Chapter 8
Automated Storage and Retrieval Systems: A Review on Travel Time Models and Control Policies

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Abstract Automated storage and retrieval system (AS/RS) is one of the major material handling systems, which is widely used in distribution centers and automated production environments. AS/RSs have been utilized not only as alternatives to traditional warehouses but also as a part of advanced manufacturing systems. AS/RSs can play an essential role in modern factories for work-in-process storage and offer the advantages of improved inventory control and cost-effective utilization of time, space and equipment. Many issues and approaches related to the efficiency improvement of AS/RSs have been addressed in the literature. This chapter presents an overview of this literature from the past 40 years. It presents a comprehensive description of the current state-of-the-art in AS/RSs and discusses future prospects. The focus is principally on travel time estimates and different control policies such as dwell-point of the stacker crane, storage assignment, request sequencing and so on. In particular, this chapter will provide researchers and decision makers with an understanding of how to apply existing approaches effectively.

8.1 Introduction

The chapter is presented in four sections. The current section and Sect. 8.2 provide brief background information on facilities planning and design, material handling, material handling equipment and Automated Storage and Retrieval System

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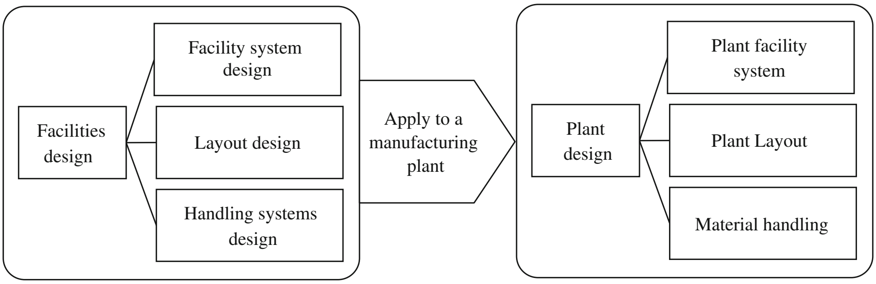

Fig. 8.1 Facilities design hierarchy for a manufacturing plant (Modified after Tompkins et al. 1996)

(AS/RS). Section 8.3 comprehensively reviews existing travel time models on different aspects of the AS/RS, especially its control policies. Finally, Sect. 8.4 presents conclusions and promising areas for further research.

8.1.1 Facilities Planning and Design

Manufacturing and service firms spend a considerable amount of time and money on planning or re-planning of their facilities. In broad terms, facilities planning determines how tangible fixed assets of an activity best support achieving the activity's objective. For a manufacturing firm, facility planning involves the determination of how the manufacturing facility best supports production (Tompkins et al. 1996). Facilities planning can be divided into its location and its design components. In this regard, facilities design is an extremely important function, which must be addressed before products are produced or services are rendered. A poor facility design can be costly and may result in poor-quality products, low employee morale and customer dissatisfaction. Facilities design is the arrangement of the company's physical facilities to promote the efficient use of the company's resources such as equipment, material, energy and people. Facilities design in a manufacturing plant includes not only plant facility system and plant layout but also material handling (Fig. 8.1) (Heragu 1997; Meyers and Stephens 2005).

8.1.2 Definition and Scope of Material Handling

Material handling is defined simply as moving material. The current widely used definition of material handling was presented by Tompkins et al. (1996) as the function of "providing the right amount of the right material, in the right condition, at the right place, at the right time, in the right position, in the right sequence, and for the right cost, by using the right method(s)". The American Society of Mechanical Engineers (ASME) defines material handling as "the art and science of moving, packaging, and storing of substances in any form". However, in recent years it has taken on broader connotations. Material handling may be thought as having five distinct dimensions: movement, quantity, time, space and control (Meyers and Stephens 2005). Raw material and parts must be delivered to the automated work cell, and the finished parts must be removed. Material handling systems are responsible for this transfer activity (Rehg 2003). Material handling is also defined by the Material Handling Industry of America as: "The movement, storage, protection and control of materials throughout the manufacturing and distribution process including their consumption and disposal" (Groover 2001). To begin with, any definition of material handling should include the concept of time and place utility. Material handling should also be investigated within a system context. In addition to these, a thorough definition of material handling must include the human aspect. Moreover the facility or space in which operations are housed should be considered as a part of the system. Finally, the definition of material handling must contain an economic consideration. Considering all the factors, a more complete definition might be the following (Kulwiec 1985): "Material handling is a system or combination of methods, facilities, labor, and equipment for moving, packaging, and storing of materials to specific objectives". It is important to note the factors that are not part of definition, as well as those that are. For instance, size and degree of mechanization are not parts of the definition. Material handling operation can either be simple and small, and involve only a few pieces of basic equipment, or it may be large, complex, or automated.

8.1.3 Material Handling Equipment

A wide variety of material handling equipment is available commercially. Material handling equipment includes (Groover 2001): (1) transport equipment, (2) storage systems, (3) unitizing equipment and (4) identification and tracking systems. Traditionally, material handling equipment has been grouped into four general categories (Table 8.1). The first category includes the fixed-path or point-to-point equipment such as automated guided vehicles (AGVs). Fixed path material handling systems are also referred to as continuous-flow systems. The second category is the fixed-area equipment such as AS/RSs. The third category is variable-pass variable-area equipment such as all manual carts and the fourth category consists of all auxiliary tools and equipment (Meyers and Stephens 2005).

Table 8.1 Four general categories of material handling equipment (Adapted from Meyers and Stephens 2005)

Category	Description	Example
Fixed-path or point-to-point equipment, (or continuous-flow systems)	This class of equipment serves the material handling need along a predetermined, or a fixed path	• Train and railroad track • Conveyor systems • Gravity-fed • AGVs
Fixed-area equipment	This class of equipment can serve any point within a 3D area or cube	• Jib cranes • *AS/RSs* • Bridge cranes
Variable-path variable-area equipment	This class of equipment can move to any area of the facility	• All manual carts • Motorized vehicles • Fork trucks
Auxiliary tools and equipment	This class of equipment consists of all auxiliary tools and equipment	• Pallets • Skids • Containers • Automated data collection systems

8.2 Automated Storage and Retrieval System

8.2.1 Definitions of AS/RS

AS/RS has been one of the major tools used for warehouse material handling and inventory control, since its introduction in 1950s. AS/RSs are widely used in automated production and distribution centers and can play an essential role in integrated manufacturing systems, as well as in modern factories for work-in-process (WIP) storage. AS/RSs offer the advantages of improved inventory control and cost-effective utilization of time, space and equipment (Hur et al. 2004; Manzini et al. 2006; Van den Berg and Gademann 1999).

In the broadest sense, AS/RSs (Fig. 8.2) can be defined as a combination of equipment and controls which automatically handle, store and retrieve materials with great speed and accuracy, without direct handling by a human worker (Linn and Wysk 1990b; Manzini et al. 2006; Lee et al. 1996). This definition covers a wide variety of systems with varying degrees of complexity and size. However, the term automated storage and retrieval system has come to mean a single type of system comprising one or multiple parallel aisles with multi-tiered racks; stacker crane (also referred to as storage/retrieval machine or S/R machine); input/output (I/O) stations (pickup/delivery stations, P/D stations or docks); accumulating conveyors and a central supervisory computer and communication system (Lee et al. 1996; Van den Berg and Gademann 2000).

Fig. 8.2 Automated storage and retrieval systems (Courtesy of Stöcklin Logistik AG)

Racks are typically steel or extruded aluminum structures with storage cells that can accommodate loads which need to be stored. Stacker cranes are the fully automated storage and retrieval machines that can autonomously move, pick up and drop-off loads. Aisles are formed by the empty spaces between the racks, where the stacker cranes can move. An I/O station is a location where retrieved loads are dropped off, and where incoming loads are picked up for storage. Pick positions (if any) are locations where human workers remove individual items from a retrieved load before the load is sent back into the system (Roodbergen and Vis 2009). Figure 8.14 (see Appendix to this chapter) illustrates the generic structure and principal constituents of an AS/RS. The AS/RS will automatically put away the product or parts, or take out the product, move it to where required and adjust the inventory level at both ends of the move (Meyers and Stephens 2005). AS/RSs are automated versions of the standard warehouses and come in a wide variety of sizes. Some are very large and some are no longer than a vertical file cabinet (Rehg 2003). Briefly, a conventional AS/RS operates as follows: the incoming items are first sorted and assigned to the pallets or boxes. The loads are then routed through weighing station to ensure that those are within the load weight limit. For the pallet loads, their sizes should also be within the load size limit. Those accepted are transported to I/O station(s), with the contents of the loads being communicated to the central computer. This computer assigns the load a storage location in the rack, and stores the location in its memory. The load is moved from the I/O station to storage by stacker crane. Upon receipt of a request for an item, the computer will search its memory for the storage location and direct the stacker crane to retrieve the load. The supporting transportation will transport the loads from the I/O station to its final destination (Linn and Wysk 1987).

8.2.2 Types and Applications of AS/RS

Several types of the AS/RS can be distinguished according to size and volume of items to be handled, storage and retrieval methods and interaction of a stacker crane and a human worker. The following are the principal types (Groover 2001; Automated Storage Retrieval Systems Production Section of the Material Handling Industry of America 2009):

1. *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 system is computer controlled, and the stacker cranes are automated and designed to handle unit-load containers. The unit-load system is the generic AS/RS. Other systems described below represent variations of the unit-load AS/RS.
2. *Deep-lane AS/RS*. The deep-lane AS/RS is a high density unit-load system that is appropriate when large quantities of stock are stored, but the number of separate stock types is relatively small. The loads can be stored to greater depths in the storage rack and the storage depth is greater than two loads deep on one or both sides of the aisle.
3. *Miniload AS/RS*. This storage system is generally smaller than a unit-load AS/RS and it is used to handle small loads (individual parts or supplies) that are contained in small standard containers, bins or drawers in the storage system. A miniload AS/RS works like a unit-load system, except that the insertion/extraction devices are designed to handle standard containers, totes or trays that store pieces, components and tools instead of unitized loads.
4. *Man-on-board AS/RS*. A man-on-board (also called man aboard) storage and retrieval system represents an alternative approach to the problem of retrieving individual items, from storage. In this system, a human operator rides on the stacker crane's carriage.
5. *Automated item-retrieval system*. These storage systems are also designed for retrieval of individual items or system product cartons; however, the items are stored in lanes rather than bins or drawers.
6. *Vertical lift storage modules* (*VLSM*). These are also called vertical lift automated storage/retrieval system (VL-AS/RS). 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 modules, some with height of 10 m (30 foot) or more, are capable of holding large inventories while saving valuable floor space in the factory.

Since in the material handling industry the carousel-based storage systems are distinguished from AS/RSs, they are not included in the above classification. A carousel storage system consists of a series of bins or baskets suspended from on

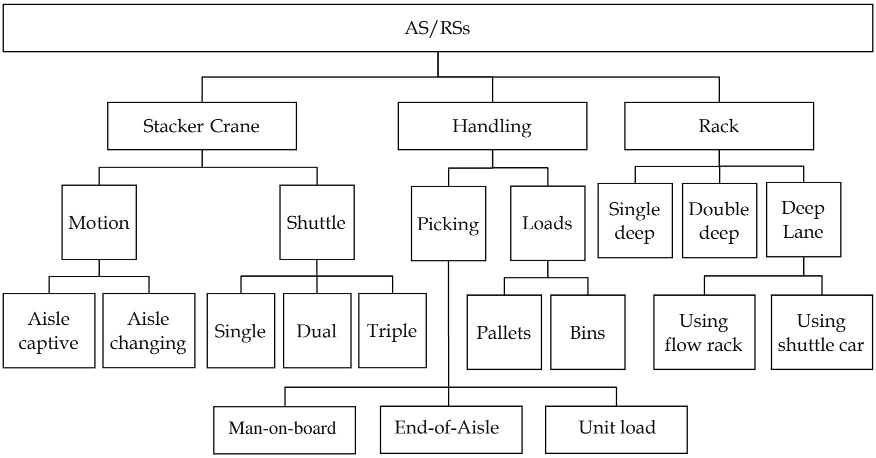

Fig. 8.3 Various system concepts for AS/RSs (Modified after Roodbergen and Vis 2009)

overhead chain conveyor that revolves around a long oval rail system. A general comparison between an AS/RS and a carousel storage system can be found in (Groover 2001). Based on the rack structure, stacker crane capabilities and its interaction with the worker and the product handling and picking methods, a large number of system options can be found for the AS/RSs. The most basic version of an AS/RS has in each aisle one stacker crane, which cannot leave its designated aisle (aisle-captive) and which can transport only one unit-load at a time (single shuttle). Product handling in this case is by unit-load (any load configuration handled as a single item, e.g., full pallet quantities) only; no people are involved to handle individual products. The racks in the basic version are stationary and single-deep (see Fig. 8.15 in Appendix to this chapter), which means that every load is directly accessible by the stacker crane. This AS/RS type is referred to as a single unit-load aisle-captive AS/RS. Numerous variations exist from this basic AS/RS. An overview of the main concepts is presented in Fig. 8.3. Recall that carousel storage systems with rotating racks are not considered in this overview.

Often an AS/RS is used for handling unit-loads only. If the unit-loads are bins, then the system is generally called a miniload AS/RS. Unit-loads arrive at the I/O station of the AS/RS from other parts of the warehouse by means of automated guided vehicles, conveyors and so on. The AS/RS stores the unit-loads and retrieves them again after a period of time. In some cases only part of the unit-load may be required to fulfill a customer’s order. This can be resolved by having a separate picking area in the warehouse; in which case the AS/RS serves to replenish the picking area. Alternatively, the picking operation can be integrated with the AS/RS. One option is to design the crane such that a person can ride along (man-on-board). Instead of retrieving a full pallet automatically from the location, the person can pick one item from the location. Another option to integrate item picking is when the AS/RS drops off the retrieved unit-loads at a workstation. A picker at this workstation takes the required amount of products from the unit-load after which the AS/RS moves the remainder of the load back into the rack. This system is often referred to as an end-of-aisle (EOA) system (Roodbergen and Vis 2009).

The AS/RSs are typically used in the applications where there is a very high volume of loads being moved into and out of the storage locations; storage density is important due to the space constraints; no value adding content is present in this process, and where the accuracy is critical in order to prevent potentially costly damages to the loads (ASAP Automation 2008). Under such circumstances, most applications of AS/RS technology have been associated with warehousing and distribution operations. An AS/RS can also be used to store raw material and WIP in manufacturing. Three application areas can be distinguished for AS/RSs (Groover 2001): (1) unit-load storage and handling, (2) order picking, and (3) WIP storage systems.

8.2.3 Types of Stacker Crane in AS/RS

In an AS/RS, the stacker crane (storage/retrieval, S/R machine) is a rectangular geometry robot and it is used to store and retrieve loads into/from the storage cells. This autonomous vehicle is equipped with a vertical drive, a horizontal drive and typically one or two shuttle drives. The vertical drive raises and lowers the load. The horizontal drive moves the load back-and-forth along the aisle. The shuttle drives transfer the loads between the stacker crane's carriages and the storage cells in the AS/RS rack (carriage is that part of a stacker crane by which a load is moved in the vertical direction). For greater efficiency, the vertical and horizontal drives are capable of simultaneous operations (Hu et al. 2005). Figure 8.4 shows some common types of stacker crane in AS/RSs.

8.2.4 Automatic Identification System in AS/RS

Load identification is the primary role of automatic identification in AS/RSs. The scanners are located at the induction or transfer location, to scan a product identification code. The data are sent to AS/RS computer, which upon receipt of load identifications, assigns and directs the load to the storage location. Working this sequence in reverse can effectively update inventory file based on transaction configuration. Scanners also play an important role in integrating AS/RSs, AGVs, conveyors and robotics in the automated factory by providing discrete load or product information to the appropriate controllers/computers as transfers occur (Kulwiec 1985).

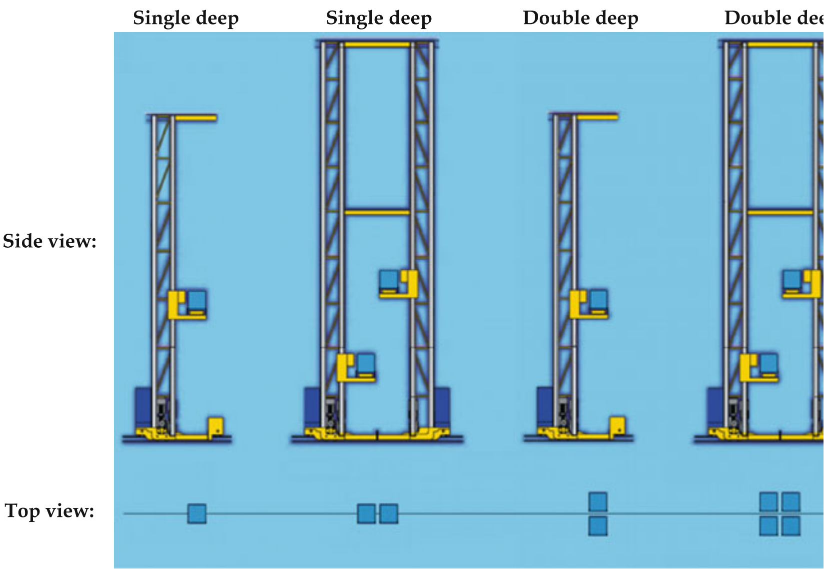

Fig. 8.4 Some common types of stacker cranes in AS/RSs (Courtesy of Stöcklin Logistik AG)

8.2.5 AS/RS Design Decisions

In the last decades there have been several studies which present general overviews of warehouse design and control include Van den Berg (1999), Rouwenhorst et al. (2000), De Koster et al. (2007), Gu et al. (2007) and Baker and Canessa (2009). These papers discuss only a fraction of the AS/RS issues and the literature, due to their broad scope. More specifically, Roodbergen and Vis (2009) presented an extensive explanation of the current state-of-the-art in AS/RS design for a range of related issues. This paper seems to be the first review paper over last 10 years devoted exclusively to AS/RSs, and the first ever to give a broad overview of all design issues in AS/RSs. Therefore some part of this paper related to AS/RS design is investigated in the following.

Due to the complexity and enormous cost associated with automated material handling systems, it is crucial to design an AS/RS in such a way that it can efficiently handle current and future demand requirements, while avoiding overcapacity and bottlenecks. Furthermore, due to the inflexibility of the physical layout and the equipment, it is essential to design it right at once. Figure 8.5 presents a schematic view of design issues and their interdependence for AS/RSs and provides an overview of all design decision problems that may need to be selected. These policies will be discussed later in the Sect. 8.3.

It is important to realize that the AS/RS is usually just one of the several systems to be found in a warehouse. The true performance of the AS/RS is typically influenced by the other systems as are the other systems' performances influenced by the AS/RS. As depicted in Fig. 8.5, part of the actual design of an

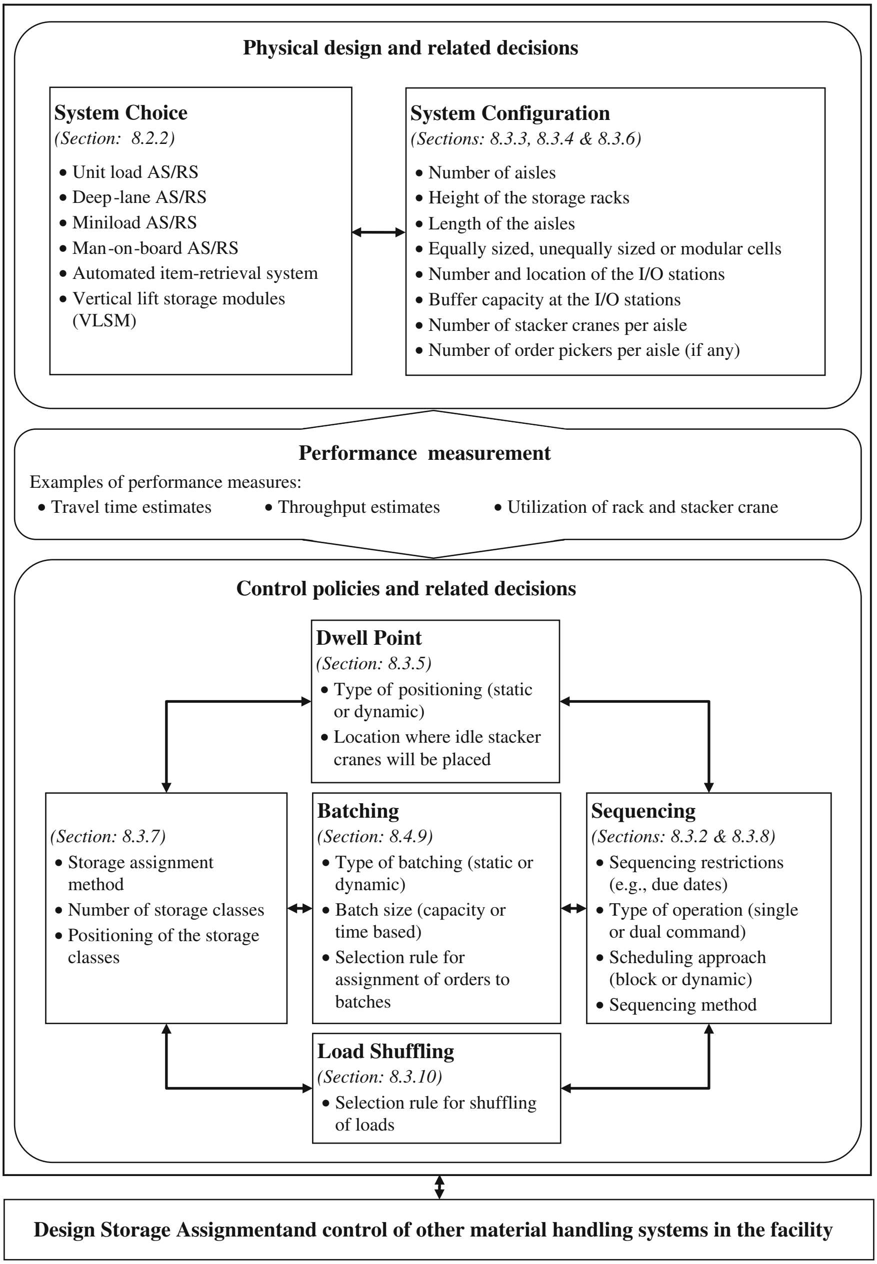

Fig. 8.5 Design of an AS/RS and related decisions (Modified after Roodbergen and Vis 2009)

AS/RS consists of determining its physical appearance. The physical design consists of two aspects which together determines the physical manifestation of the system. First is the choice of the AS/RS type (system choice). Second, the selected system must be configured, for instance, by deciding on the number of aisles and the rack dimensions (system configuration). These interrelated choices can be made based on, among others, historical and forecasted data, product characteristics, the available budget, required throughput, required storage space and available land space. Various concepts for AS/RS types were displayed in Fig. 8.3; however, little research can be found to support the selection of the best type of system from the available concepts.

Control policies are methods which determine the actions performed by the AS/RS. Typically, the operation of an AS/RS is administrated by a coherent set of such control policies, which each take care of a specific subset of the activities. The position where an idle crane (i.e., a crane that has no jobs to perform) waits is determined by a dwell-point policy. The dwell-point is best chosen to minimize the expected time to travel to the next (still unknown) request. A storage assignment policy serves to determine which products are assigned to which locations. Meanwhile, updating and shuffling of items and reconsidering storage assignment decisions can be vital in current dynamic environments to meet the fluctuating, short-term throughput requirements imposed on the AS/RSs. The objective of load-shuffling strategy is to shuffle (i.e., pre-sort, relocate or rearrange) the loads to specified locations during the slacker crane idleness, in order to minimize the response time of retrieval. A tour of an AS/RS consists of a sequence of requests, starting at the origin of the first request and ending at the destination of the last request. Sequencing rules can be used to create tours such that the total time to handle all request is minimized or the due times are least violated. As another control policy of AS/RS, batching considers how one can combine different customer orders into a single tour of the crane. This policy is mainly applicable to man-on-board AS/RS.

For a typical design problem, total capacity is given beforehand. This essentially means that the mathematical product of the number of aisles, rack height, and rack length is constant.

Increasing the number of aisles thus implies reducing rack length and/or height to maintain the desired storage capacity. Because of this relation, having more aisles indirectly results in shorter response times, due to the decreased rack length and height. Furthermore, design changes often have an impact in multiple ways at the same time. In a standard system with one crane per aisle, having more aisles also means having more cranes, which in turn results in a higher throughput and higher investment costs.

8.3 Existing Travel Time Models on Different Aspects of AS/RS

8.3.1 AS/RS Travel Time Interpretations

Travel time for an AS/RS is the service time for a transaction including both stacker crane travel time and pick up/deposit time. The pick up/deposit time is generally independent of the rack shape and travel velocity of the slacker crane.

Hence, in order to simplify the derivations, in analytical approaches the pick up/deposit time are often ignored without affecting the relative performance of the control policies (Hausman et al. 1976; Bozer and White 1984; Hu et al. 2005; Sari et al. 2005 and so on). Therefore the travel time for an AS/RS is the time used by stacker crane to move from its dwell-point to the location of requested item and lastly return to its dwell-point position. Due to the fact that the stacker crane has independent drives for horizontal and vertical travel, the travel time of the stacker crane may be measured by the Chebyshev metric (i.e., the travel time of the stacker crane is the maximum of the isolated horizontal and vertical travel times). Thus if Dx and Dy denote the translations in horizontal and vertical direction, respectively, and v^x and v^y denote the maximum speeds in the horizontal and vertical direction, respectively, then the associated travel time is $\max\{Dx/v^x, Dy/v^y\}$. The Chebyshev metric is also known as the maximum metric or the L_∞-norm (Van den Berg 1999). The AS/RS travel time models are based on either the discrete-approach or continuous-approach. In the discrete-approach travel time models, the AS/RS rack face is considered as a discrete set of locations. However using a continuous-approach to represent the rack, the rack is normalized to a continuous pick face. In practice, there is no significant difference between the results obtained from the continuous-approach-based expressions and the ones from the discrete-approach-based solutions (Sari et al. 2005). Discrete representation of the rack, for example, was investigated by Egbelu (1991), Thonemann and Brandeau (1998), Ashayeri et al. (2002), Sari et al. (2005) and so on. Continuous representation of the rack has received considerable interests since the study of Hausman et al. (1976) and these literatures can be classified into two groups according to the shape of the AS/RS: (1) square-in-time and (2) rectangular-in-time. In a square-in-time AS/RS, the dimensions of the rack and the vertical and horizontal speeds of the stacker crane are such that the time to reach the most distant row (tier) from the I/O station equals the time to reach the most distant bay (column) (Sarker and Babu 1995). Any rack that is not square-in-time is called rectangular-in-time.

Based on a continuous rack approximation approach, Bozer and White (1984) presented expressions for the expected cycle times of an AS/RS performing single-command (*SC*) and dual-command (*DC*) cycles. They normalized the rack as a continuous rectangular pick face with length of 1.0 and height of b in terms of time. By definition, $T_v = H/s_v$ and $T_h = L/s_h$. Let $T = \max\{T_v, T_h\}$ and $b = \min\{T_v/T, T_h/T\}$, which implies that $0 \leq b \leq 1$, where L is length of the rack, H is height of the rack, s_h and s_v are the speed of stacker crane in the horizontal and vertical directions, respectively, T_h represents the horizontal travel time required to go the farthest column from I/O station and T_v denotes the vertical travel time required to go to the farthest row (level). As the value of b may represent the shape of a rack in terms of time, b was referred to as the "shape factor". An illustration of the continuous, normalized rack face is shown in Fig. 8.6. As illustrated in Fig. 8.6, to analyze the expected travel time between two points, any storage (or retrieval) point is represented as (x, y) in time, where $0 \leq x \leq 1$ and

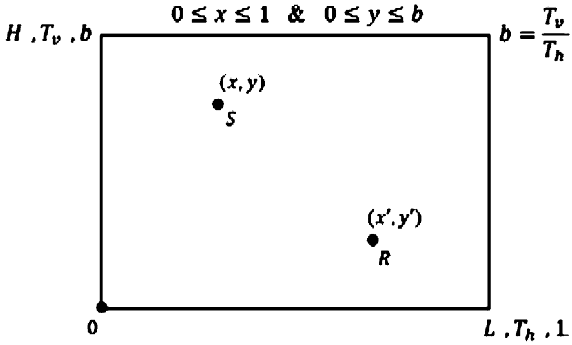

Fig. 8.6 Illustration of AS/RS continuous rack face (Modified after Peters et al. 1996)

$0 \le y \le b$. Hence, the normalized rack is b time units long in vertical direction and 1.0 time units long in the horizontal direction.

Example (Bozer and White 1984) Suppose that rack dimensions and the stacker crane speed in such that $L = 348$ ft, $H = 88$ ft, $s_h = 356$ fpm, and $s_v = 100$ fpm. Using the approach explained earlier, so $T_h = L/s_h = 348/356 = 0.9775$ min, and $T_v = H/s_v = 88/100 = 0.8800$ min and $T = \max\{T_v,\ T_h\} = T_h$. Therefore the shape factor is $b = T_v/T_h = 0.8800/0.9775 = 0.90$. Hence, the normalized rack is 0.90 time units long in the vertical direction and 1.0 time units long in the horizontal direction

8.3.2 Different Command Cycles of the Stacker Crane

In the single-shuttle AS/RSs, the stacker crane can operate under SC cycle and/or DC cycle. In a SC, only one operation of storage or retrieval of item is conducted. However, in a DC both storage and retrieval of items are conducted during one cycle of the stacker crane (Lee et al. 2005). In multi-shuttle system with two transport unit-load (TUL), (i.e., twin-shuttle system) the stacker crane can perform up to two storages and two retrievals in a cycle, which is called a quadruple command (*QC*) cycle (Meller and Mungwattana 1997; Potrc et al. 2004). A QC cycle transports two storages and two retrievals at the same AS/RS cycle. The first transaction must always be a storage transaction and the last transaction must always be a retrieval one. The second and the third transaction must be storage transaction and the retrieval transaction (Sarker and Babu 1995; Meller and Mungwattana 1997; Potrc et al. 2004). Likewise, in multi-shuttle system with three TUL (i.e., triple-shuttle systems) the stacker crane can perform up to three storages and three retrievals in a cycle, which is called a sextuple command (STC or SxC) cycle (Meller and Mungwattana 1997; Potrc et al. 2004). However, the stacker cranes capable of transporting more than two loads are still rarely seen and it is believed that there are no systems in practice with more than three shuttles (Meller

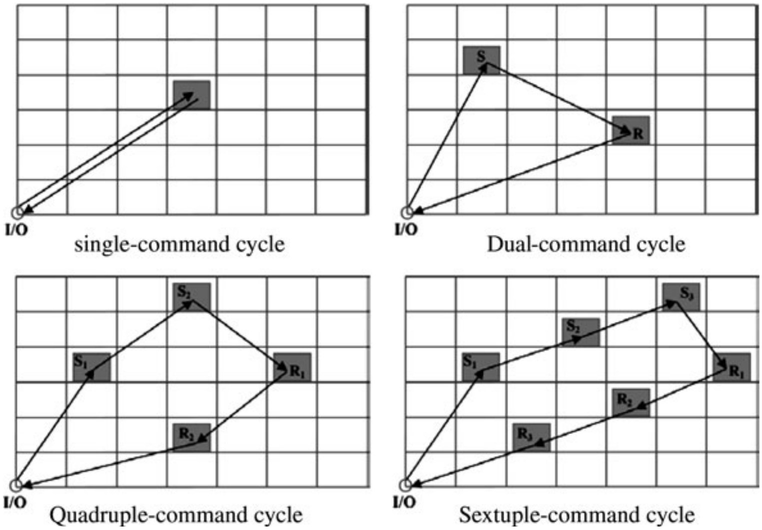

Fig. 8.7 Different command cycles of the stacker crane

and Mungwattana 1997; Roodbergen and Vis 2009). The storage (S) and retrieval (R) operations in an AS/RS rack for different command cycles are shown in Fig. 8.7.

Hausman et al. (1976) analyzed the travel time of AS/RS only for the SC cycle in a single-shuttle system. Graves et al. (1977), Bozer and White (1984) and Pan and Wang (1996) studied the single- and dual-operating modes together with other control policies for AS/RS. Bozer and White (1984) developed analytical models for calculating SC and DC cycles under a single-shuttle system. By assuming uniformly distributed coordinate locations for random storage, they used a statistical approach to develop expressions for travel time. For discrete rack model, the expected travel times were computed using the expressions,

$$E(\overline{SC}) = \frac{1}{N}\sum_{i=1}^{N} 2t_{0i} \tag{8.1}$$

$$E(\overline{DC}) = \frac{2}{N(N-1)}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left[t_{0i} + t_{ij} + t_{0j}\right] \tag{8.2}$$

where, $E(\overline{SC})$ is the expected SC cycle travel time, $E(\overline{DC})$ is the expected DC cycle travel time, N is the total number of openings in the rack, t_{0i} is the one-way travel time between the I/O station (which is located at the lower left-hand corner of the rack) and the ith opening ($t_{0i} = t_{i0}$), and t_{ij} is the one-way travel time between the ith opening and the jth opening ($t_{ij} = t_{ji}$) and t_{0j} is the travel time from jth opening to I/O station ($t_{0j} = t_{j0}$). Using the method explained in Sect. 8.3.1, Bozer and White (1984) derived expected travel times models for both SC and DC cycles based on a continuous rack approximation approach. The expressions are,

$$E(SC) = \frac{1}{3}b^2 + 1, \tag{8.3}$$

$$E(DC) = \frac{4}{3} + \frac{1}{2}b^2 - \frac{1}{30}b^3. \tag{8.4}$$

Note that the above expressions provide results corresponding to the normalized continuous rack. In order to obtain the results corresponding to the original rack, the above travel times should be denormalized to obtain:

$$E(\overline{SC}) = E(SC) \cdot T = \left[\frac{1}{3}b^2 + 1\right] \cdot T, \tag{8.5}$$

$$E(\overline{DC}) = E(DC) \cdot T = \left[\frac{4}{3} + \frac{1}{2}b^2 - \frac{1}{30}b^3\right] \cdot T. \tag{8.6}$$

Referring to the example in Sect. 8.3.1, when $T = 0.9775$ and $b = 0.90$, thus $E(\mathrm{SC}) = 1.27$ time units and, $E(DC) = 1.7140$ time units. To obtain the results corresponding to the original rack, the above travel times are denormalized to obtain $E(\overline{SC}) = E(SC) \cdot T = 1.2414$ min and $E(\overline{DC}) = E(DC) \cdot T = 1.6754$ min.

Sarker et al. (1991) analyzed the travel time and the performance of a double-shuttle AS/RS operating on a QC cycle under nearest-neighbor (NN) and class-based storage scheduling techniques. It was observed that a dual-shuttle AS/RS operating under the proposed scheduling techniques would significantly improve system throughput performance over a single-load shuttle system. Since the majority of researchers investigated single-shuttle system, throughput capacity is thus limited with maximal technical characteristics of stacker crane and optimal geometry of high storage racks. In general, the throughput capacity of an AS/RS increases as the number of shuttles increases, since the amount of empty travel decreases correspondingly. Hence, in order to increase the throughput capacity, it is necessary to employ the stacker crane that can store and retrieve several TUL at the same time. Analytical models under multi-shuttle system were presented by Meller and Mungwatana (1997). Within storage operation of QC and STC cycles, modified NN storage strategy was used. Storage in single- and multi-shuttle systems were investigated by Potrc et al. (2004). Comparison of the single-shuttle system and multi-shuttle system showed large improvements in throughput capacities of multi-shuttle system. Foley and Frazelle (1991) considered EOA miniload AS/RSs and derived the distribution of the DC cycle time for uniformly distributed activity in a square-in-time rack. Using this distribution, they obtained closed form expressions for the maximum throughput of minload systems with deterministic or exponentially distributed pick times.

In order to handle extra heavy loads (loads above 20 tons, such as sea container cargo) at high speed, a new kind of S/R mechanism in split-platform AS/RS, or

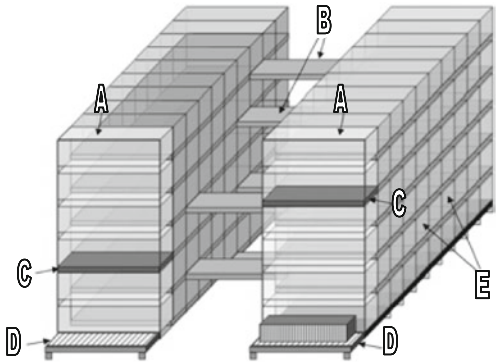

Fig. 8.8 A schematic view of split-platform AS/RS (SP-AS/RS) (Modified after Hu et al. 2005)

SP-AS/RS in short, was presented by Chen et al. (2003) and Hu et al. (2005). They developed discrete (Chen et al. 2003) and continuous (Hu et al. 2005) travel time models for the proposed system under SC cycle. In the SP-AS/RS transports of the load within individual storage aisles are separated into vertical and horizontal movements and handled by different devices, namely the vertical platform and the horizontal platform, respectively. Figure 8.8 gives a schematic view of a standard aisle in the SP-AS/RS. By separating the mechanisms for vertical and horizontal movements, the proposed system can handle heavier loads at a higher speed. High lifting capacity enables the SP-AS/RS to deal with all the different types and sizes of containers which pass through the container terminals (Hu et al. 2005). A container terminal in a port is the place where container vessels dock on berths and unload inbound (import) containers (empty or filled with cargo) and load outbound (export) containers. The terminals have storage yards for the temporary storage of these containers (Murty et al. 2005).

From the literature survey in this section, it is concluded that most of the literature assumes single-shuttle systems that the stacker crane performs only either SC or DC at each operation. However, the throughput capacity of an AS/RS increases as the number of shuttles increases, since the amount of empty travel decreases correspondingly.

8.3.3 Operating Characteristics of the Stacker Crane

The majority of studies have assumed a constant stacker crane velocity and instantaneous acceleration. Gudehus (1973) proposed a method to adjust the previous results when the acceleration and deceleration of the stacker crane are taken into account. Guenov and Raeside (1989) observed in their experiments that an optimum tour with respect to Chebyshev travel may be up to 3% above the optimum for travel times with acceleration/deceleration. Hwang and Lee (1990) presented continuous analytical travel time models which integrate the operating characteristics of the stacker crane. Using a randomized assignment policy, travel times are determined for both SC and DC cycles and the models are validated through discrete evaluation procedures. They defined the acceleration/deceleration rate and maximum velocities in the horizontal and vertical directions as three important elements in the travel time model. Considering these three elements which describe the capabilities of the stacker crane, they derived the travel time of the stacker crane as,

$$E(SC) = 2 \int_{0}^{\max(t_h, t_l)} z g_k(z) \mathrm{d}z, \quad k = 1, 2, 3. \tag{8.7}$$

where $E(SC)$ is SC travel time, $G(z)$ is the probability that travel time to the point (x, y) on the aisle is less than or equal to z and $g_k(z)$ is the probability density function. They used the same relation for the DC cycle time, but calculated the $E(TB)$ using a different expression as,

$$E(TB) = \int_{0}^{\max(t_h, t_l)} z b_k(z) \mathrm{d}z, \quad k = 1, 2, 3. \tag{8.8}$$

where $E(TB)$ is the expected travel time between to randomly selected points, $b_k(z)$ is the probability density function of travel time between. Their model gives values very close to those obtained by the discrete rack methods.

Chang et al. (1995) proposed a travel time model for AS/RS by considering the speed profiles that exist in real-world applications. Compact forms of expected travel-times under randomized storage conditions are determined for both SC and DC cycles. An extension of Chang et al. (1995) was proposed by Chang and Wen (1997) to investigate the impact on rack configuration on the speed profile of the stacker crane. The results demonstrate that the optimal rack configuration of the SC is square-in-time whereas the DC cycle may not be. Furthermore, the travel times for both SC and DC cycles are quite insensitive to the deviation in the length of the rack configuration. As another extension of Chang et al. (1995), Wen et al. (2001) proposed travel time models that consider various travel speeds with known acceleration and deceleration rates. Compact forms of expected travel time under class-based and full-turnover storage assignments were determined. Their results show that both the proposed exponential travel time model and the adjusted exponential model perform satisfactorily and could be useful tools for designing an AS/RS in real-world applications.

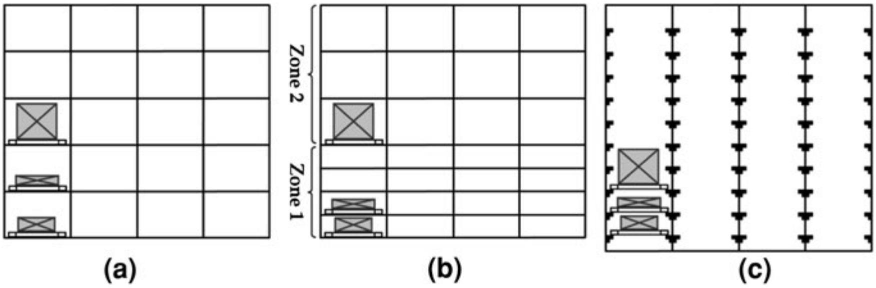

Fig. 8.9 Structure of the rack with **a** Equal sized, **b** Unequal sized and **c** Modular cells

8.3.4 Storage Cells in a Rack, Design of the Rack Structure and Physical Layout

8.3.4.1 Storage Cells in a Rack

The storage cells in an AS/RS rack may be considered homogeneous or may be partitioned into several areas called classes (Hu et al. 2005). There are various types of AS/RS with equally sized cells according to the size and volume of items to be handled, storage and retrieval methods and interaction of a stacker crane with the worker such as unit-load AS/RS, mini-load AS/RS, man-on-board AS/RS, automated item-retrieval system and deep-lane AS/RS (Groover 2001). Many researchers have studied the optimal design of AS/RS with the rack of equally sized cells for using the concept of unit load (Fig. 8.9a). However, in terms of the flexibility of storage capability, the existing rack configuration using the concept of unit load is inefficient and inadequate for the storage of various types and various sizes of customers' demands. Moreover, if the various sizes of products are to be stored in existing systems, the space utilization will be considerably decreased due to the increase of lost space in each cell (Lee et al. 2005). Lee et al. (1999) proposed a model for AS/RS with the rack of unequally sized cells. In this model, the cells within a zone have the same size, but the sizes of cells in the different zones are different in height such that the rack can hold various types of the load (Fig. 8.9b). This model will be a good alternative for coping with those problems described above. However, if the quantity of the storage demands for different sized products fluctuates in large, even the model proposed by Lee et al. (1999) will not basically be able to overcome inflexibility and low-space utilization problems in the existing AS/RS rack structures. Lee et al. (2005) presented the model of AS/RS with the rack of modular cells (Fig. 8.9c). They determined the best size of modular cell as a decision variable, and presented the effectiveness of the model. This type of AS/RS is more flexible to the size and has higher space utilization than those of existing rack structure, and could be a useful alternative for the storage of different unit-load sizes.

8.3.4.2 Design of Rack Structure and Physical Layout Design in an AS/RS

AS/RSs are very expensive investments. Once installed, the technical characteristics are difficult to modify. Therefore a formalized decision model should be available in the design process (Ashayeri et al. 1985). The design of AS/RS involves the determination of the number of stacker cranes, their horizontal/vertical velocities and travel times, the physical configuration of the storage racks, etc. Only a few researches address the design of AS/RSs in combination with the design of other material handling systems in the facility. Most of these researches consider manufacturing environments. The design of warehouses has been studied basically with two approaches: (i) analytical optimization methods; and (ii) simulation. The studies which cover such approaches are investigated in the following.

(i) *Analytical Optimization Methods*

As for the analytical methods, Roberts and Reed (1972) presented an optimization model to determine the warehouse bay configuration that minimizes the cost of handling and construction, ignoring the constraints on handling capacity of equipment and building sites. It was assumed that storage space is available in units of identical bays, and the optimal bay configuration was determined to minimize the construction and material handling cost. According to De Koster et al. (2007), one of the first publications in the subject of optimizing the warehouses was presented by Bassan et al. (1980). The optimum dimensions of the warehouse were analyzed, considering the chosen volume of the warehouse in dependence on the various storage strategies. Two configurations of racks in a homogeneous or a zoned warehouse were compared, considering handling costs as well as costs associated with the warehouse area and perimeter. From these, expressions for optimal design parameters were developed. It was shown that, depending on ratios between the relevant costs, some general preference rules for the two layouts examined can be laid down. A Design package based on a cost model for AS/RS was developed by Zollinger (1975). According to Zollinger's cost model, the mathematical properties of the cost functions were defined corresponding to various elements in the system. Subsequently, the minimum-cost design was determined by performing a Fibonacci search over the number of aisles in the system. Hodgson and Lowe (1982) studied a layout problem involving the placement of items in a storage rack serviced by a stacker crane. The analysis was restricted to the case of dedicated storage and SC cycles.

Karasawa et al. (1980) developed a non-linear mixed-integer programming (MIP) for a deterministic model of an AS/RS to minimize the total cost. The objective function included three main decision variables: the number of stacker cranes, the height and the length of the rack. Constant values involved were cost of the land, cost of the warehouse, cost of the rack construction and cost of stacker cranes. Optimization was performed as a function of sufficient storage volume for all items and sufficient number of cranes to serve all storage and retrieval requests. The main disadvantage of this model is that it refers only to the single-aisle AS/RS and the warehousing operation of only the SC cycle. Ashayeri et al. (1985)

described a model which allows the determination of the major design characteristics of the warehouse. The objective of the model was to minimize the investment and operating costs over the project lifetime. They presented this mathematical model for the calculation of the optimal number of cranes and the optimal width and length of the warehouse subject to constraints on the constant crane velocities, the throughput and the length and width of building site. Park and Webster (1989) investigated the design of warehouses by proposing an approach that simultaneously selects the used storage equipment, that might be an AS/RS, and the overall size and shape of the storage area. The objective was to develop an optimization procedure to aid a warehouse planner in the design of selected three-dimensional (3D), palletized storage systems. All alternatives were compared in the overall model while simultaneously considering the following factors: control procedures, handling equipment movement in an aisle, storage rules, alternative handling equipment, input and output patterns for product flow, storage rack structure, component costs and the economics of each storage system.

Bozer and White (1990) addressed the design of EOA order picking systems by focusing on a miniload AS/RS. Performance models and a design algorithm were developed and presented. The objective of the design algorithm was the minimization of the number of storage aisles subject to two types of capacity constraints: throughput and storage space. Although the system with two pick positions can be modeled directly as a closed queuing network with two servers and two customers, its special structure led to an alternative approach in developing the performance model. For two and more pick positions, the results obtained were compared with those obtainable using simulation and a diffusion approximation. However, since the analysis assumes that the requests are always available, it represents an overestimation of the system throughput. In a later study, Bozer and White (1996) presented an analytical design algorithm to determine the near-minimum number of pickers required in a same EOA miniload AS/RS. The algorithm was for general system configurations with two or more pick positions per aisle and/or two or more aisles per picker. Moreover, for systems with two pick positions, the possibility of improving the picker utilization by sequencing container retrievals within each order was investigated. In many man-on-board AS/RSs, some very typical, recurrent orders have to be retrieved. Van Oudheusden and Zhu (1992) presented a straightforward methodology to design the storage layout of a rack when such recurrent orders represent a high percentage of total turnover. The approach makes use of sorting, assignment, and traveling salesman like algorithms. The resulting layouts were compared against more classical arrangements. Based on numerical simulations it was observed that, in specific situations, more than a significant saving in travel time of the retrieval crane can be expected.

Malmborg (2001) modified a well-known rule of thumb for evaluating storage rack configurations in AS/RSs to avoid the need for two key assumptions. These assumptions are the proportion of SC and DC order picking cycles used in operating a system and the total storage capacity requirements when randomized versus dedicated storage is used. Procedures for generating AS/RS cost estimates were also directly coupled with models for estimating the utilization of stacker cranes.

The modified rules of thumb were also designed for implementation on PC-level hardware, but with adequate computational efficiency for analyzing a broad range of rack design alternatives in large-scale applications. Hwang et al. (2002) investigated the design of miniload AS/RSs in combination with AGVs. Both nonlinear model and heuristics have been proposed to determine the optimal number of loads to be transferred by each AGV to machines in combination with an optimal design of the AS/RS. Bozer and Cho (2005) derived the results which can be used in the design or evaluation of new/proposed systems. Assuming a particular dwell-point strategy for the storage/retrieval machine, they derive closed-form analytical results to evaluate the performance of an AS/RS under stochastic demand and determine whether or not it meets throughput.

Design of a new compact 3D AS/RS was proposed by Le-Duc et al. (2006) and De Koster et al. (2006). The research objective was to analyze the system performance and optimally dimension the system. Under SC cycle a closed-form expression was developed for the expected retrieval travel time of the system. From the expected travel time, the optimal ratio between 3D that minimizes the travel time for a random storage strategy was calculated. In addition, an approximate travel time expression for the DC cycle was derived for the system with powered and gravity conveyors, respectively, and it was used to optimize the system dimensions. Kuo et al. (2007) proposed computationally efficient design conceptualization models for unit-load AS/RSs based on autonomous vehicle technology (AVS/RS). Vehicle and lift travel times and the probability distribution for twelve service scenarios occurring under realistic operating assumptions were formulated and used to generate expected transaction service times. Additional measures of system performance including transaction waiting time and vehicle utilization are formulated for systems using random storage and point-of-service-completion dwell-point rules. The models provide a practical means of predicting key aspects of system performance based on five design variables that drive the majority of system costs.

(ii) *Simulation*

Owing to the complexity and enormous cost involved in automated material handling systems, there is a growing need to use computer simulation in both the physical aspect and control software design of such systems. Simulation models can be developed to test not only the final system configuration, but also each installation phase (Raghunath et al. 1986). Simulations are mandatory to adequately model all operational features of the AS/RSs, since existing analytical models only apply to special instances (Van den Berg and Gademann 2000). As for the simulation methods, Bafna and Reed (1972) developed a design package where the optimum configuration is determined by using simulation in conjunction with a search procedure. A similar approach was presented by Koenig (1980), where the search for the optimum configuration was limited to certain values of the design variables specified by the user. Perry et al. (1984) presented an optimum-seeking approach to the design of AS/RS. The method was developed to improve the effectiveness with which simulation models of such systems can be used as design aids. The system modeled consists of several aisles of storage bins, storage-retrieval devices (stacker cranes), closed loop conveyor, work stations, and input/output buffers to interface with the conveyor. Optimum-seeking rules or heuristics were used in conjunction with the simulation model to reach a local optimum solution. Rosenblatt and Roll (1984) presented a search procedure for finding a global optimal solution for a specific formulation of the warehouse design problem. In this formulation three types of costs were considered: costs associated with the initial investment (construction and handling facilities), a shortage cost and costs associated with the storage policy. The search procedure for finding the optimal storage design was developed, comprising analytical optimization and simulation techniques.

Raghunath et al. (1986) described the development of an interactive and flexible simulation software for AS/RS of the miniload variety. A modular approach was taken in the development of the simulation software so that the user, through an interactive menu, has the capability to model an AS/RS by selecting a combination of modules that define the AS/RS. The user then enters the values of the system variables specified for each module. This user-defined simulation model is translated into a simulation language source code and then executed. The study of AS/RS in warehouses has developed along two main lines: One seeks to minimize the total cost of an AS/RS, while the other explores the dynamic behavior of such a system. Rosenblatt et al. (1993) addressed the two issues simultaneously and presented a combined optimization and simulation approach for designing AS/RSs. A heuristic recursive optimization/simulation procedure was developed and applied to several situations, and converged within a few iterations. This model finds the physical characteristics of the AS/RS, however the relationship between dimension of rack and capacity of stacker crane that could affect its performance was not considered in this model. Randhawa and Shroff (1995) performed the most extensive simulation study. They examined the effect of different sequencing rules on six layout configurations (with a varying I/O-point, item distribution over racks, rack configuration and rack dimensions). Based on a limited number of experiments they concluded, among other things, that locating the I/O-point at the middle of the aisle, instead of at the end of the aisle, results in a higher throughput. Manzini et al. (2006) presented a multi-parametric dynamic model of a product-to-picker storage system with class-based storage allocation of products. Thousands of what-if scenarios were simulated in order to measure the impact of alternative design and operating configurations on the expected system performance and to identify the most critical factors and combinations of factors affecting the response of the system. Class-based storage was found to be a very effective way of both reducing the picking cycle time and maximizing the throughput of the system. The rapid effectiveness of visual interactive simulation (VIS) in supporting the design and control of new warehouses emerges, responding to the need for flexibility which modern companies need in order to adapt to strongly changing operating conditions quickly.

Based on examination of the literature, it can be concluded that the strength of simulation could be better exploited in AS/RS researches to compare numerous designs, while taking into account more design aspects, especially in combination with control policies. Sensitivity analyses on input factors should also be performed such that a design can be obtained which can perform well in all applicable scenarios. As a result more general information could be obtained on good design practices (Roodbergen and Vis 2009).

8.3.5 Dwell-Point Policy of the Stacker Crane

The dwell-point in an AS/RS is the position where the stacker crane resides, or dwell, when the system is idle (Van den Berg 1999). Hu et al. (2005) defined the dwell-point policy as the policy to decide where the stacker crane will stay when it becomes idle. The dwell-point is selected such that the expected travel time to the position of the first transaction after the idle period is minimized (Van den Berg 1999). There is extensive research in the area of dwell-points for stacker cranes. The dwell-point of a stacker crane is the rest or home position of the machine when it becomes idle. A machine is said to be idle if it is functional but has no assignment in progress. Machine idleness occurs when a stacker crane completes a task and there is no immediate other storage or retrieval request task to reassign the machine. Machine idleness is not a continuous process: idle periods are broken up by periods of busy activity by the machine. Thus every instance of a machine idleness involves a time during which the machine has no assignment. Strategic pre-positioning of stacker cranes when they become idle, in anticipation of incoming requests for order storage and retrieval, is one method of improving the system response time (Chang and Egbelu 1997a). Graves et al. (1977) selected the dwell-point of the stacker crane at the I/O station. They introduced the design, planning and control of warehousing systems as new research topics. Bozer and White (1984) and Linn and Wysk (1987) investigated various dwell-point policies. For the dwell-point specification problem, the following static dwell-point rules were outlined by Bozer and White (1984), although they provided no quantitative comparison of their performance:

1. Return to the input station following the completion of a SC storage; remain at the output station following the completion of either a SC retrieval or DC cycle;
2. Remain at the storage location following the completion of a SC storage; remain at the output station following the completion of either a SC retrieval or a DC cycle;
3. Travel to a midpoint location in the rack following the completion of any cycle;
4. Travel to the input station following the completion of any cycle.

Linn and Wysk (1987) investigated two dwell-point policies for AS/RS: (1) single addressing; and (2) pursuit mode. Under single addressing mode, the storage or retrieval command is initiated at the I/O station, which is the stacker crane home base. Given a storage request, the stacker crane picks up the load, stores it in its assigned location, then, returns empty to home base; given a retrieval request, the stacker crane goes, from the home base, to retrieve the pallet, and bring it back to I/O station. However, under pursuit mode, the stacker has no fixed home base, and remains in the position of the last completed command. Depending on the next command issued, it may go on to retrieve a pallet, or return to I/O station to pick up a pallet for storage. The results show that the pursuit mode appears to be better than single addressing mode, and should always be used for AS/RS control strategy when both types of requests are available.

Egbelu (1991) showed that the expected travel time of stacker crane could be obtained by summing the expected travel time to each location in the rack from an unknown dwell-point and then obtaining the expected travel time of stacker crane as a linear program. For this purpose, a linear programing methodology was developed which minimizes the service response time in an AS/RS through the optimal selection of the dwell-point of the stacker crane. A framework for selecting the dwell-point location of the stacker crane was proposed and two formulations based on the relative likelihood that the next request was a storage or a retrieval request were developed. The first formulation uses an objective of minimizing the expected response time and the second one uses an objective of minimizing the maximum response time for an AS/RS. He then transformed these nonlinear programing formulations into linear programing problems that can be solved optimally. Egbelu and Wu (1993) presented the comparison of six dwell-point rules under randomized and dedicated storage policies by means of simulation. They compared the two formulations presented by Egbelu (1991) and the four rules proposed by Bozer and White (1984). It was found that the solution from the minimum expected response time formulation performed well, as did the dwell-point strategy of Bozer and White (1984) to always return to the input point. Hwang and Lim (1993) showed that the two formulations of Egbelu (1991) could be transformed to the single-facility location problem with Chebyshev distance, and the Chebyshev minimax facility location problem, respectively, in order to reduce the computational time. These transformations reduced the required computational times by two orders of magnitude.

Peters et al. (1996) proposed analytical models using continuous rack approximation for determining the optimal dwell-point locations for the stacker crane. These models provide closed-form expressions for the dwell-point location in an AS/RS. Extensions are made to consider AS/RS with a variety of configurations including multiple input and output stations. The models not only provide solutions to the dwell-point location problem, but also provide considerable insight into the nature of dwell-point positioning problem, which is particularly valuable when the requirements facing the AS/RS are uncertain. However, a computational study of the effectiveness of the optimal dwell-point strategy is not provided in Peters et al. (1996). Chang and Egbelu (1997a, b) presented formulations for pre-positioning of stacker cranes to minimize the expected system response time (Chang and Egbelu 1997a) and minimize the maximum system response time (Chang and Egbelu 1997b) for multi-aisle AS/RS. Park (1999, 2001) developed two models to obtain optimal dwell-point under square-in-time rack with dedicated storage (Park 1999) and uniformly distributed rectangular racks (Park 2001).

A closed-form solution was presented for the optimal dwell-point in terms of the probability of the next transaction demand type, storage or retrieval in a non-square-in-time rack. He also introduced various return paths to the dwell-point for the efficient operation of the stacker crane. Van den Berg (2002) determined a dwell-point position which minimizes the expected travel time to the position of the first operation after the idle period. He referred to this problem as the dwell-point problem (DPP) and demonstrated that the DPP may be modeled as a facility location problem with rectilinear distances (FLPrd). He considered the continuous situation and derived analytic expressions for the optimal dwell-point position under the randomized and class-based storage policies, respectively. The expressions may be incorporated in a design framework for estimating the system performance.

Hu et al. (2005) developed a reliable travel time model for SP-AS/RS (see Fig. 8.8) under stay dwell-point policy (i.e., the platforms remain where they are after completing a storage or retrieval operation). The travel time model is validated by means of simulation. Vasili et al. (2006) extended the study of Hu et al. (2005) and developed two reliable travel time models for the SP-AS/RS under return to middle and return to start, dwell-point policies. Under return to middle dwell-point policy the horizontal platform returns to middle of tier and the vertical platform returns to middle of handover station upon finishing a job. However, under return to start dwell-point policy the horizontal platform returns to the handover station and the vertical platform returns to the I/O station upon finishing a job.

Based on examination of the literature, although many dwell-point strategies have been suggested, and an optimal strategy defined, there does not appear to exist a computational study that illustrates the benefits of using the optimal dwell point over the more simple rules suggested by Bozer and White (1984). Moreover, for AS/RSs with high system utilizations, it is not clear what opportunity exists in a practical sense to take advantage of the dwell-point strategies since the stacker crane will not be idle very often (Meller and Mungwattana 2005).

8.3.6 Position of the I/O Station(s)

The position of the I/O station(s) is also a factor that affects the AS/RS operation. Bozer and White (1984) analyzed and derived the expected travel time of the following alternative configurations for the I/O station:

1. Input and Output at opposite ends of the aisle;
2. Input and Output at the same end of the aisle, but at different elevations;
3. Input and Output at the same elevation, but at a midpoint in the aisle;
4. Input and Output elevated at the end of the aisle.

For the travel time models which were investigated in Sect. 8.3.2 (Eqs. 8.3 and 8.4) it had been assumed that the I/O station is located at the lower left-hand corner of the rack and every trip originated and terminated at the I/O station. Bozer and White (1984) then relaxed this assumption and analyzed the above four alternative configurations. In the followings, these four configurations and their corresponding expected travel time expressions are reviewed.

8.3.6.1 Input and Output at Opposite Ends of the Aisle

For this configuration, first, assuming the dwell-point strategy (1) (see Sect. 8.3.5), the expected travel time model per operation $E_1(T)$ was shown to be,

$$E_1(T) = E(V)(1+\alpha) + \frac{1}{2}E(TB)(1-\alpha) + \frac{1}{2}K\left[1-\frac{\alpha}{2}\right] \tag{8.9}$$

where$\alpha$is percent of storages which are performed using SC cycles. $E(V)$ is the expected travel time from any corner of the rack to a randomly selected point or vice versa and can be obtained by dividing $E(SC)$ by 2 (for $E(SC)$ refer to Eq. 8.3), so

$$E(V) = \frac{1}{6}b^2 + \frac{1}{2} \tag{8.10}$$

Operations are equally storages and retrievals. K is the fixed travel time from the output to the input station. $E(TB)$ is the expected travel time between to randomly selected points and it is given by the following expression, where b is the shape factor:

$$E(TB) = \frac{1}{3} + \frac{1}{6}b^2 - \frac{1}{30}b^3 \tag{8.11}$$

Second, considering the dwell-point strategy (2) (see Sect. 8.3.5), the following expression was obtained for the expected travel time model per operation $E_1(T)$ for this configuration,

$$E_1(T) = \left(\frac{1-\alpha}{2}\right)\left\{\frac{1}{2}E(V)(\alpha+2) + \frac{1}{2}E(TB)(1-\alpha) + \frac{1}{2}K\right\} + \frac{\alpha}{2}\left\{\frac{3}{2}E(V) + \frac{1}{2}E(TB)\right\}. \tag{8.12}$$

From the results it was observed that using the dwell-point strategy (2) generates a reduction in the expected travel time in comparison with the dwell-point strategy (1) for a SC cycle.

8.3.6.2 Input and Output at the Same End of the Aisle, but at Different Elevations

For the second configuration, it was assumed to have the input station at the lower left-hand corner of the rack while the output station is located d time units above

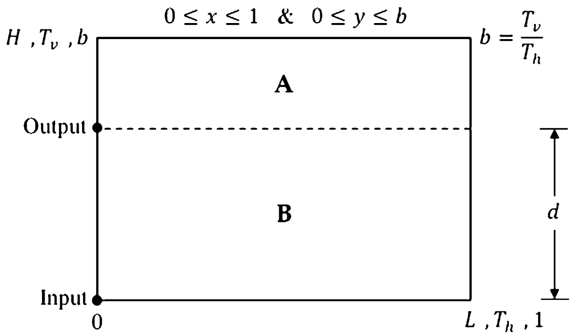

Fig. 8.10 Input and output at the same end of the aisle, but at different elevations (Modified After Bozer and White 1984)

the input station, where $d < b$ (Fig. 8.10). Furthermore, it was assumed that the vertical travel yields the value of b. As shown in Fig. 8.10, the rack can be visualized as being two separate racks (as indicated by the dashed line). However, on going from the random point to the output station, Eq. 8.10 is not appropriate. The output station may be considered to be located at the corner of racks A and B. Considering $E_0(V)$ as the expected travel time for returning to the output station, thus,

$$E_0(V) = \frac{1}{6}b^2 + \frac{1}{2} - \frac{1}{2}d(b - d). \tag{8.13}$$

Therefore, assuming the dwell-point strategy (1) (see Sect. 8.3.5), the expected travel time model per operation $E_2(T)$ for the this configuration was shown to be,

$$E_2(T) = \frac{\alpha}{2}\left\{\alpha E(V) - \frac{1}{2}\alpha E(TB) + \frac{1}{2}[E(V)E(TB) + E_0(V)]\right\}$$
$$+ (1 - \alpha/2)\left\{\frac{1}{2}\alpha[E(V) - E(TB) + E_0(V)] + \frac{1}{2}[E(V) + E(TB) + E_0(V)] + \frac{1}{2}d\right\}. \tag{8.14}$$

The values of $E(V)$, $E(TB)$ and $E_0(V)$ can be determined by using Eqs. 8.10, 8.11 and 8.13, respectively. From a travel time standpoint, it was found that the second configuration performs better than the first configuration. The reason for this is due to the fact that elevating the output station will save some travel time in the vertical direction.

8.3.6.3 Input and Output at the Same Elevation, but at a Midpoint in the Aisle

The third configuration alternative considered was based on the I/O station being located at the center of the rack. Such a configuration can be visualized as having the delivery and take-away conveyors running halfway into the aisle, through a set of rack openings located at the midlevel on either side of the aisle. It was further assumed that vertical travel time is between 0 and b, and horizontal travel time is between 0 and 1. Hence, the I/O station is assumed to be located at (1/2, b/2) for the normalized rack where $0 \leq b \leq 1$. Considering $E_{\mathrm{M}}(V)$ as expected travel time from the center of rack to a randomly selected point, thus

$$E_M(V) = \frac{1}{12}b^2 + \frac{1}{4}. \tag{8.15}$$

For this configuration, the input and output stations are coincident. Considering the dwell-point strategy (1) described earlier, the strategy is equivalent to the case where every trip originates and terminates at the I/O station. Hence, the expected travel time model per operation $E_3(T)$ for the this configuration was shown to be,

$$E_3(T) = \alpha[2E_M(V)] + (1-\alpha)[2E_M(V) + E(TB)]. \tag{8.16}$$

The results indicated that this configuration provides a reduction in the expected travel time, in comparison with the second configuration.

8.3.6.4 Input and Output Elevated at the End of the Aisle

The forth configuration alternative considers the situation where the I/O station has the location (0, d). As before, it is assumed that the maximum horizontal and vertical travel times are 1.0 and b, respectively. The analysis of the configuration is involving input and output stations at the end of aisle, but at different elevations. From previous discussions, it is straightforward to obtain the following expected travel times for SC and DC cycles:

$$E(SC) = \frac{1}{3}b^2 + 1 - d(b-d), \tag{8.17}$$

$$E(DC) = \frac{4}{3} + \frac{1}{2}b^2 - \frac{1}{30}b^3 - d(b-d), \tag{8.18}$$

Comparing Eqs. 8.17 and 8.18 with Eqs. 8.3 and 8.4, elevating the I/O station d time units introduces a correction factor of $d(b - d)$ in the computation of cycle times.

Randhawa et al. (1991) analyzed and compared the effect of the number of I/O stations on the mean waiting time and maximum waiting time, for three different unit-load AS/RSs operating under DC cycle. The AS/RS layouts differ in the number of I/O stations per aisle, and the relationship between the storage and retrieval sources. A simulation model was used to evaluate the systems on three performance criteria, including system throughput, mean waiting time and maximum waiting time. From the results it was observed that the efficiency of the AS/RS can be improved by the introduction of two I/O stations per aisle with the input/output pallets for each station being independent of each other, the input pallet storage based on closest open location policy, and output pallet withdrawal based on a nearest-neighbor policy (or its variant, with a maximum waiting time limit). Randhawa and Shroff (1995) extended the study of Randhawa et al. (1991) by means of an extensive simulation study. They evaluated and analyzed six different layouts with single I/O station using three different scheduling policies. The results were compared considering the system throughput as the primary criterion. Other performance measures investigated were storage and retrieval waiting times, and rejects due to the rack or input/output queues being fully utilized.

Ashayeri et al. (2002) presented a geometrical-based algorithmic approach for determining the travel times and throughput for class-based storage assignment layouts in an AS/RS with single, double or multiple I/O stations. In the double I/O stations layout the AS/RS is equipped with two I/O ports at floor level on opposite ends of each aisle. The results indicated that, by applying the algorithm a significant reduction in the expected cycle time per transaction is produced. Vasili et al. (2008) proposed a new configuration for the I/O station in split-platform AS/RS (SP-AS/RS) in order to reduce average handling time of this system. In their proposed configuration the I/O station is located at the center of the rack. They developed a continuous travel time model for this new configuration. The travel time model was validated by using Monte Carlo simulation. The results and comparisons show that within a range of shape factors this new configuration is more preferable than those introduced by Chen et al. (2003) and Hu et al. (2005).

8.3.7 Storage Assignment

Another topic that has received considerable attention in the literature is the assignment of incoming stock to the storage locations. A storage assignment policy serves to determine which products are assigned to which locations and establishes a framework for allocating the incoming products to the storage locations (Roodbergen and Vis 2009).

A storage policy is considered optimal if it minimizes the average time required to store and retrieve a load while satisfying the various constraints placed upon the system (Goetschalckx and Ratliff 1990). A storage assignment policy based on the needs of manufacturing operations can increase not only the performance of the AS/RS but also the performance of the production system (Hsieh and Tsai 2001). Several storage assignment policies can be found in the literature for AS/RSs. The five often used policies are: randomized storage; closest open location storage assignment; class-based storage; full-turnover-based storage and dedicated storage (see e.g., Hausman et al. 1976; Graves et al. 1977; Schwarz et al. 1978; Goetschalckx and Ratliff 1990; Van den Berg 1999; Roodbergen and Vis 2009).

Randomized storage policy allows the products to be stored anywhere in the storage area. Using this policy, all empty locations have an equal probability of having an incoming load assigned to them. If the closest open location storage is applied, the first empty location that is encountered will be used to store the products. This typically leads to an AS/RS where racks are full around the I/O stations and gradually more empty toward the back (if there is excess capacity).

Class-based storage policy distributes the products based on their demand or movements frequency, among a number of classes, and for each class it reserves a region within the storage area. Accordingly, an incoming load is stored at an arbitrary open location within its class (randomized storage is applied within each class).

Full-turnover storage policy determines storage locations for the products based on their demand or turnover frequency. Frequently requested products get the easiest accessible locations, usually near the I/O-points. Slow-moving products are located farther away from the I/O-point. An important assumption for this rule is that the turnover frequencies need to be known beforehand. Randomized and full-turnover storage policies are in fact extreme cases of the class-based storage policy. Randomized storage considers a single class and full-turnover storage considers one class for each product. The class-based storage policy and the full-turnover storage policy attempt to reduce the mean travel times for storage and retrieval operations by storing products with high demand at locations that are easily accessible. According to Van den Berg and Gademann (1999), the demand for a product may be estimated by the cube-per-order index (COI) which has been presented by Heskett (1963). Dedicated storage policy assigns each product type to a fixed location. These locations may be determined by activity and inventory levels or by stock number (Lee and Schaefer 1997). Replenishments of that product always occur at this same location. The main disadvantages of this policy are its high-space requirements and consequent low-space utilization. This is due to the fact that locations are reserved even for products that are out of stock. Furthermore, for each product type sufficient space must be reserved to accommodate the maximum inventory level that may occur. Most advantages of dedicated storage, such as locating heavy products at the bottom or matching the layout of stores, are related to non-automated orderpicking areas and are not as interesting for AS/RSs. For practical purposes it is easiest if a full-turnover policy is combined with dedicated storage.

Hausman et al. (1976) investigated and compared the operating performance of the three storage assignment policies: randomized storage; class-based storage and full-turnover policy. It was observed that significant potential reductions in stacker crane travel times in automatic warehousing systems is possible based on class-based turnover assignment policies rather than closest open-location (essentially random) policies. However, in this study the interrelationship between storage assignment and requests sequencing rules was not investigated. Linn and Wysk (1987) presented a simulation study to consider the storage assignment rules similar to Hausman et al. (1976) but with other control decisions. Performance of different control algorithms for a unit-load AS/RS for various storage and retrieval rates under seasonal demand was analyzed. Furthermore, the effect of workload intensity on the control algorithms and the effect of product mix on the control algorithms were investigated. They used the following storage location assignment rules:

1. *Random assignment* (*RNDM*). A location is randomly picked and assigned to the pallet to be stored if it is empty. Otherwise, another location will be picked.
2. *Pattern search, lowest tier first* (*LTF*). The storage location is selected by searching for the closest open location in the lowest tier first. If no empty one is found, the next lower tier will be searched.
3. *Shortest processing time* (*SPT*). The empty location with the minimum travel time from input station is assigned for next storage.
4. *Turnover rate based zone assignment* (*ZONE*). The storage rack is partitioned into number of zones, which is equal to the number of product types. The zone closest to the I/O station is assigned to store pallets of highest turnover rate. When searching for an empty location, if an empty location cannot be found in its own zone, the next lower turnover zone will be searched. If all the lower turnover zones are full, then the next higher turnover zone is searched.

The results indicated that, the storage location assignment rules affect the system performance in the following manner: when the traffic intensity is low (below a critical value), the random location assignment is better; as the traffic becomes heavier, the pattern search (lowest tier first) becomes better; if the traffic intensity increases further, the shortest processing time rules and zone-based rules will be better rules. Rosenblatt and Eynan (1989) developed the optimal boundaries for a general *n*-class storage rack in AS/RS. A solution procedure was developed which required only a one-dimensional (1D) search procedure. It was shown that most of the potential improvement in the expected one-way-travel time can be obtained when the warehouse is divided into a relatively small number of regions (<10). Thus, there is no need to use the full-turnover approach, which is difficult to implement and administer.

Goetschalckx and Ratliff (1990), with regard to storing unit-loads, classified the storage policies in two major classes: dedicated storage policies and shared storage policies. Dedicated storage policies require that a particular storage location be reserved for units of a single product during the entire planning horizon. Shared storage policies allow the successive storage of units of different products in the same location. Under these definitions, randomized and class-based storage policies are placed in the category of shared storage policies. They proposed an optimal storage policy based on duration-of-stay (DOS) with respect to travel time and storage space for the systems with balanced input and output. The DOS-based policy classifies the units of all items according to their expected DOS. Then the class of units having the shortest DOS is assigned to the closest AS/RS region. Based on the same principles, two heuristic policies were developed for more complex systems. Simulation results were presented to compare travel times for dedicated storage, random storage, turnover-based storage classes and DOS-based storage classes. It was shown that for SC storage and retrieval, shared storage policies based on duration-of-stay of individual unit-loads in the system have the potential to significantly decrease travel time. Kim and Seidmann (1990) presented a framework for obtaining analytic expressions of the expected throughput rate in AS/RSs. These expressions were developed based on generalized full-turnover item allocation policies and random storage and retrieval requests. Both SC and DC operations were considered and a general expression for the expected cycle time in a SC class-based system was also developed. The results demonstrated the potential for significant reductions in the expected cycle time in the case of full-turnover item allocation.

Van den Berg (1996) investigated the class-based storage allocation problem. He presented a polynomial-time dynamic programing algorithm that distributes products and locations among classes such that the mean SC travel time is minimized. The algorithm outperforms previous algorithms (e.g., Graves et al. 1977; Hausman et al. 1976; Rosenblatt and Eynan 1989). He claimed that, this algorithm may be applied to a wide variety of warehousing systems, since it holds for any demand curve, any travel time metric, any warehouse layout and any positions of the input station and output station. Moreover, it allows that the inventory level varies and determines the storage space requirements per class by imposing a risk-level on stock overflow.

Thonemann and Brandeau (1998) applied the turnover-based and class-based assignment policies of Hausman et al. (1976) to a stochastic environment. An expression for expected one-way travel time with given uniform and exponentially distributed demand was developed. It was observed that the turnover-based policy applied to the stochastic environment is optimal as it minimizes one-way travel time. Both the turnover-based and class-based assignment policies applied in the stochastic environment reduce the expected time of storage and retrieval in comparison with randomized assignment. These savings can be directly translated into increased throughput capacity for existing systems and can be used to improve the design of proposed systems. Based on the same approach as in Goetschalckx and Ratliff (1990), and using computer simulation, Kulturel et al. (1999) compared two shared storage assignment policies in an AS/RS. The AS/RS was assumed to operate under a continuous review, order quantity and reorder point inventory policy. The average travel time of the stacker crane for storing and retrieving products was used as the main performance measure. Sensitivity of the system to product variety, inventory replenishment lead time and demand rate were investigated, as well as the effects of the inventory policy and the product classification technique used. The results indicated that the turnover-based policy, in general, outperforms the duration-of-stay-based policy. However, the difference between the performances of the two policies becomes insignificant under certain conditions.

A bill of materials (BOM) contains a listing of all of the assemblies, sub-assemblies, parts, and raw materials that are needed to produce one unit of finished product. Thus, each finished product has its own BOM (Stevenson 2005). Generally, the requirements of manufacturing operations are embedded in material attributes, and the BOM is the best source to link material attributes. By employing the BOM as the backbone structure of a production system, a computer integrated manufacturing (CIM) system can be thoroughly configured. In this regard, Hsieh and Tsai (2001) presented a BOM-oriented class-based storage assignment method for an AS/RS. The proposed method possesses not only the advantage of a class-based storage method, but also the feasibility to integrate an AS/RS into a CIM system. The effectiveness of the proposed method was illustrated through a case study. A random storage assignment method was also employed to obtain the solution for the illustrative example. From the results of comparative studies, the proposed BOM-oriented class-based AS/RS assignment method was shown to be efficient. Wen et al. (2001) presented compact forms of expected travel time under the class-based and full-turnover-based storage assignments considering various travel speeds with known acceleration and deceleration rates. Ashayeri et al. (2001) presented an exact, geometry-based analytical model for computing the expected cycle time for a stacker crane operating under SCs, DCs or both, in a rack structure that has been laid out in pre-specified storage zones for classes of goods. The rack may be either square-in-time or non-square-in-time. The approach is intuitively appealing, and it does not assume any certain layout shape, such as traditional "L-shaped" class layouts. The model can be used by designers as a tool for quickly evaluating alternative layout configurations with respect to expected S/R cycle time in an AS/RS, and thereby the throughput of an automated warehouse over time. In a later study, Ashayeri et al. (2002) presented the use and extension of the geometrical-based algorithmic approach proposed by Ashayeri et al. (2001), for determining the expected stacker crane cycle times, and therefore warehouse throughput, for class-based storage assignment layouts in an AS/RS. The algorithm may be used for the rack layouts with single double or multiple I/O stations. They derived the travel time expressions of the stacker crane for an AS/RS having two I/O station, for SC and DC cycles as,

$$E(SC) = \sum_{i}\sum_{k}\sum_{m} P_{k\cdot i} \cdot P_{i\cdot m}(E_{k\cdot i} + E_{i\cdot m}), \tag{8.19}$$

$$E(DC) = \sum_{i}\sum_{k}\sum_{m}\sum_{j} P_{k\cdot i} \cdot P_{i\cdot j} \cdot P_{j\cdot m}\left(E_{k\cdot i} + E_{i\cdot j} + E_{j\cdot m}\right). \tag{8.20}$$

where $P_{k.i}$ is the probability that a movement from input port k to zone i takes place. $E_{i\cdot m}$ is the probability that a movement from zone i to output port m takes place. $E_{k\cdot i}$ is the expected travel time between input port k and a random location in zone i. $E_{i\cdot m}$ is the expected travel time between a random location in a storage zone and an output port m. $E_{i\cdot j}$ is the expected travel time between a random point in zone i and a random point in zone j. $P_{i\cdot j}$ is the probability that a movement from zone i to zone j takes place. k and m represent I/O 1 and I/O 2, respectively. Note that the expected travel time in an AS/RS with a single I/O port located at one end of the aisle can be found by setting $P_{i\cdot m} = 1$ and $E_{k\cdot i} = E_{i\cdot m}$ in Eq. 8.19. In order to apply Eq. 8.19 in a more general form for an AS/RS with p input ports and q output ports (multiple I/O stations) allow the indices of k and m to range over all I/O ports, i.e., $k = \text{I/O } 1, 2, \ldots, p$, and $m = \text{I/O } 1, 2, \ldots, q$.

Foley and Frazelle (1991) derived the distribution of the DC cycle time for a square-in-time rack under randomized storage, and used it to determine the throughput of miniload AS/RSs. Park et al. (2003) analyzed the travel time of minload AS/RSs for turnover-based storage systems and determined the mean and variance of DC travel times. Detailed numerical results for selected rack shape factors and ABC inventory profiles were presented and the effect of alternative rack configurations on travel time performance measures was investigated. They demonstrated how to determine the throughput of EOA miniload systems with turnover-based storage and exponentially distributed pick times. Petersen et al. (2004) compared the performance implications of class-based storage to both randomized and full-turnover-based storage for a manual order picking warehouse by means of simulation. In addition, the effect of the number of storage classes, the partition of storage classes and the storage implementation strategy applied in the warehouse were investigated. From the simulation results it was observed that class-based storage provides savings in picker travel over random storage and offers performance that approaches full-turnover-based storage. Park et al. (2006) investigated the performance of EOA miniload system with a square-in-time rack containing two storage zones (two-class storage): high turnover and low turnover. The distribution of the DC travel time and closed-form expressions for throughput for two important families of pick time distributions: deterministic and exponential were derived. In a later study, Park (2006) determined the same issues for systems with non-square-in-time racks. Yu and De Koster (2009a, b) extended the study of De Koster et al. (2006) on compact 3D AS/RS by investigating two different storage assignment policies. They derived the expected SC cycle time under the full-turnover-based storage policy and proposed a model to determine the optimal rack dimensions by minimizing this cycle time (Yu and De Koster 2009a). It was observed that, under the full-turnover-based storage policy, significant cycle time reduction can be obtained compared with the random storage policy. In the later study the optimal storage zone boundaries were determined for this system with two product classes: high- and low-turnover, by minimizing the expected stacker crane travel time (Yu and De Koster 2009b). They formulated a mixed-integer non-linear programing model to determine the zone boundaries. The results indicated that significant reductions of the machine travel time are obtainable by using class-based storage.

Comparing all the mentioned storage policies in this section, randomized storage is the most commonly used method because it is simple to administer. However, the policies based on the demand frequency of products are generally most effective at improving performance, but they are information intensive and far more difficult to administer than a random storage policy (Bozer and White 1984; Petersen et al. 2004). White and Kinney (1982) stated that in comparison to class-based storage, random storage generally requires less storage space because the maximum aggregate storage requirement is generally less than the aggregate maximum storage requirements for each product in storage. In comparison to random storage, class-based storage results in reduced travel time if equal storage is assumed. However, since the class-based storage policy is based on turnover frequency (used to determine the classes) for each product, it is difficult to use, if the turnover frequencies of the products vary with time. Random storage policy is not affected by varying turnover frequencies.

8.3.8 Request Sequencing

Request sequencing rules determine the queuing discipline for the storage and retrieval request queues (Linn and Wysk 1987). Storage requests in distribution or production environments are usually stored according to the first-come-first-served (FCFS) principle. In sequencing retrievals usually due times of retrievals should be met. Hence, by sequencing the retrievals in a smart way, improvements in the overall throughput of the AS/RS can be obtained (Roodbergen and Vis 2009). When sequencing requests on an AS/RS, it is necessary to make a trade-off between efficiency and urgency (Van den Berg and Gademann 1999). The Request sequencing policies may also be used to improve the design of proposed systems to achieve a more desirable balance between throughput and storage capacity (Graves et al. 1977).

The term "interleaving" refers to the pairing of storage and retrieval transactions on the same cycle to generate DC cycle cycles (Fukunari and Malmborg 2009). Hausman et al. (1976) investigated optimal storage assignment, without regard to interleaving. Graves et al. (1977) extended the study of Hausman et al. (1976) to include the following interleaving rules: (1) mandatory interleaving with FCFS queue discipline of retrieves and (2) mandatory interleaving with selection queue of K retrieves. The results indicated that significant reductions in crane travel time (and distance) are obtainable using the proposed interleaving rules. These reductions may be directly translated into increased throughput capacity for existing systems. Schwarz et al. (1978) by means of simulation, validated the analytical works presented by Hausman et al. (1976) and Graves et al. (1977), in a deterministic environment and extended the results to conditions of imperfect information. Later, Bozer and White (1984) developed analytical models for SC and DC cycles and FCFS sequencing of the storage and retrieval requests. In order to create a DC from the storage and retrieval requests, sequencing retrieval requests optimally is a complex problem. The list of retrievals continuously changes over time as old requests are filled and new requests appear. Han et al. (1987) suggested two alternatives to deal with this dynamic problem. The first alternative is to select a "block" of the most urgent storage and retrieval requests, sequence these requests in the block, and when the block of requests has been completed, select another block and so on. This is referred to as "block sequencing". The second alternative is to re-sequence the list every time a new request is added and employ due dates or priorities to ensure that a retrieval at the far end of the aisle is not excessively delayed (i.e., the whole retrieval queue is a block). This is called "dynamic sequencing". They showed that the throughput capacity can be increased by replacing the FIFO strategy with a new heuristics strategy, which is NN, when several retrieval requests are available and DC cycles are performed. The NN rule was studied for selecting storage locations and sequencing retrieval requests, so that the interleaving travel time between storage and retrieval locations in a DC cycle is reduced. Two simple greedy heuristics were developed to select a pair of S/R locations to minimize T_{BW} (called the

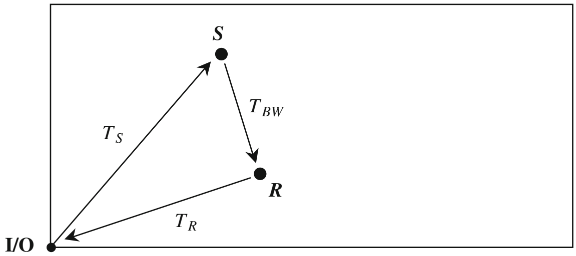

Fig. 8.11 An illustration of DC cycle for nearest-neighbor (NN) and shortest-leg (SL) policies

nearest-neighbor, NN) or $T_S + T_{BW}$ (called the shortest-leg, SL), where T_{BW} is the interleaving time the crane travels empty to the retrieval location after depositing the storage load (Fig. 8.11). The results indicated that SL is better than NN in terms of dual cycle time in a few trials. However, over the long run SL is much worse than NN because SL attempts to occupy the locations near the I/O station (called cluster phenomenon) and drive the rest of the open locations farthest from the I/O station. The performance of both "block sequencing" and "dynamic sequencing" approaches differs per situation.

Eben-Chaime (1992) showed that if the NN strategy is applied to the blocks of fixed size in a non-deterministic environment, it has destructive effects in terms of waiting times, queue length and system stability. They proposed instead to use dynamic nearest-neighbor (DNN) strategy where the whole retrieval queue is the block. It was observed that the performance level of DNN is surprisingly high in terms of average waiting time, average queue length and maximum queue length. Later, Lee and Schaefer (1996) proved that total travel time (TT) is superior to SL and NN strategies. TT selects a pair of S/R locations such that $T_S + T_{BW} + T_R$ (shortest total-travel, STT) is the minimum (See Fig. 8.11).

Bozer et al. (1990) explained that the DC scheduling of AS/RSs can be formulated as a Chebyshev traveling salesman problem (CTSP), which has numerous applications in materials handling and information storage-retrieval. Several heuristic procedures based on geometric concepts have been developed for the CTSP. The study was concerned with evaluating the performance of geometric approaches as a function of the shape of the service region and the number of points to be sequenced.

In the two aforementioned studies, Bozer et al. (1990) and Han et al. (1987) studied the sequencing problem of retrievals without reflecting the dynamic nature of an AS/RS, which is the realistic operating characteristic. These studies especially assumed that all storage and retrieval orders are known in advance. Taking the dynamic operating characteristics of an AS/RS into account, these studies either under-estimate or over-estimate the performance of the stacker crane. Thus, these studies could not provide feasible alternatives for the important design factors of an AS/RS, such as the buffer size, utilization of the stacker crane and so on. Linn and Wysk (1987) presented a simulation model to evaluate the following sequencing rules when the product demand shows seasonal trend:

1. *First-Come-First-Serve* (*FCFS*). All the requests are served on FCFS basis.
2. *Shortest Completion Time* (*SCT*). The request which needs the shortest completion time is served first.
3. *Shortest Completion Time with output priority* (*SCTop*). This is a modified SCT rule, in which the retrieval requests have first priority, to clear the room for storage.
4. *Shortest Completion Time with controlled output priority* (*SCTcop*). This is another modified SCT rule in which the retrieval requests would have the first priority only when the retrieval queue is longer than the storage queue.

The results indicated that, when arrival rate is such that the traffic intensity is low (below a critical value), the sequencing rules produce little improvement in system performance. When arrival rate increases until the traffic intensity goes beyond the critical value, job sequencing rules begin affecting the system performance. Considering the product mix, it was observed that SCTop sequencing rule was better than SCT rule in five product type system; however, SCT became better in ten product type system.

Linn and Wysk (1990a, b) presented an expert system framework for the control of an AS/RS. Their expert system-based control uses a hierarchical control structure which partitions the AS/RS control decision process into strategic, tactical and process control levels, and employs a multi-pass simulation technique to tactically adapt control policies to system changes. The results demonstrated the ability of the system to include control flexibility, for adapting the system to fluctuations in demand and maintain quality performance. It was also observed that the system performed very well particularly at high demand levels. Linn and Xie (1993) presented a simulation study to investigate the effect of job sequencing rule on delivery performance of an ASRS, in an assembly environment with given due dates. The interaction of the sequencing rules with other control variables was also examined. Hwang and Song (1993) analyzed the order sequencing problem in a man-on-board storage and retrieval warehousing system which is suitable for storing items of small size and light weight. Considering the operating characteristics of the man-on-board system, a combined hull heuristic procedure was presented for the problem of sequencing a given set of retrieval requests. The procedure was validated through simulations and the results showed that the procedure performs satisfactorily. Lee and Schaefer (1996) presented an algorithm for the unit-load AS/RSs with non-dedicated storage. The algorithm combines the Hungarian method and the ranking algorithm (Murthy's ranking algorithm) for the assignment problem with tour-checking and tour-breaking algorithms. They showed that their algorithm finds either a verified optimal or near-optimal solution quickly for moderate size problems. Lee (1997) presented an analytical stochastic approach for performance analysis of unit-load AS/RSs, using the queuing model. He established an M/M/1-type queuing model with two waiting spaces for storage requests and retrieval requests. The analysis assumed the exponential distribution of the travel times of a stacker crane. Experimental results showed that the proposed method was effective for both short-term and long-term planning of AS/RSs.

Lee and Schaefer (1997) investigated the effect of sequencing storage and retrieval requests on the performance of AS/RS where a storage request is assigned a predetermined storage location. By exploiting this unique operating characteristic, several optimum and heuristic sequencing methods under static and dynamic approaches were presented. Applications of such sequencing methods include unit-load AS/RS with dedicated storage, EOA miniload AS/RS and potentially unit-load AS/RS with randomized storage. The results indicated that the sequencing methods can significantly reduce travel time by a storage and retrieval machine, thereby, increasing throughput, and that the dynamic heuristic method is simple and fast, yet considerably outperforms the others.

Mahajan et al. (1998) developed a retrieval sequencing scheme for the purpose of improving the throughput of EOA miniload AS/RS in an order picking environment. It was assumed that an order comprised of retrieval requests is always available such that DC cycles are always performed. A NN retrieval sequencing heuristic was presented, an analytical model was developed to predict its performance, and this model was validated by means of simulation. The results showed that the heuristic improves the throughput of the system, over traditional FCFS retrieval sequencing. The heuristic achieves this improvement by properly sequencing the retrieval requests within an order and also optimizing the retrieval requests among successive orders. However, since the analysis assumes that the requests are always available, it represents an over-estimation of the system throughput. Van den Berg and Gademann (1999) studied the optimal sequencing of requests with dedicated storage using the block sequencing approach. It was assumed that a set of storage and retrieval requests are given beforehand and no new requests come in during operation. The objective for this static problem was to find a route of minimal total travel time in which all storage and retrieval requests may be performed. Considering the problem of retrievals sequencing equivalent to the traveling salesman problem (TSP), they showed that the special case of sequencing under the dedicated storage policy can be solved in polynomial time. Van den Berg and Gademann (2000) evaluated the performance of various control policies for the AS/RS by using computer simulation. For the sequencing of storage and retrieval requests they developed policies based on the heuristics presented in Van den Berg and Gademann (1999). By means of these policies, they analyzed the trade-off between efficient travel of the stacker cranes and response time performance.

Hur et al. (2004) and Hur and Nam (2006) presented stochastic approaches for the performance estimation of a unit-load AS/RS by using an M/G/1 queuing model with a single server and two queues. They assumed that the storage and retrieval commands arrive at the system according to Poisson processes with different rates. Comparing the results with simulation results it was observed that the proposed approach gives satisfactory results with very high accuracy. Based on the same approach as in Linn and Wysk (1990a, b), Yin and Rau (2006) studied dynamic selection of sequencing rules for a class-based unit-load AS/RS. They developed a multi-pass and genetic algorithm (MPGA) simulation system which divides storage and retrieval requests or DCs into a series of blocks, and then conquers each block to find the most promising combination of sequencing rules. They considered the following sequencing rules: FCFS, shortest total-travel time (STT) and shortest due time (SDT), where these rules could be chosen dynamically in any decision points in the system. The results showed that the proposed approach with dynamic rules was much better than those approaches with any single rule used from the beginning to the end in the whole system. The results of this study provide a better way to control and manage the operation of AS/RS. Dooly and Lee (2008) presented a shift-based sequencing problem for twin-shuttle AS/RS, where replenishment and depletion (storage and retrieval operations) of items occur over different shifts. For instance, certain warehouses or distribution depots deplete their items in stock during morning shifts and replenish during later shifts. They showed that this problem can be transformed into the minimum-cost perfect matching problem and presented an efficient polynomial-time optimum method that can achieve a large throughput gain over other methods. Average-case and lower bound analyses for this problem were presented as well.

8.3.9 Order Batching

Batching is a control policy which considers how one can combine different customer orders into a single tour of the crane (Roodbergen and Vis 2009). When orders are fairly large, each order can be picked individually (i.e., one order per picking tour). This way of picking is often referred as the single order picking policy (or discrete picking or pick-by-order). However, when orders are small, there is a potential for reducing travel times by picking a set of orders in a single picking tour. Order batching is the method of grouping a set of orders into a number of sub-sets, each of which can then be retrieved by a single picking tour (De Koster et al. 2007). Based on the previous literature, only a few papers have addressed the batching of orders in combination with the AS/RS, since this policy is mainly applicable to man-on-board AS/RS. In a man-on-board AS/RS, orders are combined into batches and each batch is processed in a tour of the stacker crane. Batching policy determines the way to combine orders to form batches. Since botching is an NP-hard (i.e., non-deterministic polynomial-time hard) problem, in order to obtain solutions for large problems in acceptable computation times, heuristic algorithms have been proposed (Pan and Liu 1995).

Most heuristic algorithms for order batching basically follow the same three steps (Fig. 8.12): (1) a method of initiating batches by selecting a seed; (2) a method of allocating orders to batches (addition of orders to batches) and (3) a stopping rule to determine when a batch has been completed. An important assumption in all batching heuristics is the fact that a single order cannot be split over various batches, but needs to be picked as a whole (Pan and Liu 1995; Roodbergen and Vis 2009). De Koster et al. (2007) distinguished two types of order-batching heuristics: seed and savings algorithms. Seed algorithms construct batches in two phases: seed selection and order congruency. Seed selection rules

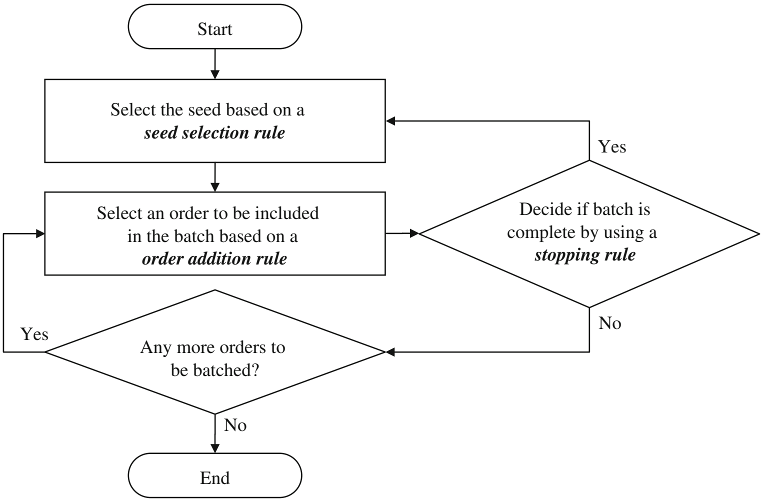

Fig. 8.12 Common procedure for order-batching Heuristics (Modified after Pan and Liu 1995; Roodbergen and Vis 2009)

define a seed order for each batch. Order congruency rules determine which unassigned order should be added next into the current batch. Usually, an order is selected, to be included in a batch, based on a measure of the 'distance' from the order to the seed order of the batch. In saving algorithms a saving on travel distance is obtained by combining a set of small tours into a smaller set of larger tours.

Elsayed (1981) presented four heuristic algorithms for handling orders in single aisle man-on-board AS/RSs. He used the following heuristic algorithms: order with largest number of locations to be visited; order with smallest number of locations to be visited; order with largest volume; and order with smallest volume. The algorithms select the orders that will be handled in one tour in order to minimize the total distance travelled by the stacker crane within the warehouse system. The optimal tours for the four algorithms were found by using the traveling salesman algorithm. Elsayed and Stern (1983) used a cumulative rule for the seed selection in single aisle man-on-board AS/RSs. Contrary to a single seeding rule, a cumulative seeding rule uses all orders that are already in the batch as the seed. Hwang et al. (1988) and Hwang and Lee (1988) presented heuristic algorithms based on cluster analysis for order-batching problem in a single aisle man-on-board AS/RS. The algorithms process the orders by batching some of them according to the value of the similarity coefficient which is defined in terms of attribute vectors. In order to find the minimum travel time for each batch of orders, the traveling salesman algorithm was used. The performances of the algorithms were analyzed using simulations. The results and comparisons indicated that some algorithms developed represent satisfactory performance.

Pan and Liu (1995) presented a comparative study of order-batching algorithms composed of four seed selection rules and four order addition rules for order-batching problems based on average travel times. The performances of these algorithms were compared along the 3D of shape factor, capacity of the stacker crane and storage assignment policy. The results indicated that only the capacity of the stacker crane has effect in the selection of order-batching algorithms. It was concluded that the heuristic which was presented by Hwang and Lee (1988) generates the most efficient batches for a small capacity stacker crane as well as for large one. It was recommended to use this heuristic for order batching under any type of shape factor, capacity of the stacker crane, and storage assignment policy. The above-mentioned studies have not taken into account the time constraints on retrievals (e.g., order due time and the penalty of violating the due time). Elsayed et al. (1993) and Elsayed and Lee (1996) investigated the order-batching problem in a man-aboard system where a due date is specified for each retrieval order. The grouping of orders into batches (batching process) was performed based on a penalty function, which incorporates both the earliness and the tardiness of the orders. They developed efficient procedures for order sequencing and grouping the orders into batches such that the penalty function is minimized.

All mentioned papers in this section assume that the arrival patterns of orders are known before the start of the operations. However, it is obvious that order-batching problem can become more difficult when orders arrive on-line. It stands for reason that, for on-line arrivals there is a trade-off between reducing waiting times and reducing travel times.

8.3.10 Load Shuffling and Sorting Heuristics

Although AS/RSs allow random access to any storage cells, often it is advantageous to shuffle (i.e., pre-sort, relocate or rearrange) the loads in order to minimize the retrieval time (Hu et al. 2010). Updating and shuffling of items and reconsidering storage assignment decisions can be vital in current dynamic environments to meet the fluctuating, short-term throughput requirements imposed on the AS/RSs. An AS/RS needs to store and retrieve loads in the shortest possible time period. Compared with storage, the quick response of retrievals is often more critical. This is because when a load is to be stored into an AS/RS rack, it can be put into any empty storage cell. While for retrieval, only the designated one is valid. In order to retrieve loads as quickly as possible, a solution is to shuffle the items to specified locations to minimize the response time of retrieval. In other words, the shuffling of the items with a high expectancy of retrieval closer to the I/O station of each storage rack during off-peak periods will reduce the expected travel time for the stacker cranes during future peak periods of the planning horizon (Hu et al. 2004; Jaikumar and Solomon 1990; Roodbergen and Vis 2009). Using the load-shuffling strategy to some extent can also speed up the storage operation. It stands for reason that during a storage operation, a load can be stored

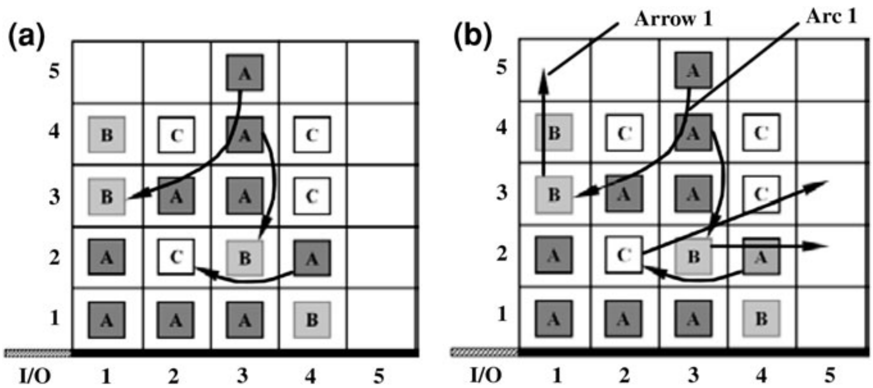

Fig. 8.13 (**a**, **b**) Matching for load shuffling in an AS/RS (Modified after Muralidharan et al. 1995)

into the most convenient storage location so as to reduce the storage travel time. Later during stacker crane idleness, the loads can be shuffled into the more suitable locations. Applying the shuffling scheme also imposes positive influences on the rack and stacker crane utilization (Hu et al. 2010). However, very little information about the load-shuffling strategy can be found in the literature.

Jaikumar and Solomon (1990) presented an efficient algorithm that minimizes the number of load-shuffling operations in order to meet the expected throughput. It was assumed that there is sufficient time, so that travel time considerations were omitted from the model. Considering the fluctuation in order volume, they proposed two heuristic methods. The first method enlarges the order pick system by one new zone during peak periods; and the second one reduces the system by one zone during off-peak periods. The purpose of these heuristic methods is to maintain the regular workloads so that no picker is overloaded during peak periods and/or light-loaded during off-peak periods. Such adjustments balance the workloads among all pickers and keep the continuity of the pick lane. All the proposed methods were validated through simulation experiments.

Muralidharan et al. (1995) proposed a shuffling heuristic-based approach that combines the random storage and class-based storage assignments for the storage location assignment in an AS/RS. They described the proposed shuffling algorithms and showed that the waiting time and service time reduced considerably for this storage policy. Their approach for shuffling the loads can be briefly described as follows. When the slacker crane is idle, a shuffling cycle is initialized. There may be a number of class A products (very important/high-turnover products) that have been stored farther away from the I/O station and class B and C products stored near the I/O station. As shown in Fig. 8.13a, all the class A products farther away from the I/O station are matched to the class B or C product or an empty location closest to the I/O location for shuffling. Each match is represented by a directed arc which corresponds to the planned movement of class A pallets.

In order to move a class A pallet into the location of a class B or C pallet, the B or C pallet must he moved to a near-by empty location to make room for the class A pallet. So the class B or C product is matched to the nearest empty location away from the I/O station that is not matched with a class A product. These matchings are represented by another set of directed arcs shown in Fig. 8.13b. The direction of arrow corresponds to the planned movement of the class B or C pallets. For each pair of arrow and arc, the arrow must be traversed prior to traversing the arc. When forming a route through these arcs and arrows, the precedence constraints must be met. Based on the results they observed that the load shuffling is clearly an appropriate strategy to increase the AS/RS operating efficiency.

By means of a simulation study Moon and Kim (2001) demonstrated that the load-shuffling strategy can be valuable if the quantities of products belonging to different classes vary over different time horizons. It helps to maintain stable throughputs with any storage assignment policies, and it can alleviate the waiting line for the AS/RS rack. Load-shuffling strategy does not cause a bottleneck in the stacker crane operations, since the time to shuffle the items in an AS/RS is too small to affect the stacker crane utilization. Hu et al. (2004, 2010) investigated the issue of shuffling loads in the SP-AS/RS which is suitable to handle extra heavy loads. The objective was to shuffle the loads into any specified locations in order to minimize the response time of retrievals. 1D, 2D and 3D AS/RS racks were designed in order to achieve the shuffling efficiently. They described the shuffling algorithms and derived expressions for calculating the response time of retrieval. Results of the analysis and numerical experiments showed that the proposed shuffling algorithms are quite efficient.

Based on examination of the literature it can be observed that the load-shuffling strategies for AS/RS have not been adequately investigated in previous studies which implies a need for further studies in this area. Moreover, existing shuffling algorithms are applicable only during the slacker crane idleness. For AS/RSs with high system utilizations, as discussed earlier, it is not clear what opportunity exists in a practical sense to take advantage of existing load-shuffling strategies since the stacker crane will not be idle very often.

8.4 Conclusions and Further Research Issues

From the literature survey and discussions in this chapter it can be observed that a considerable amount of research has been carried out over the years to evaluate, improve and optimize the physical structure, operational features and control policies of the AS/RSs. Most of the existing studies only discuss a fraction of these AS/RS issues. Therefore, development of comprehensive evaluating and improving procedures would seem to be necessary in order to simultaneously address all these issues. In addition, regardless of the actual improving and optimization procedures, a system of performance measurement is needed to evaluate the overall performance of the resulting system at every stage. In this regard, many publications have appeared on performance measurement. Most studies have analyzed the performance of AS/RSs under a balanced situation so that inbound work-flow is equal to the outbound work-flow. However, considering the dynamic nature and realistic operating characteristic of an AS/RS, during certain time slots, the system operates under an unbalanced situation. A perfectly balanced system is a very idealized situation which is unlikely to occur in real storage systems. Hence, the research in this field should move toward developing models, algorithms and heuristics that include the dynamic and stochastic aspects of current business. The performance of an AS/RS varies according to the definition of measure and the operating strategies. Performance measures for an AS/RS may include: system throughput, utilization of rack and stacker crane and expected travel time of stacker crane. Travel time estimates in different types of AS/RS configurations are appropriate analytical tools for evaluating and comparing the system performance and control policies.

In the preceding sections the existing travel time models on different aspects of the AS/RS, especially its control policies were investigated. Considering different control policies, dwell-point policy of the stacker crane is the strategy that can affect and contribute to the system response time of AS/RS. Several dwell-point policies for AS/RS have been introduced in the literature. Meanwhile, development of expected travel time (i.e., average travel time) models for AS/RS based on different dwell-point policies has been the subject in much research over the past several years. Although many dwell-point strategies have been suggested, and an optimal strategy defined, however for AS/RSs with high system utilizations, the dwell-point strategies may have no significant effect on the system response time, since the stacker crane will not be idle very often. Other control policies for AS/RSs that have received considerable attention in the literature are storage assignment and request sequencing. Majority of the literature addresses single aisle AS/RSs with single I/O station. Hence, storage assignment and request sequencing policies for other types of configurations (e.g., multiple I/O stations) or non-traditional AS/RSs (e.g., multiple shuttle AS/RSs) deserve further study. Order batching policy is the method of grouping a set of orders into a number of sub-sets, each of which can then be retrieved by a single picking tour. Almost all research on the batching of orders has assumed that the arrival patterns of orders are known before the start of the operations. However, it is obvious that order-batching problem can become more difficult when orders arrive on-line. It stands for reason that, for on-line arrivals there is a trade-off between reducing waiting times and reducing travel times. Another strategy which can result in minimizing the AS/RS travel time and consequently increasing its throughput performance is to use the load-shuffling procedures. The objective is to shuffle (i.e., pre-sort, relocate or rearrange) the loads to specified locations to minimize the response time of retrieval. However, based on examination of the literature it can be observed that the load-shuffling strategies for AS/RS have not been adequately investigated in previous studies which implies a need for further studies in this area.

Appendix A

Figures 8.14, 8.15

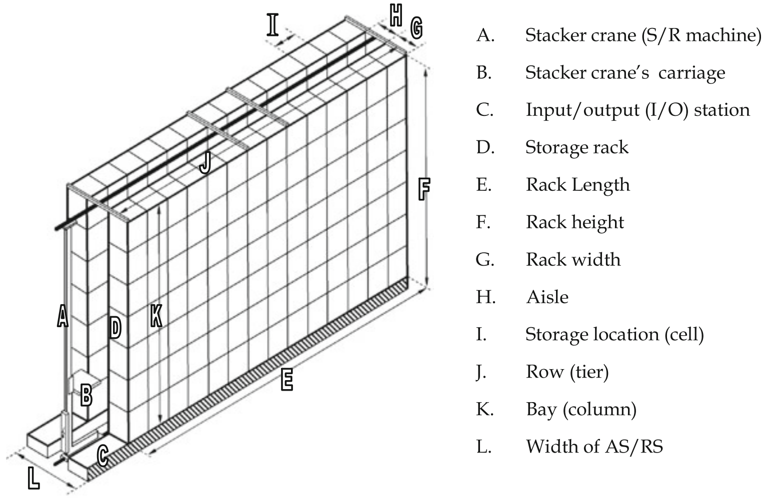

Fig. 8.14 Generic Structure and principal constituents of an AS/RS

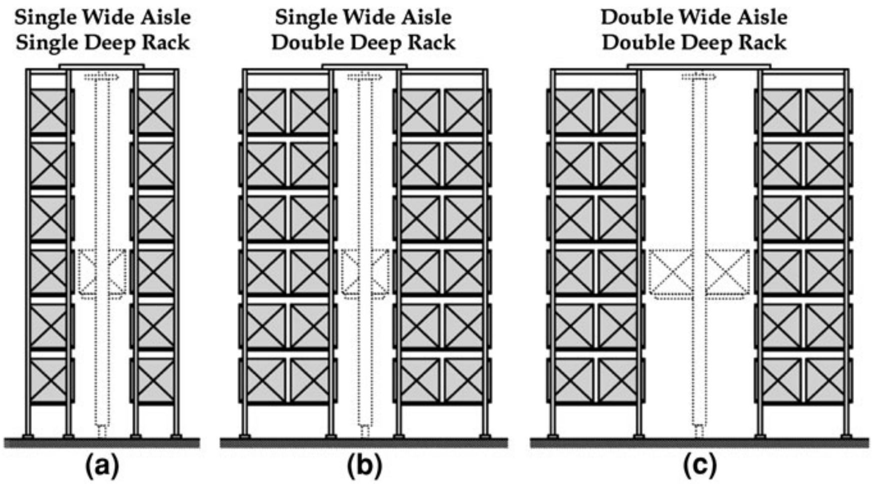

Fig. 8.15 Some common types of rack structures in AS/RSs. **a** Single wide aisle, single deep rack. **b** Single wide aisle, double deep rack. **c** Double wide aisle, double deep rack

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