Open-Rack Structure for Miniload Automated Storage and Retrieval Systems: An Innovative Design Approach

M.R. Vasili[a,1], S.H. Tang[a], N. Ismail[a], S. Sulaiman[a]
[a] Department of Mechanical & Manufacturing Engineering,
University Putra Malaysia, 43400 UPM, Serdang, Selangor Darul Ehsan Malaysia

ABSTRACT

Miniload automated storage and retrieval systems (AS/RSs) is a type of automatic 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. In this paper, the open-rack structure with unidirectional-upward mobile loads within the rack is applied in 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. The proposed miniload AS/RS has one storage platform for each rack to unload several loads at the same time into the rack. Heuristics algorithms and models are developed for load shuffling and travel time of the storage platform, respectively. The Travel time and the Performance of proposed AS/RS is analyzed using Monte Carlo simulation and is 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, Load shuffling, Travel time and Monte Carlo simulation.

1. INTRODUCTION

Automated storage and retrieval systems (AS/RS) have been greatly used not only as alternatives to traditional warehouses but also as part of advanced manufacturing systems. Improved inventory management and control, increased storage capacity to meet long-range plans, quick response to locate/store/retrieve items, and reduced labor cost due to automation are among the major advantages provided by AS/RS. A typical AS/RS is composed of storage racks, stacker cranes (storage/retrieval, S/R machines) and input/output (I/O) stations. Several types of AS/RS are distinguished based on size and the volume of inventory items. These different types include unit-load, mini-load, man-on-board, deep-lane and so on [1]. Groover [2] defined miniload AS/RS as a storage system which is used to handle small loads (individual parts or supplies) that are contained in small containers, bins or drawers in the storage system. In conventional miniload AS/RSs, 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. 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 [3]. Performance of a conventional 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 (i.e. one storage operation and one retrieval operation are performed in a cycle) [4].

In many real applications of 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 the 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.

2. RELATED WORKS

Groover [2] 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 used to handle small loads (individual parts or supplies) that are contained in small containers, bins or drawers in the storage system. There is extensive research in the area of development of expected travel time (i.e., average travel time) models for AS/RSs. A comparative study based on expected travel-time of stacker crane for randomized and dedicated storage policies has been presented by Hausman et al. [5]. An extension of [5] has been proposed by Graves et al. [6]. They present analytical and empirical results for various combinations of alternative storage assignment rules and scheduling policies. Each alternative is compared on the basis of the expected travel-time of the stacker crane. Based on a continuous rack approximation approach, Bozer and White [7] presented expressions for the expected

[1] Corresponding author. Tel.: +603-89466332; Fax: +603-86567099/7122, *E-mail address:* vasili@eng.upm.edu.my (M.R. Vasili)

cycle times of an AS/RS performing single and dual command cycles. Foley and Frazelle [8] derived the distribution of the dual command cycle time for a square-in-time rack under randomized storage and used it to determine the throughput of a miniload AS/RS. Hwang and Lee [9] presented travel-time models which include constant acceleration and deceleration rates with a maximum-velocity restriction. Chang et al. [10] proposed travel-time models that consider various travel speeds with known acceleration and deceleration rates. Chang and Wen [11] extended the work presented in [10] by investigating the rack configuration problem.

Chang and Egbelu [12,13] presented formulations for prepositioning of S/R machines to minimize the maximum system response time, and minimize the expected system response time for multi-aisle AS/RS. Sari et al. [1] developed closed-form travel-time expressions for flow-rack AS/RSs based on a continuous approach. Potrc et al. [14] presented heuristics travel-time models for AS/RS with equal-sized cells in height and randomized storage under single and multi-shuttle system. Hu et al. [3] presented split-platform AS/RS (SP-AS/RS) to handle extra heavy loads such as sea container cargo and a reliable continuous travel-time model for this system was presented under stay dwell point policy. Vasili et al. [15] developed two reliable travel-time models for the SP-AS/RS under return to middle and return to start, dwell point policies.

3. OPEN-RACK SYSTEM FOR MINILOAD AS/RSs

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 the 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. 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. However, applying this mechanism to the storage of heavy product may be limited.

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 the SP (Figure 3). According to Bozer and White [7], 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 $0 \le b \le 1$. As the value of b may represent the shape of a rack in terms of time, b is referred to as the shape factor. With the AS/RS, the symmetry of the vertical and horizontal movements allows to assume that $0 \le b \le 1$. With the SP-AS/RS, b can be an arbitrary positive value [3].

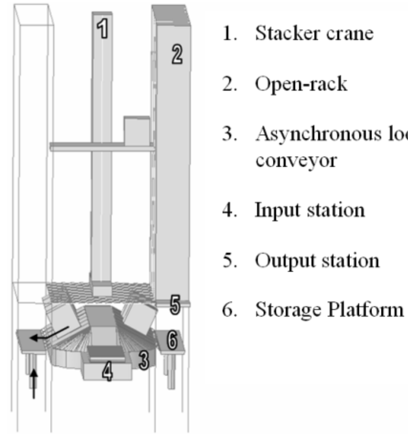

Figure 1: An illustration of open-rack AS/RS

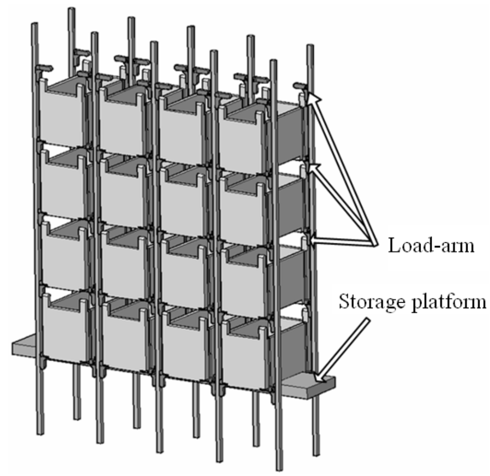

Figure 2: An illustration of open-rack AS/RS

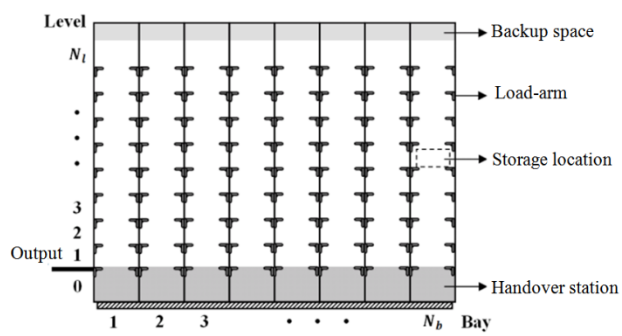

Figure 3: Definition of locations in open-rack structure

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 the SP in its dwell point position.

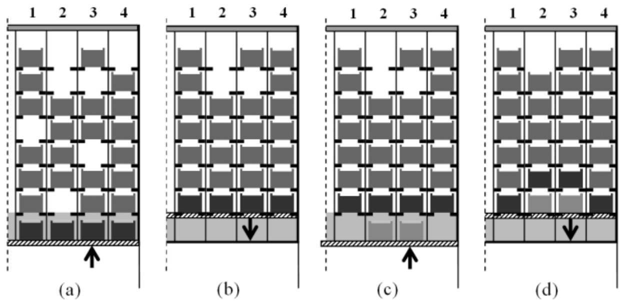

Figure 4: An illustration of loads shuffling in open-rack

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. 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 $(H_s + H_a + \delta)$.

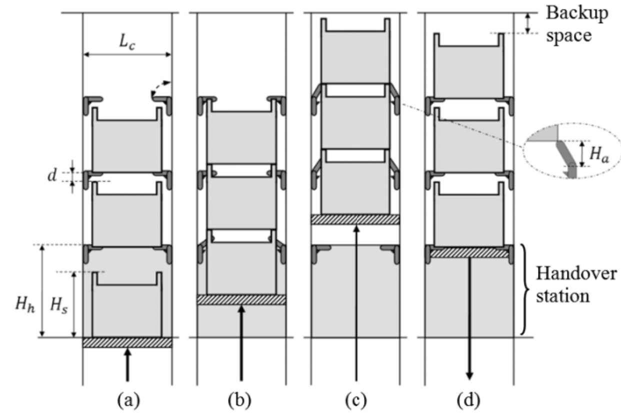

Figure 5: An illustration of load shuffling in a bay of open-rack

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

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

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

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

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

Thus,

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

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 another word, in our defined algorithm, the level-altering of each load should be one level. While 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.

The travel time for the 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,

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

and

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

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 the SP movements for different rack dimensions are summarized in Table 1.

Table 1: The SP movements for different rack dimensions

(N_l)	(N_b)	Movements (m)					Travel Time (sec.)
		H_h–H_s	(N_l– 1)d	H_s+ H_a+δ	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

4. SIMULATION STUDY

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. The purpose of this section is to analyze the performance of the Open-rack AS/RS using the computer simulations. Here, throughput is defined as the reciprocal of the average travel time for the S/R mechanism to handle a job.

Travel-time analysis

For the simulations Monte Carlo simulation is used, considering the ratios of (α) and (1– α) for storage and retrieval operations, respectively. Note that, the SP stores a batch of loads during each operation. Let ρ represent the size of this batch and $\overline{E[SC]}$ denotes the stacker crane expected retrieval time. Considering Eq. (3), the expected travel time for open-rack AS/RS under single command cycle and randomized storage can be expressed as,

$$\overline{E[T]} = \alpha\left(\frac{1}{\rho}\right)T_p + (1-\alpha)\overline{E[SC]} \quad (3)$$

where, $1 \leq \rho \leq N_b$

In order to obtain the travel time for the S/R mechanism, the simulation contains a randomized number generation for x and y to choose a new destination for new operation. Then using Tchebychev travel time (i.e. the travel time of the stacker crane is the maximum of the isolated horizontal and vertical travel times) the retrieval operation time $\left(\overline{E[SC]}\right)$ for this randomized destination is obtained. 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 the SP is used (i.e. when the SP has been loaded for all the bays which have empty cell). Finally, the total cycle time of S/R mechanism is calculated through Eq. (3). Average of all simulated results represents the travel time of proposed AS/RS and using this travel time, the system throughput is obtained. Figure 6 illustrates macro flow chart of the simulations.

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–α). Parts of the travel time results are shown in Tables 2 and 3.

Table 2: Simulation results when α = 0.5

No. of tiers	No. of bays	Cells in rack	Shape factor, b	Simulation results
20	30	600	1.00	12.48
15	40	600	0.56	12.76
12	50	600	0.36	14.26
10	60	600	0.25	16.16
8	75	600	0.16	19.31
6	100	600	0.09	24.97

Table 3: Simulation results when b = 1

No. of tiers	No. of bays	Cells in rack	α	Simulation results
20	30	600	0.1	18.28
20	30	600	0.2	16.84
20	30	600	0.3	15.40
20	30	600	0.4	13.94
20	30	600	0.5	12.48
20	30	600	0.6	11.05
20	30	600	0.7	9.62
20	30	600	0.8	8.18
20	30	600	0.9	6.76
20	30	600	1	5.35

Tables 2 and 3 show the travel time results for open-rack AS/RS through different values of b and α. The performance of the Open-rack AS/RS under different configurations is investigated in following Section by a more detailed comparison with the conventional one.

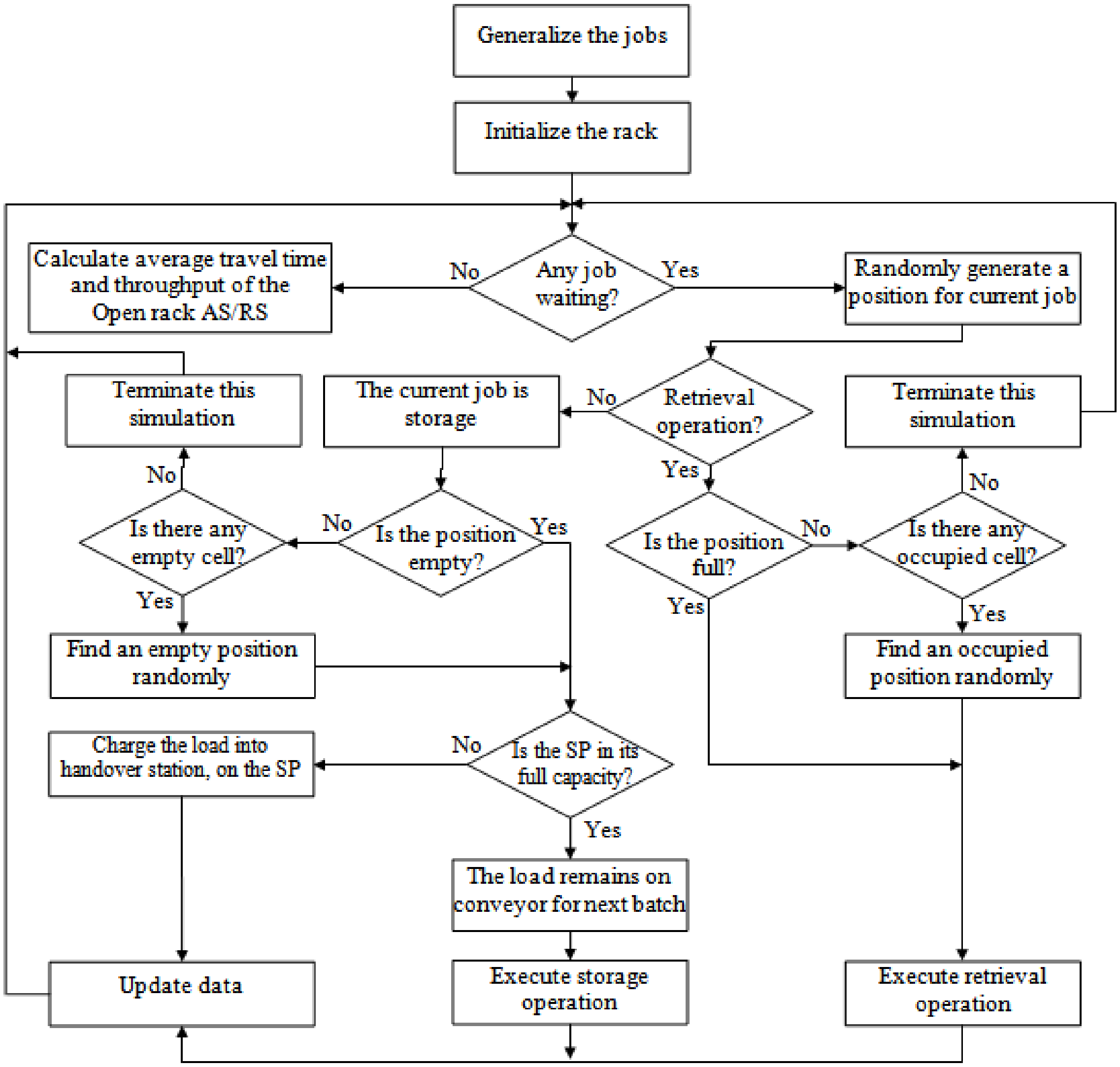

Figure 6: Macro flow chart for open-rack AS/RS simulation models

Figures 7 and 8 illustrate the influences of b and α on the expected travel time, respectively. What can also be observed from the graphs 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 $b = 1$.

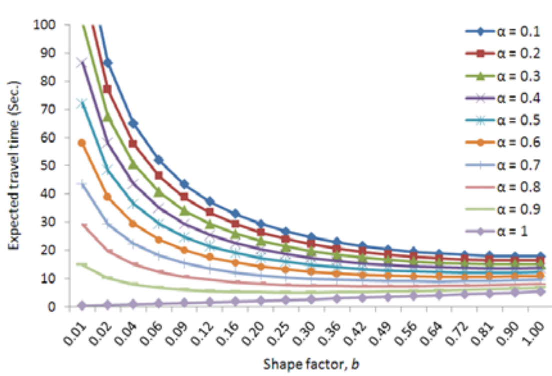

Figure 7: The expected travel time versus b

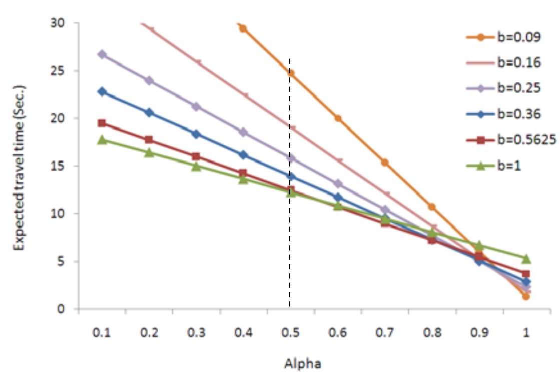

Figure 8: The expected travel time versus α

Performance analysis

In this section, the performance of the Open-rack AS/RS is compared with that of the conventional AS/RS, under different rack configurations. Recall that, the throughput is defined as the reciprocal of the average travel time for the S/R mechanism to handle a job.

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%.

Table 4: 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***

5. CONCLUSION

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 only 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. The Travel time and the Performance of proposed AS/RS have been analyzed using Monte Carlo simulation and are compared with a conventional one. Results and comparisons 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. 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.

6. REFERENCES

[1] Z. Sari, C. Saygin, N. Ghouali, Travel-time models for flow-rack automated storage and retrieval systems. **International Journal of Advanced Manufacturing Technology,** Vol. 25, No. 9-10, 2005, pp. 979–987.

[2] M.P. Groover, **Automation, production systems, and computer integrated manufacturing**, Prentice-Hall, Inc., New Jersey, USA, 2001.

[3] Y.H. Hu, S.Y. Huang, C. Chen, W.J. Hsu, A.C. Toh, C.K. Loh, T. Song, Travel time analysis of a new automated storage and retrieval system. **Computers and Operations Research**, Vol. 32, No. 6, 2005, pp. 1515-1544.

[4] T. Le-Duc, M.B.M. Koster, Y. Yugang. **Optimal Storage Rack Design for a 3-dimensional Compact AS/RS**. Erasmus Research Institute of Management. ERS-2006-027-LIS, 2006.

[5] W.H. Hausman, L.B. Schwarz, S.C. Graves, Optimal storage assignment in automatic warehousing systems. **Management Science,** Vol. 22, No. 6, 1976, pp: 629–638.

[6] S.C. Graves, W.H. Hausman, L.B. Schwarz, Storage-retrieval interleaving in automatic warehousing systems. **Management Science,** Vol. 23, No. 9, 1977, pp. 935–945.

[7] Y.A. Bozer, J.A. White, Travel-time models for automated storage and retrieval systems. **IIE Transactions,** Vol. 16, No. 4, 1984, pp. 329–338.

[8] R.D. Foley, E.H. Frazelle, Analytical results for miniload throughput and the distribution of dual command travel time. **IIE Transactions,** Vol. 23, No. 3, 1991. pp. 273–281.

[9] H. Hwang, S.B. Lee, Travel-time models considering the operating characteristics of the storage and retrieval machine. **International Journal of Production Research,** Vol. 28, No. 10, 1990, pp. 1779–1789.

[10] D.T. Chang, U.P. Wen, J.T. Lin, The impact of acceleration/deceleration on travel-time models for automated storage retrieval systems. **IIE Transactions,** Vol. 27, No. 1, 1995, pp.108–111.

[11] D.T. Chang, U.P. Wen, The impact on rack configuration on the speed profile of the storage and retrieval machine. **IIE Transactions,** Vol. 29, No. 7, 1997, pp. 525-531.

[12] S.H. Chang, P.J. Egbelu, Relative pre-positioning of storage and retrieval machines in automated storage and retrieval systems to minimize maximum system response time. **IIE Transactions,** Vol. 29, No. 2, 1997, pp.303–312.

[13] S.H. Chang, P.J. Egbelu, Relative pre-positioning of storage and retrieval machines in automated storage and retrieval systems to minimize expected system response time. **IIE Transactions,** Vol. 29, No. 2, 1997, pp. 313–322.

[14] I. Potrc, T. Lerher, J. Kramberger, M. Sraml, Simulation model of multi shuttle automated storage and retrieval systems. **Journal of Materials Processing Technology,** 157-158(SPEC. ISS.), 2004. pp. 236-244.

[15] M.R. Vasili, S.H. Tang, S.M. Homayouni, N. Ismail, Comparison of different dwell point policies for split-platform automated storage and retrieval system. **International Journal of Engineering and Technology,** Vol. 3, No. 1, 2006, pp. 91-106.