CLASS-BASED STORAGE ASSIGNMENTS FOR MINILOAD AS/RS WITH OPEN-RACK STRUCTURE

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ABSTRACT

Automated Storage and Retrieval Systems (AS/RSs) are warehousing systems that are used for the storage and retrieval of products in both distribution and production environments. This paper presents an open-rack structure with unidirectional-upward mobile loads within the rack, for miniload AS/RS, in which the stacker crane is only used for the retrieval operations, and the storage operations are carried out by separate devices namely, storage platforms. Heuristics algorithms and models are developed for load shuffling and travel time of the storage platform, respectively. The well-known ABC approach is used to classify inventory items for determination of class-based storage assignments. Then the expected travel time of the proposed AS/RS is derived. The travel time model and the performance of proposed AS/RS are validated using Monte Carlo simulation and are compared with a conventional one. The results show that the open-rack AS/RS represents a higher performance and the proposed models are reliable for the design and analysis of this kind of AS/RS.

Keywords: *Automated storage and retrieval systems (AS/RS), Open-rack structure, ABC approach, Travel time, Monte Carlo simulation.*

INTRODUCTION

Automation can generally be justified for use in the workplace through four approaches: manufacturing necessity, economic payback, intangible benefits and future benefits. A key reason that automation and robotics are extensively used in so many manufacturing arenas is that the systems are designed to eliminate jobs that are repetitious or dangerous for humans, with cost benefits resulting from longer operating hours [1]. Innovations in robotic and automated systems have allowed industries to reduce payrolls while increasing production and quality. This ultimately translates into a more consistent product leading to higher customer satisfaction. Automated Storage and Retrieval Systems (AS/RSs) have the ability to provide a competitive advantage for manufacturers for several reasons; reduced cycle time, reduced inventories and better overall utilization of capital and labour [2]. If material is not properly moved, a product cannot efficiently or profitably be provided. Since in-process material handling is a direct cost, any reduction in this cost diminishes the cost of production [3]. ASRS systems are designed to combine different types of material handling equipment in order to meet the user's specific operational requirements. Ideally, these systems should reflect the operating strategy of the user, employ flexibility and should be able to generate variable performance levels based on production requirements [4].

Groover [5] distinguished six types of AS/RS; unit load AS/RS, deep-lane AS/RS, miniload AS/RS, man-on-board AS/RS, automated item retrieval system and vertical lift storage modules (VLSM). Miniload AS/RS is defined by Groover [5] as a storage system which is used to handle small loads (individual parts or supplies) that are contained in bins or drawers in the storage system. MHIA [6] defined the Miniload AS/RS as a type of automated storage and retrieval system that handles loads that are typically contained in small containers or totes, with load weights typically falling in the100 to 500 lb. Range, and occasionally as much as 750 to 1000 lbs. Industry often uses the miniload AS/RS to store and retrieve small parts, tools, supplies, fixtures and the like, for use in automated order picking and assembly operations [7]. A general description of a miniload AS/RS and its operation can be found in [8]. The basic components of the type of miniload AS/RS which are considered in this paper are storage racks, stacker cranes (storage/retrieval, S/R machines), input/output (I/O) stations, and interface conveyors. Stacker cranes are used to store and retrieve loads into or from the storage cells. The stacker cranes can travel simultaneously in the vertical and horizontal directions and perform a sequence of storage and retrieval operations. Each stacker crane is equipped with a vertical drive, a horizontal drive and one or two shuttle drives. The vertical drive raises and lowers the load, whereas the horizontal drive moves the load back-and-forth along the aisle. The shuttle drives transfer the loads between the stacker cranes carriages and the storage cells in the AS/RS rack [9]

A miniload AS/RS can operate in two ways, namely in a single command cycle or in a dual command cycle. In a single command cycle the crane performs either a single storage or a single retrieval request. If an AS/RS performs both a storage and a retrieval request in a single cycle, it will be a dual command cycle. Performance of a conventional miniload AS/RS can be enhanced when the ratios of storage and retrieval operations are approximately, equally distributed and in this case, a single shuttle stacker crane can operate up to dual command cycle [10]. In other word, the possibility of performing dual command cycles depends on the availability of storage and retrieval requests. If both types of requests are available, dual command cycles give advantages with respect to travel times [11].

In many real applications of the miniload AS/RSs (such as automated libraries), for several periods of a working day, the ratios of storage and retrieval operations are not equally distributed. For instance, all the operations at the end of a working period in a library are storage operation and the stacker crane is faced to perform an enormous sequence of storage operations one by one. Similarly, during the working period in the library, the ratios of retrieval operations are approximately more than storage operations. The purpose of this study is to investigate an AS/RS that can handle many loads at the same time. In this paper, the open-rack structure with unidirectional-upward mobile loads within the rack is applied in AS/RS, in which the stacker crane is only used for the retrieval operations and the storage operations are carried out by separate devices, namely, storage platforms (SPs). The proposed AS/RS has one SP for each rack to store several loads at the same time (Figure 1). Handover stations are located at the lowest levels of the racks and the dwell point positions of SPs are lowest point of handover stations. A loop conveyor along with entrance gate systems is used in order to transfer the storage items from input station and unload them inside the handover stations, on the SPs. The loads are remaining on the loop conveyor until they are charged to handover station. The loaded SPs move upward through the handover stations and unload the items into the rack open bays.

MATERIALS AND METHODS

Open-rack structure

The structure of open-rack with unidirectional-upward mobile loads within the rack to be modeled in this paper is depicted in Figures 1 and 2. The open-rack structure considered in this research is defined as follows: The rack can handle the loads that are contained in small standard containers. The rack consists of open bays (i.e. the top and bottom of the cells are not closed from bottom to top of the rack), which allows the loads to have unidirectional-upward movement within the bays in the rack. The upward motion is provided by SP. The storage locations (cells) are distinguished with 4 load-arms (brackets) as the seat of containers. The hinge joint load-arms with 90° rotation and a simple gravity mechanism, help to stabilize movement and stoppage of containers and also act to prevent their extra downward movements.

Load shuffling

The levels (i.e. tiers) are numbered by integers from 0 onwards; the bays (i.e. columns) are numbered from 0 onwards, all according to their distances from the output station. There is no storage cell in level 0 (handover station) because it is used by SP (Figure 3). According to [12], by definition, $T_v = VL/vv$ and $T_h = HL/hv$. Let $T = \max\{ T_v , T_h\}$ and $b = \min\{ T_v /T , T_h /T\}$, which implies that $0 \leq b \leq 1$. As the value of b may represent the shape of a rack in terms of time, b is referred to as the shape factor.

Load shuffling in open-rack

An example of loads shuffling (load sorting) in open-rack structure is illustrated in figure 4. Consider that, there are tree sequential storage operations. In the first step (Figure 4a) because there are empty storage locations in all four bays thus, the SP beneath the bays is loaded with four containers. In the next step, the SP unloads the containers into the bays in the rack (Figure. 4b). In the third step because there are no more empty locations in the bays 1 and 4, the SP is only loaded for the bays 2 and 3 (Figure 4c) and finally, the platform unloads these containers into bays 2 and 3 in the rack. It is clear that for the next storage operation, the SP can be loaded just for bays 2. For the retrieval operations, the stacker crane can be run after stoppage of SP in its dwell point position.

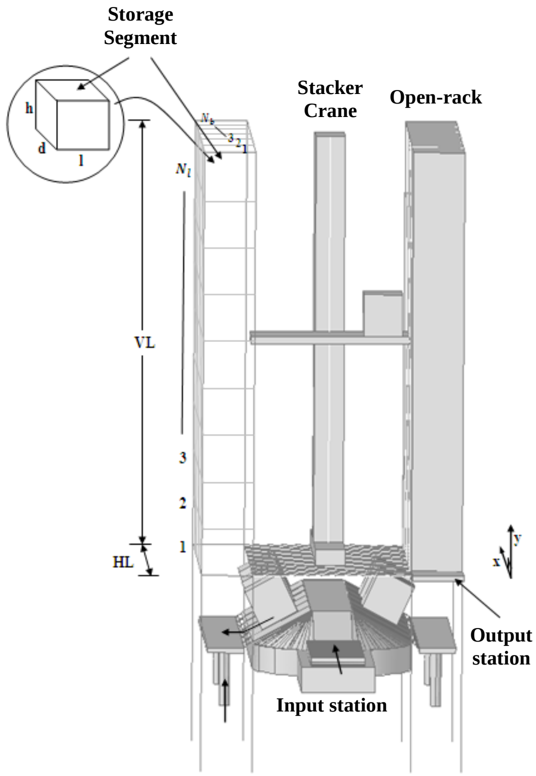

Figure 1: An illustration of open-rack AS/RS

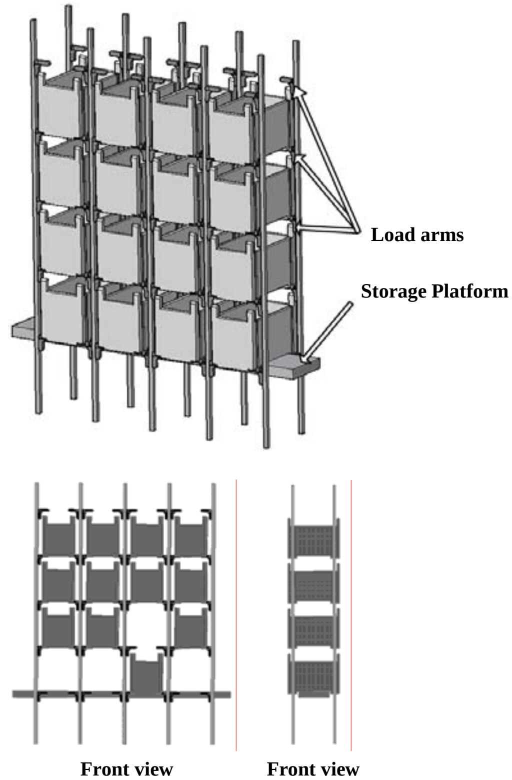

Figure 2: An illustration of open-rack structure

In this paper, the following notations are used:

N_l , N_b	number of levels and bays of an open-rack AS/RS, respectively
SP	storage platform
M_p	movement of storage platform
T_p , V_p	Travel time of storage platform and speed of storage platform, respectively
vv , hv	speed of stacker crane for vertical and horizontal movement, respectively
VL, HL	height and length of the rack, respectively
H_h , H_s	Height of handover station and standard containers, respectively
T_v , T_h	the time to reach the top of the rack vertically and the time to reach the end of the rack horizontally, respectively
d , L_c	spaces between standard containers and width of bays, respectively
δ , ρ	safety factor and batches size of storage operation in the open-rack, respectively
H_a	vertical height of load-arms when it is maximally open
α , b	ratio for storage operations and shape factor, respectively

Load shuffling in a bay of open-rack

Consider that, there is an empty cell in level i of a bay. Figure 5 illustrates different steps of the load shuffling in one bay. In the first movement, the SP moves from its dwell point to lift the container in level 0 (handover station) until this container is connected to its upper container in level 1, thus the platform movement (M_p) for this step is (H_h – H_s). In the second movement, the SP continues to push the containers upward until the container in level 1 is connected to its upper container and similarly up to last container in level i–1. During this movement all the containers in inferior levels of level i, are connected to each other and all the spaces between the containers (d) are filled, so the M_p of this step is $(i–1)d$. Note that, the SP has been dedicated to all bays in the rack and empty locations in different bays are in varying levels.

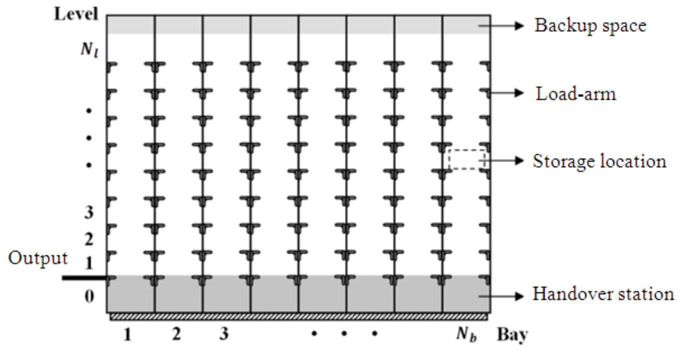

Figure 3: An illustration of open-rack structure

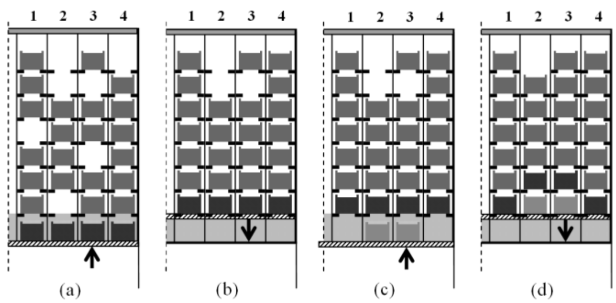

Figure 4: An illustration of loads shuffling in open-rack structure

Thus, in order to generalize, $(N_l - 1)d$ is selected for movement of platform in this step to enable the platform to push the containers into empty locations in all levels. In the last movement, the SP continues to push the connected containers upward until the load in level i–1 is transferred to the empty location in level i. Hence, the platform movement of this step is $(H_s + H_a + \delta)$. Therefore Eqs. (1) and (2) represent the the minimum and maximum values of M_p to perform the a storage operation.

$$Min\ M_p = (H_h - H_s) + (N_l - 1)d + (H_s + H_a + \delta) \qquad (1) \qquad Max\ M_p = H_h + H_s + d + H_a - \delta \qquad (2)$$

Where, $N_l \le \dfrac{H_s + 2d - 2\delta}{d}$

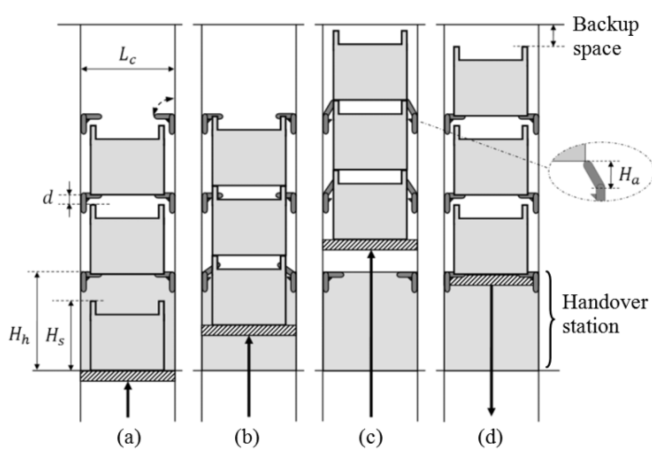

Figure 5: An illustration of load shuffling in a bay of open- rack

For constraint of N_l, consider that the maximum value of M_p is independent from N_l whereas, minimum value of M_p is increased by increase of N_l and getting closer to the maximum value of M_p , but it should not exceed that value, hence

$$[(H_h - H_s) + (N_l - 1)d + (H_s + H_a + \delta)] \leq [H_h + H_s + d + H_a - \delta]$$

Thus,

$$N_l \leq \frac{H_s + 2d - 2\delta}{d}$$

If the M_p is selected between the minimum and maximum values of M_p (Eqs. 1 and 2), then each load in a bay with *i* level, is transferred to its upper neighbor position with *i*+1 level upon finishing platform movement. In other word, in our defined algorithm, the level-altering of each load should be one level. As long as the selected M_p is less than Min M_p mentioned above, there is no change in the positions of loads after finishing platform movement (the level-altering of each load is zero) and it will contribute to fault in storage operation. Furthermore, when the selected M_p is more than Max M_p, it will lead to faulty storage operation too, because the level-altering for some of the loads is more than one level.

Example: Suppose that open-rack, stacker crane and SPs specifications are such that:

H_h = 0.55 m, H_s = 0.35 m, H_a = 0.5 m, d =0.01 m, δ=0.01 m, V_p = 0.01 m/s and total number of cells in the rack ($N_l \times N_b$) is 600. Using the approach explained earlier, the calculations of SP movements for different rack dimensions are summarized in Table 1.

Table1: The SP movements for different rack dimensions

No. of	No. of	Movements (m)					Travel Time (sec.)
Tiers (N_l)	Bays (N_b)	$H_h - H_s$	$(N_l - 1)d$	$H_s + H_a + \delta$	Min M_p	Max M_p	T_p^*
30	20	0.20	0.29	0.41	0.90	0.95	180
25	24	0.20	0.24	0.41	0.85	0.95	170
20	30	0.20	0.19	0.41	0.80	0.95	160
15	40	0.20	0.14	0.41	0.75	0.95	150
12	50	0.20	0.11	0.41	0.72	0.95	144
10	60	0.20	0.09	0.41	0.70	0.95	140
8	75	0.20	0.07	0.41	0.68	0.95	136
6	100	0.20	0.05	0.41	0.66	0.95	132

* The formula to obtain T_p is explained in section 4.2

Loads classification for class-based storage assignments

It is routinely accepted that there are three ways of assigning products to storage locations in warehouses: randomized storage, class-based storage and dedicated storage [13]. Class-based storage is effective when there are many products having different residence times in the storage system. The assignment of products to storage zones can be done with the help of an ABC analysis [14]. In this analysis all inventory items are ranked and classified by some measure of importance, such as ‘number of movements per time period’. The inventory items on the resulting list are divided into groups or classes (in practice, often the number of classes is restricted to three). Each class is then assigned to a zone of the warehouse consisting of a certain number of contiguous storage rack locations. As an advantage of Open-rack AS/RS, it represents the concepts of randomized and class-based storage assignments simultaneously. In other words, Open-rack AS/RS under randomized storage assignment, by its nature and over the time, places the items that generate the largest number of movements into areas closest to the I/O point. The items with lowest number of movements are deported to the uppermost levels in the open-rack. According to this natural classification, most of the empty locations occurring in the areas close to the I/O point and obviously close to the SP and it helps the SP to lift a small amount of loads during each storage operation. Figure 6 illustrates loads classification in the open-rack AS/RS under a single platform and three classes of loads. For different classes of the loads, this arrangement can be more accurate using multiple SPs. Figure 7(a) shows the loads classification in the open-rack AS/RS under two SPs and six classes of loads. These two SPs may move independently and concurrently. Figure 7(b) describes different classes, based on the number of movements for the loads in each class.

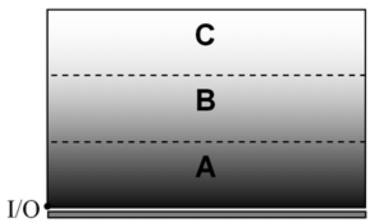

Figure 6: An illustration of loads classification in the open-rack AS/RS under a single SP and three classes of loads

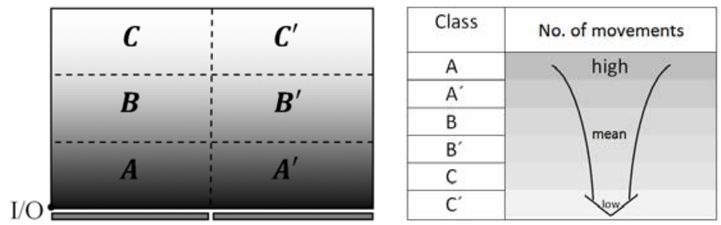

Figure7: An illustration of loads classification in the open-rack AS/RS under two SPs and six classes of loads

Travel-time model for the open-rack AS/RS

Assumptions

In order to illustrate the proposed ideas in this paper, an AS/RS is considered with the following assumptions:

1) The stacker crane operates on single command basis. In open-rack AS/RS, the dwell-point positions for the stacker crane and the SP are Output station and lowest point of handover station, respectively;
2) There are no technical problems for the construction of the proposed open-rack AS/RS. However, applying this model to the storage of heavy product may be limited;
3) Output station is located at the lower left-hand corner of the rack and input station is an asynchronous loop conveyor (i.e. operates with stop-and-go motion) beneath the rack;
4) Specifications of the rack, the stacker crane and the platforms are known. The stacker crane and SPs accelerations and decelerations and the load transfer times are ignored without affecting the relative performance of the control policies;
5) Randomized storage is used, which means that any cell within the rack is equally likely to be selected for storage or retrieval;
6) All the storages are served on first-come-first-served (FCFS) basis since they are accumulated on only one input conveyor;
7) During each operation, there is no prior information of subsequent job, and there are no concurrent movements of stacker crane and SP for different operations.

Moreover, it is assumed that for conventional AS/RS the dwell point positions of the stacker crane is I/O station which is located at the lower left-hand corner of the rack.

Analysis

Due to the fact that there is no significant difference between the results obtained from the continuous-approach-based expressions and the ones from the discrete-approach-based exact solutions [15] in this section the travel time is analyzed by using discrete models. The travel time for SP is the time for it to moves from its dwell point position, execute the storage operation and returns to its dwell point position. The objective is to pre-sort (shuffle) the loads and at the same time minimize the response time of storage operation. Therefore, the minimum value of M_p is used to obtain the total travel time of the SP for performing the storage operation. Hence,

$$T_p = \frac{2}{V_p}[(H_h - H_s) + (N_l - 1)d + (H_s + H_a + \delta)] \quad \text{and} \quad T_p = \frac{2}{V_p}[H_h + (N_l - 1)d + (H_a + \delta)] \tag{3}$$

As different expressions must be used to obtain the expected travel time for a storage operation and a retrieval operation, it is necessary to distinguish the operation type in order to obtain the formula to describe the expected travel time. The formula is,

$$E[T] = P(s)E[T_s] + P(r)E[T_r] \tag{4}$$

Where T denotes the cycle time for the stacker crane and SP to complete an operation. T_s indicates the time spent if the current job is storage, while T_r is the time spend for a retrieval operation. Thus, it is clear that $E[T]$denotes the expected travel time for one operation, E[T_s] gives the expected travel time if the current job is storage and $P(s)$ is the probability for the current job to be storage. E[T_r] and $P(r)$ are similarly defined for the case of retrieval. By definition, $P(r)= 1 - P(s)$. Assume that the ratio for storage operations is α in an arbitrary finite job sequence. Since randomized storage policy is used,

$P(s) = \alpha$ and $P(r) = 1 - P(s) = 1 - \alpha$

Substituting the above expressions in Eq. (4) so,

$$E[T] = \alpha\, E[T_s] + (1-\alpha)E[T_r] \tag{5}$$

In the case of retrieval, because the stacker crane is used to perform the retrieval operations, using Tchebychev travel time (i.e. the travel time of the stacker crane is the maximum of the isolated horizontal and vertical travel times), travel time between cells (i, j) and (i', j') is,

$$t\big((i, j), (i', j')\big) = \max\left(\frac{T_h}{N_b}\left|i'-i\right|,\ \frac{T_v}{N_l}\left|j'-j\right|\right)$$

Where, $1 \le i \le N_b$ & $1 \le j \le N_l$

Similarly, two-way travel time between I/O station (0, 1) and cell (i, j) is,

$$t\big((0,1), (i, j)\big) = 2\left[\max\left(\frac{T_h}{N_b}\left|0-i\right|,\ \frac{T_v}{N_l}\left|1-j\right|\right)\right] \tag{6}$$

Thus, the stacker crane expected retrieval time based on a discrete rack face approach under single command cycle and randomized storage can be expressed as,

$$\overline{E[SC]} = \frac{2}{N_l N_b}\sum_{i=1}^{N_b}\sum_{j=1}^{N_l}\max\left[\left(\frac{T_h}{N_b}\right)i,\ \left(\frac{T_v}{N_l}\right)(j-1)\right] \tag{7}$$

Note that, the SP stores a batch of loads during each operation. Let ρ represent the size of this batch. Considering Eqs. (3), (5) and (7), the expected travel time for open-rack AS/RS under single command cycle and randomized storage can be expressed as,

$$\overline{E[T]} = \alpha\left(\frac{1}{\rho}\right)T_p + (1-\alpha)\overline{E[SC]}$$

where, $1 \le \rho \le N_b$

And finally,

$$\overline{E[T]} = \alpha\left(\frac{1}{\rho}\right)\left(\frac{2}{V_p}\right)[H_h + (N_l-1)d + (H_a+\delta)] + (1-\alpha)\frac{2}{N_l N_b}\sum_{i=1}^{N_b}\sum_{j=1}^{N_l}\max\left[\left(\frac{T_h}{N_b}\right)i,\ \left(\frac{T_v}{N_l}\right)(j-1)\right] \tag{8}$$

where, $1 \le \rho \le N_b$, $1 \le i \le N_b$, $1 \le j \le N_l$

& $N_l \le \dfrac{H_s + 2d - 2\delta}{d}$

RESULTS AND DISCUSSIONS

Validation of the travel-time model

Monte Carlo simulation methods are statistical techniques and can be defined in general terms to be any method which utilizes sequences of random numbers to perform the simulation. It has been used for centuries, but only in the past several decades has gained the status of a full-fledged numerical method capable of addressing the most complex applications. Monte Carlo simulation methods may be contrasted to conventional numerical discretization methods, which typically are applied to ordinary or partial differential equations described as underlying physical or mathematical. To evaluate the travel time model for its accuracy, the results obtained from the model are compared with those from the computer simulations.

For the simulations Monte Carlo simulation is used, considering the ratios of (α) and ($1-\alpha$) for storage and retrieval operations, respectively. The simulation contains a randomized number generation for x and y to choose a new destination for new operation. Then the exact equation of t (Eq. 6) is used to obtain retrieval operation time for this randomized destination. Using equation of T_p (Eq. 3), the response time for storage operations of batches of loads are calculated. For the size of batches (ρ) in storage operations, full capacity of SP is used (i.e. when the SP has been loaded for all the bays which have empty cell). After obtaining the average of all simulated results, the results of travel time model must be approximately close to this average.

The specifications which are used for the simulations are such that H_h = 0.55 m, H_s = 0.35 m, L_c = 0.48 m, H_a = 0.5 m, d = 0.01 m, δ = 0.01 m, V_p = 0.01 m/s, total number of cells in the rack ($N_l \times N_b$) is 600, vv = 0.50 m/s, and hv =1.00 m/s. A series of 100,000 jobs (which is considerably large compared with the number of cells in an AS/RS rack) were executed in each experiment to simulate the infinite sequence of jobs. Recall that for each operation, the probability that the preceding operation is a storage is set to be (α) and this probability for retrieval operation is ($1-\alpha$). Parts of the results are shown in Tables 2 and 3.

From Table 2, it can be observed that the maximum '% deviation' is less than 3%, and this shows that the travel time model performs quite well. It is also observed that the performance of the model improves as the rack becomes non-square. From Table 3, it can be seen that with fixed shape factor b, the model also gives satisfactory results in the cases of different values of α. Figures 8 and 9 illustrate the influences of b and α on the expected travel time, respectively.

Table 2: Simulation results versus travel time model results when α = 0.5

No. of Tiers	No. of Bays	Cells in rack	Shape factor, b	Model results	Simulation results	% Deviation
20	30	600	1.00	12.22	12.48	2.08
15	40	600	0.56	12.57	12.76	1.49
12	50	600	0.36	14.10	14.26	1.12
10	60	600	0.25	16.04	16.16	0.74
8	75	600	0.16	19.26	19.31	0.26
6	100	600	0.09	24.94	24.97	0.12

Table 3: Simulation results versus travel time model results when b = 1

α	Model results	Simulation results	% Deviation
0.1	17.72	18.28	3.06
0.2	16.35	16.84	2.91
0.3	14.97	15.40	2.79
0.4	13.59	13.94	2.51
0.5	12.22	12.48	2.08
0.6	10.84	11.05	1.90
0.7	9.46	9.62	1.66
0.8	8.09	8.18	1.10
0.9	6.71	6.76	0.74
1	5.33	5.35	0.28

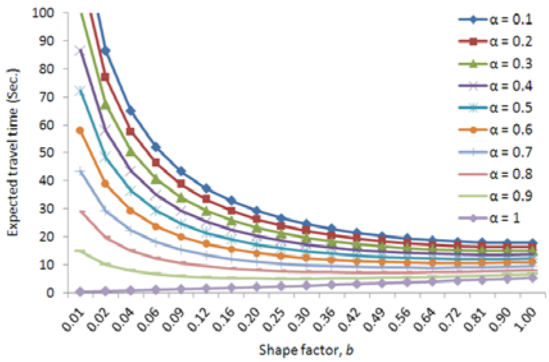

Figure 8: The expected travel time versus b

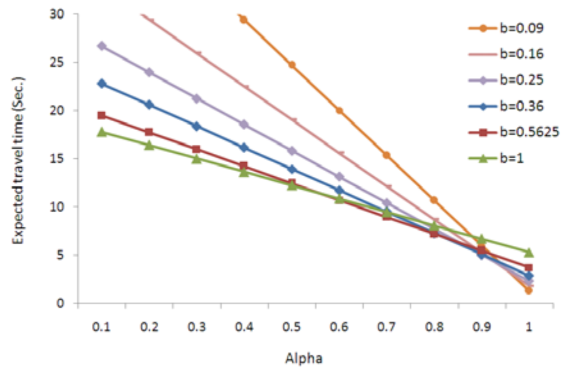

Figure 9: The expected travel time versus α

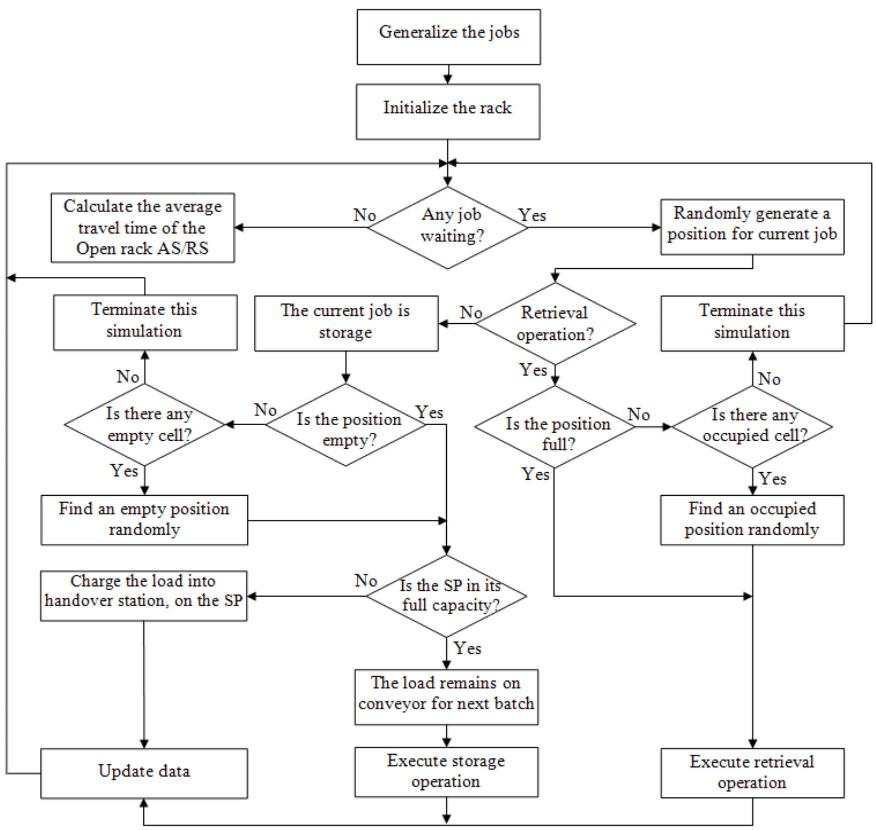

Figure 10: Macro flow chart for open-rack AS/RS simulation models

What can also be observed from the Figures 7 and 8 is that when $\alpha > 0.5$ the expected travel time will improve as the rack becomes non-square, whereas for $\alpha \leq 0.5$ the global optimum of the expected travel time is obtained around $b = 1$. Figure 10 illustrates macro flow chart of the simulations.

Performance comparisons

Compared with the traditional AS/RSs, the open-rack AS/RS offers many advantages such as high throughput, more flexible AS/RS rack configuration and high fault tolerance. In this section, the performance of the Open-rack AS/RS is compared with that of the conventional AS/RS under different rack configurations. Here, throughput is defined as the reciprocal of the average travel time for the S/R mechanism to handle a job [9]. The specifications of open-rack AS/RS which were used in previous section will also hold for our analysis in this section. For the conventional AS/RS, Speeds of stacker crane are the same as those in the open-rack AS/RS. The travel time shown in Table 4 is the average cycle time for these two mechanisms to finish one job. The results show that the open-rack AS/RS represents a higher performance up to 94.4%.

Table 1 Performance comparisons between an open-rack AS/RS and a conventional one

No. of tiers	No. of bays	S/R mechanism travel time (S)		
		Open-rack AS/RS	Conventional AS/RS	Improvement (%)
30	20	16.27	23.62	**31.12**
25	24	14.10	21.13	**33.27**
20	30	12.48	19.75	**36.81**
15	40	12.76	21.81	**41.49**
12	50	14.26	25.60	**44.26**
10	60	16.16	30.01	**46.15**
8	75	19.31	36.77	**47.48**
6	100	24.97	48.55	**48.57**
		AS/RS throughput (loads/h)		
30	20	221.27	152.41	***45.18***
25	24	255.32	170.37	***49.86***
20	30	288.46	182.28	***58.25***
15	40	282.13	165.06	***70.93***
12	50	252.45	140.63	***79.51***
10	60	222.77	119.96	***85.70***
8	75	186.43	97.91	***90.41***
6	100	144.17	74.15	***94.43***

CONCLUSIONS

In this study an open-rack structure with unidirectional-upward mobile loads within the rack has been applied in AS/RS that enables it to efficiently handle several loads at the same time. In this open-rack AS/RS, the stacker crane is just used for the retrieval operations and the storage operations are carried out by the separate devices namely, storage platforms. Using this mechanism, the average handling time for a batch of jobs can be greatly reduced. The advantages of this AS/RS include high throughput, more flexible AS/RS rack configuration and high fault tolerance. However, applying this mechanism to the storage of heavy product may be limited. Heuristics algorithms and models have been developed for load shuffling and travel time of the storage platform, respectively and the expected travel time model of the proposed AS/RS has been derived. The travel time model has been validated using Monte Carlo simulation. Results and comparisons show that the model performs quite satisfactory. The results of sensitivity analysis on b and α indicate that, for $\alpha > 0.5$ the expected travel time will improve as the rack becomes non-square, whereas for $\alpha \leq 0.5$ the global optimum of the expected travel time is obtained around $b = 1$. Some recommendations for further studies to expose the potentials of the open-rack AS/RS are to study the policies for request sequencing, the policies for storage assignment (using the multiple platforms) and mixed integer non-linear programming for minimizing total lost spaces in open-rack AS/RS.

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