- and dual-command cycle times for unit load AS/RS
- Determining utilization of S/R machines

Determining Load Sizes

The variety and volume of part types and the type of production system used essentially determine the overall work flow (i.e., the movement frequency of parts, tools, fixtures, pallets, and other supplies). Work flow information is required to determine load sizes. The most important element in the design of an AS/RS is load size. Load size refers to the depth, width, and height. Normally, items are palletized into unit loads. The dimensions of the unit loads with appropriate clearances provide the individual storage space dimensions. The idea is to have uniform storage spaces that are large enough to accommodate most of the materials. AS/RS is not necessarily designed to store all kinds of items. There may be some unique items of unusual shape and sizes, that may be excluded from the AS/RS design. The weight of the unit loads is another important element that affects the structural design.

Determining Dimensions of an Individual Storage Space

To determine the dimension of an individual storage space, use the following equation:

$$\text{Height of a storage space} = h + c_1$$
$$\text{Length of a storage space} = l + c_2$$
$$\text{Width of individual storage space} = u(w + c_3)$$

where

h = height of a unit load
l = length of a unit load
w = width of a unit load
c_1 = height clearance required for a unit load
c_2 = length clearance required for a unit load
c_3 = width clearance required for a unit load
u = storage depth in number of unit loads

Normally, the storage space depth (width) is up to a maximum of three unit loads ($u = 3$).

Example 1. Determine the size of a single storage space. The dimensions of a unit load are 48 in. (width) × 52 (length) × 52 in. (height). The clearances are $c_1 = 10$ in., $c_2 = 8$ in., $c_3 = 6$ in., and $u = 3$.

SOLUTION

Height of an individual storage space = $h + c_1 = 52 + 10 = 62$ in.

Length of an individual storage space = $l + c_2 = 52 + 8 = 60$ in.

Width of individual storage space = $u(w + c_3) = 3(48 + 6) = 162$ in.

Determining the Number of Storage Spaces

We consider dedicated and randomized storage policies (4) to determine the number of storage spaces. The number thus determined should be revised considering future needs.

Determining the Number of Storage Spaces Considering Dedicated Storage Policy

Let us first understand what is a dedicated storage policy (also known as fixed-slot storage). In this policy, a particular set of storage slots or locations are assigned to a specific product. Therefore, the number of slots required to store the products equals the sum of the maximum inventory levels for all the products.

Determining the Number of Storage Spaces Considering Randomized Storage Policy

In randomized storage (also known as floating slot storage), each empty storage slot is equally likely to be selected for storage when a storage operation is performed. Likewise, each unit of a particular product is equally likely to be retrieved when a retrieval operation is performed. Therefore, in the long run, the number of storage spaces required equals maximum of the aggregate inventory level of all the products.

We illustrate two policies by a small example.

Example 2. Four products are received by a warehouse according to the following schedule given in Table 1. Determine the number of storage spaces that a storage and retrieval system should be designed for considering dedicated and randomized storage policies.

SOLUTION. Number of storage spaces required according to the dedicated storage policy is the sum of individual maximum inventory levels (2500 + 3000 + 3500 + 4000 = 13000 pallet loads). Number of storage spaces required according to the randomized storage policy is the maximum of aggregate inventory level (9000 pallet loads).

The randomized storage policy results in less storage than the dedicated storage policy. Two basic reasons (1) follow:

1. If an out-of-stock condition exists for a given stock keeping unit (SKU), the empty slot continues to remain ac-

Table 1. Pallet Loads of Products

Period	Product Types				Aggregate Inventory Level
	1	2	3	4	
1	1000[a]	1500	500	2000	5000
2	2500	700	800	500	4500
3	1500	3000	200	1300	6000
4	500	1000	3500	4000	9000
5	1100	900	200	300	2500

[a] Inventory level expressed in pallet loads.

tive with the dedicated storage, whereas it would not with the randomized storage.

2. If there are multiple slots for a given SKU, then empty slots will develop as the inventory level decreases.

There will, however, be no differences in the storage requirements for the dedicated and the randomized storage policies when the occurrences of inventory shortages are rare and single slots are assigned to SKUs. Many carousel and miniload systems meet these conditions.

Determining the System Throughput and the Number of S/R Machines

The system throughput refers to number of loads to be stored and number of loads to be retrieved per hour. The number of storing and retrievals is of course a function of production activity. Some of the factors that influence the throughput include:

- Speed of S/R machine
- Mix of single- and dual-cycle transactions
- Percent utilization of the storage racks
- Arrangement of stored items
- AS/RS control system speed
- Speed and efficiency of the material handling equipment (e.g., AGVS, conveyors, forklifts) used to move loads to the input and remove loads from the output

To efficiently carry out the production activity, the calculation of the number of S/R machines should be based on the maximum number of loads-in and loads-out per hour. The number of S/R machines can be determined as follows:

$$\text{Number of S/R machines} = \frac{\text{System throughput}}{\text{S/R machine capacity in cycles per hour}}$$

Example 3. Suppose the the single-command cycle system for the S/R machine is recommended. The average cycle time per operation is 1 min. The desired system throughput is 360 operations per hour. An operation refers to either storage or retrieval, and both take approximately same time. Determine the number of S/R machines.

SOLUTION The number of cycles per hour per machine = 60 because the cycle time is 1 min. Therefore,

$$\begin{aligned}\text{Number of S/R machines} &= \text{System throughput/(S/R machine capacity in cycles per hour)}\\ &= \text{System throughput/(S/R machine capacity in cycles per hour)}\\ &= \text{(360 operations per hour)/(60 cycles per hour per machine)}\\ &= 6\end{aligned}$$

Determining Size Parameters of Storage and Retrieval Systems

The sizing of an AS/RS system involves determining the system length, width, and height. For this purpose, it is required to determine number of rows in a system, number of bays in each row, number of loads per height, number of bays required per row, bay width, aisle width, bay depth, and aisle unit. We provide a simple analysis of the AS/RS sizing problem and illustrate the concept by an example in the following section.

Determining the Number of Rows and the Number of Bays in Each Row in a System

The S/R machines are used to store and retrieve materials, and their number is determined primarily by the system throughput and the cycle time. Normally, the S/R machines are dedicated to one aisle only. However, the machines may be used to serve more than one aisle. Each aisle has two rows. Therefore, in case of one S/R machine per aisle system, the number of rows would be

$$\text{Number of rows in the system} = 2 \times \text{Number of S/R machines in the system}$$

The number of bays can be determined as follows:

$$\begin{aligned}\text{Number of bays} = {}&\text{Number of storage spaces required/}\\ &\text{(Number of rows per S/R machine}\\ &\times \text{Number of S/R machines}\\ &\times \text{Number of storage spaces per system height)}\end{aligned}$$

$$\text{Number of storage spaces per system height} = \text{Desired system height/Storage space height}$$

The desired system height normally varies between 30 ft to 90 ft.

Example 4. Using the data from Examples 2 and 3, determine the number of rows and the number of bays in each row in the system.

SOLUTION. The number of S/R machines from Examples 2 and 3 are 6. Therefore, the number of rows in the system is $2 \times 6 = 12$.

$$\begin{aligned}\text{Number of storage spaces per system height} &= \text{Desired system height/Storage space height}\\ &= (77.5\text{ ft}) \times (12\text{ in./ft})/62\text{ in.} = 15\text{ in.}\end{aligned}$$

The total number of storage spaces using a randomized policy from Examples 2 and 3 is 9000.

$$\begin{aligned}\text{Number of bays in each row} &= \text{9000 storage spaces/(2 rows per S/R machine}\\ &\quad \times \text{6 machines} \times \text{15 storage spaces in the system height)}\\ &= 50\text{ bays}\end{aligned}$$

Determining Size Parameters

The bay width equals the length of a single storage space plus center-to-center rack support width. That is,

$$\begin{aligned}\text{Bay width} &= \text{Length of a storage space}\\ &\quad + \text{ Center to center rack support width}\\ &= l + c_2 + c_4\end{aligned}$$

where c_4 is center-to-center rack support width.

$$\begin{aligned}\text{Rack length} &= \text{ Bay width} \times \text{ Number of bays}\\ \text{System length} &= \text{ Rack length} + \text{ Clearance for S/R machine}\\ &\quad\ \text{run-out} + \text{ Clearance for the P/D area}\\ \text{Bay depth} &= \text{ Width of individual storage space}\\ &\quad + \text{ Bay side support allowance}\\ &= u(w + c_3) + c_5\end{aligned}$$

where c_5 is bay side support allowance.

$$\begin{aligned}\text{Aisle unit} &= \text{ Aisle width} = 2 \times \text{Bay depth}\\ \text{System width} &= \text{ Aisle unit} \times \text{Desired number of aisles}\end{aligned}$$

Example 5. Determine the following AS/RS sizing parameters using data from Examples 1, 2, 3, and 4. Assume that a randomized storage policy is used.

Bay width
Rack length
System length
Bay depth
Aisle unit
System width

Additional data are: c_4 = 6 in., c_5 = 6 in., desired system height = 77.5 ft, clearance for S/R machine run-out = 10 ft, clearance for the P/D area = 15 ft, aisle width = 6 ft

SOLUTION

$$\begin{aligned}\text{Bay width} &= 1 + c_2 + c_4 = 52 + 8 + 6 = 66 \text{ in.}\\ \text{Rack length} &= \text{Bay width} \times \text{Number of bays}\\ &= 66 \text{ in.} \times 50 = 3300 \text{ in.} = 275 \text{ ft}\\ \text{System length} &= \text{Rack length} + \text{Clearance for S/R machine}\\ &\quad\ \text{run-out and for the P/D area}\\ &= 275 + 10 + 15 = 300 \text{ ft}\\ \text{Bay depth} &= u(w + c_3) + c_5\end{aligned}$$

If u = 1, bay depth = 1 (48 + 6) + 6 = 60 in. If u = 2, bay depth = 2 (48 + 6) + 6 = 114 in. If u = 3, bay depth = 3 (48 + 6) + 6 = 168 in.

$$\begin{aligned}\text{Aisle unit} &= \text{Aisle width} + 2 \times \text{Bay depth}\\ &= 72 + 2 \times 60 = 192 \text{ in. for } u = 1\\ &= 72 + 2 \times 114 = 300 \text{ in. for } u = 2\\ &= 72 + 2 \times 168 = 408 \text{ in. for } u = 3\\ \text{System width} &= \text{Aisle unit} \times \text{Desired number of aisles}\\ &= 192 \times 5 = 960 \text{ in. for } u = 1\end{aligned}$$

Determining Single- and Dual-Command Cycle Times for Unit Load AS/RS

A detailed analysis for determining the cycle time for both single- and double-command cycles for unit load AS/RSs is given by Bozer and White (5) and is also described by Tompkins and White (4).

Single-Command Cycle. In a single-command cycle, either a storage or a retrieval operation is performed but not both. To determine cycle time, a storage cycle is assumed to begin with the S/R machine at the P/D station, pick up a load, travel to the storage location, deposit the load, and return empty to the P/D station. Similarly, a retrieval cycle begins with S/R at the P/D station, travels empty to the retrieval location, picks up the load, travels to the P/D station, and deposits the load.

Dual-Command Cycle. To determine cycle time, a dual-command cycle is assumed to begin with an /R machine at the P/D station, pick up a load, travel to the storage location and deposit the load there, travel empty to the retrieval location and retrieve the load from there, travel back to the P/D station, and deposit the load.

The cycle-time expressions derived by Bozer and White (5) are based on the following assumptions:

- randomized storage policy
- constant horizontal and vertical velocities
- single-sized rack openings
- P/D station located at the base and at the end of the aisle
- S/R machine travels simultaneously in the aisle both horizontally and vertically

The time required to travel from a P/D station to a storage or a retrieval station would be maximum of the horizontal and vertical travel times because of simultaneous travel of S/R machine.

The length and height of AS/RS aisle are easily obtained from the storage space dimensions as follows:

$$H = m(h + c_1)$$
$$L = n(l + c_2)$$

where

n = number of bays
m = number of storage spaces per system height

If the height H and length L of an aisle are known and the average horizontal and vertical speeds of S/R machines are V_h and V_v, respectively, then the time required to travel full horizontal length and vertical height of an aisle is given respectively by

$$t_h = L/V_h \text{ and } t_v = H/V_v$$

For the single-command cycle time,

$$T_{sc} = T\left(\frac{Q^2}{3} + 1\right) + 2T_{pd}$$

For the dual-command cycle time,

$$T_{\mathrm{dc}} = \frac{T}{30}(40 + 15Q^2 - Q^3) + 4T_{\mathrm{pd}}$$

where

$T = \max(t_h, t_v)$
$Q = \min(t_h/T, t_v/T)$
T_{pd} is the time to perform either a pick-up or deposit
t_h is the time required to travel full horizontal aisle distance
t_v is the time required to travel full vertical aisle distance

Example 6. Johnson and Johnson has an unit load AS/RS with six aisles. Six S/R machines are used, one for each aisle. From Example 5, the aisle length (rack length) is 275 ft, and the aisle height is 77.5 ft. The horizontal and vertical speeds are 300 ft/min and 70 ft/min, respectively. A P/D operation takes approximately 0.35 min of S/R machine. Determine the single- and dual-command cycle times for a unit load AS/RS of Johnson and Johnson company.

SOLUTION

$$\text{Length of an aisle} = 275\,\text{ft}$$
$$\text{Height of an aisle} = 77.5\,\text{ft}$$
$$V_h = 300\,\text{ft/min}$$
$$V_v = 70\,\text{ft/min}$$

Therefore,

$$t_h = L/V_h = (275\,\text{ft})/(300\,\text{ft/min}) = 0.9167\,\text{min}$$
$$t_v = H/V_v = (77.5\text{ft})/(70\,\text{ft/ min}) = 1.107\,\text{min}$$
$$T = \max(t_h, t_v) = \max(0.9167, 1.107) = 1.107$$
$$Q = \min(t_h/T, t_v/T) = \min(0.9167/1.107, 1.107/1.107) = 0.828$$

The single-command transaction cycle time is

$$T_{sc} = 1.107(0.828^2/3 + 1)_2(0.35) = 2.059\,\text{min}$$

The dual-command transaction cycle time is

$$T_{dc} = (1.107/30)[40 + 15(0.828)^2 - (0.828)^3] + 4(0.35) = 3.2345$$

Determining Utilization of S/R Machines

The S/R machine is the most critical component of any storage and retrieval system. Therefore, the percent utilization of S/R machine provides an interesting statistic for the performance evaluation of an automated storage and retrieval system.

Suppose the system throughput (ST) for an AS/RS is known. Remember that the system throughput is defined as the number of loads to be stored and as the number of loads to be retrieved per hour. Suppose the system throughput is ST. Suppose that each aisle is served by one S/R machine and that there are N number of S/R machines. Then the number of transactions per S/R machine per hour is

$$n_t = \text{ST}/N$$

Now suppose that the system permits a mixture of single- and dual-command transaction cycles and α and β are the percent of operations (storage and retrievals) done by single and dual-command cycles ($\alpha + \beta = 1$), respectively.

Assuming that the number of storage and retrievals are equal in the long run, the workload per S/R machine can be defined as

$$\text{Workload per machine} = \alpha n_t T_{sc} + \beta(n_t/2)T_{dc}\ \text{min per hour}$$

The $(n_t/2)$ appears in the second term in this expression because in a dual-command cycle both a storage and a retrieval are done in one cycle.

Example 7. Suppose that the system throughput is 300 storage and retrievals per hour. The AS/RS has ten aisles, and each is served by one S/R machine. Further, 30% of the operations are performed as single-command and the rest as dual-command operations. Determine the percent utilization of the machine. Other data from Example 5 apply to this problem. Determine the number of transactions at which the S/R machine is 100% utilized.

SOLUTION. Number of operations per machine per hour is

$$n_t = \text{ST}/N = 300/10 = 30$$

Therefore, the number of storage operations per hour is 15 and the number of retrievals per hour is 15, where $\alpha = 0.30$ and $\beta = 0.70$. From Example 7.8, we have $T_{sc} = 2.059$ min, $T_{dc} = 3.2345$ min. Therefore,

Workload per machine per hour

$$= \alpha n_t T_{sc} + \beta(n_t/2)T_{cd}$$
$$= 0.30(30)(2.059) + 0.70(30/2)(3.2345)\ \text{min}$$
$$= 52.49325\ \text{min}$$

Percent utilization of the S/R machine

$$= (52.49325/60) \times 100$$
$$= 87.488\%$$

For 100% utilization of S/R machine,

$$(\alpha n_t T_{sc} + \beta(n_t/2)T_{dc}) = 60$$

Therefore,

$$n_t = 120/(2\alpha T_{sc} + \beta T_{dc})$$
$$= 120/[2(0.30)(2.059) + (0.70)(3.2345)] = 34.29$$

That means that, if the number of operations per machine per hour exceed 34, the machine utilization is 100%, and there is need to look into AS/RS capacity expansion plans. Remember that, if the percent utilization is less than 50%, then one S/R machine can serve two aisles.

CONCLUSIONS

In this article, we provided an understanding of various issues on the design, planning, and control for AS/RS. AS/RSs are a major component of automated warehousing systems and are used in many warehousing situations including manufacturing and distribution.

BIBLIOGRAPHY

1. J. A. Tompkins et al., *Facilities Planning,* Toronto: Wiley, 1996.
2. N. Singh, *Systems Approach to Computer Integrated Design and Manufacturing,* New York: Wiley, 1996.
3. Y. A. Bozer and J. A. White, Optimum designs of automated storage/retrieval systems, *TIMS / ORSA Joint Nat. Meeting,* Washington, DC, 1980.
4. Tompkins and White, 1984.
5. Y. A. Bozer and J. A. White, Travel time models for automated storage/retrieval systems, *IIE Trans.,* **24** (4): 329–338, 1984.

Reading List

T. Brian and M. Pulat, Software tool automates AS/RS error recovery and preventive maintenance scheduling, *Industrial Eng.,* **21** (2): 43–45, 1989.

R. M. Eastman, *Materials Handling,* New York: Dekker, 1987, pp. 301–318.

S. Hackman and M. Rosenblatt, Allocating items to an automated storage and retrieval system, *IIE Trans.,* **22**, (1): 7–14, 1990.

M. Hwang, B. Beak, and M. K. Lee, Clustering algorithms for order picking in an automated storage and retrieval system, *Int. J. Prod. Res.,* **26**: 189–201, 1988.

M. Hwang and M. K. Lee, Order batching algorithms for a man-on-board automated storage and retrieval system, *Eng. Costs Prod. Econ.,* **13** (4): 285–294, 1988.

M. K. Lee and M. Hwang, An approach in the design of a unit-load automated carousel storage system, *Eng. Optimization,* **13**: 197–210, 1988.

R. G. T. Lindkvist, *Handbook of Material Handling,* Chichester, UK: Horwood, 1985, pp. 186–191.

W. L. Maxwell, Solving material handling design problem with OR, *Industrial Eng.,* **13** (4): 58–69, 1981.

L. L. Pan, D. Alasya, and L. D. Richards, Using material handling in the development of integrated manufacturing, *Industrial Eng.,* **24** (3): 43–48, 1992.

NANUA SINGH
Wayne State University

WAREHOUSING DATA. See DATAWAREHOUSING.
WARFARE, ELECTRONIC. See ELECTRONIC WARFARE.
WARNING SYSTEMS. See ALARM SYSTEMS.