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SIMULATION ANALYSIS OF SHUTTLE BASED STORAGE AND RETRIEVAL SYSTEMS

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Abstract

In this paper, a simulation-based performance evaluation of shuttle-based storage and retrieval system (SBS/RS) is presented. In comparison with well-known automated storage and retrieval systems, SBS/RSs can substantially increase the throughput capacity of the system. The objective of this study is to exploit the benefits of SBS/RS system design for reducing the mean cycle time of transactions and consequently increasing the throughput capacity of the system. Performance comparison of the studied SBS/RS is contrasted with alternative storage rack configurations, velocity profiles of the shuttle carriers and velocity profiles of the elevators' lifting tables in the system. The results show that SBS/RSs are effective in reducing the mean cycle time and also show large improvement by increasing throughput capacity.

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Key Words: Automated Warehouse, Shuttle Based Storage and Retrieval System, Discrete Event Simulation, Performance Analysis

1. INTRODUCTION

Automated Storage and Retrieval Systems (AS/RSs) have been widely used in warehouses since 1950s to store and retrieve unit-loads without interference of an operator. The main advantages of AS/RSs are savings in labour costs and floor space, increased reliability, and reduced error rates.

The main disadvantages are high investment costs, less flexibility, and higher investments in control systems [1]. The early version of an AS/RS is also known as Crane Based Automated Storage and Retrieval Systems (CBAS/RS) which has one Storage and Retrieval (S/R) machine in each aisle that cannot leave its designated aisle (aisle-captive system). It can transport only one load at a time. There is large number of system design options for AS/RS in the literature [2, 3].

Due to increasingly small order sizes with large product variety and faster deliveries, material handling providers are developing new solutions. To meet this demand in throughput and constraints with regard to delivery times in warehouses, SBS/RS is developed in automated material handling industry.

This new technology is developed as an alternative to mini-load CBAS/RS where it cannot handle the required throughput capacity. In this technology, mostly two elevators lifting tables capable of vertical movement of loads (totes) share a single mast to transport totes from horizontally operating shuttle carriers to input/output (I/O) locations and vice versa. Shuttle carriers are usually tier-captive, however some other designs with shuttle carriers traveling between tiers and aisles may also be considered. In this study, we consider an SBS/RS with the tier-captive shuttle carriers.

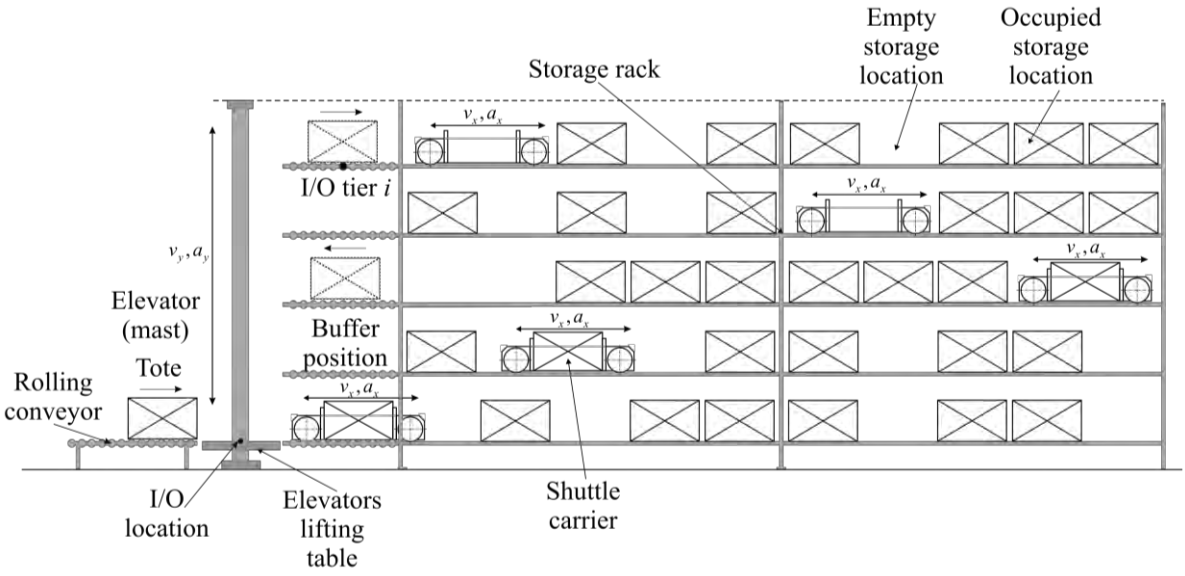

Figure 1: Shuttle based storage and retrieval system.

The purpose of this paper is to evaluate throughput performance of an SBS/RS using simulation. The performance of the studied SBS/RS is evaluated in terms of average cycle time (for dual command), which is expressed by the system throughput capacity.

The remainder of the paper is organized as follows. In section 2, an extensive literature review is presented. In section 3, SBS/RS along with the simulation model is presented. In section 4, SBS/RS design scenarios are presented. Analyses of simulation results and detailed discussions are presented in Chapter 5. Finally, in Section 6, we provide main conclusions from this study.

2. LITERATURE REVIEW

Warehouses in supply chain are moving beyond CBAS/RS technologies towards autonomous vehicle-based storage and retrieval system (AVS/RS) technologies offering additional flexibility in warehouse operations [4]. In this technology, throughput capacity can be varied by changing the number of autonomous vehicles (AVs) in the system. The main components of an AVS/RS are lifts and AVs in the rack area. Lifts provide vertical movement for transactions to travel among tiers and AVs provide horizontal movement for transaction within the tier. It has to be emphasized that AVS/RS is introduced for heavy unit-load transactions [4]. In the literature relatively a lot of papers focus on AVS/RS [4-13].

SBS/RS is relatively a new technology in AVS/RS and usually works with aisle and tier captive shuttles. This new technology is mostly used for mini-load warehouses. There are few studies considering this system in the literature.

A first study on SBS/RS is completed by Carlo and Vis [14]. They study an SBS/RS developed by the Vanderlande Industries where two non-passing lifting systems are mounted along the rack. In that paper, they focus on the scheduling problem of lifts where two (piece-wise linear) functions are introduced to evaluate candidate solutions. They develop an integrated look-ahead heuristic for the solution procedure to improve the total handling time (in terms of throughput).

Marchet et al. [15] models an SBS/RS via open queuing network to estimate the performance of the system in terms of utilization of lifts and shuttles as well as waiting times for lifts and queues. To validate the analytical models, they utilize simulation modelling. The developed analytical models demonstrate good estimates for the performance measures. Later, Marchet et al. [16] present main design trade-offs for SBS/RS using simulation. They

complete their study for several warehouse design scenarios for tier captive shuttle vehicles. They present several performance measures from the system – utilizations of lifts and shuttles, average flow time, waiting times as well as cost – for the pre-defined rack designs.

Recently, Lerher et al. [17] and Lerher [18] have studied SBS/RS by considering energy efficiency concept in the system design. The proposed models provide several warehouse designs and their performances. Designs are considered in terms of velocity profiles of lift and shuttle carriers while performances are considered as amount of energy (electricity) consumption, amount of CO_2 oscillation and throughput capacity. These studies provide significant contribution in automated warehouse planning by taking into consideration the environment friendly design concept.

Smew at al. [19] presented a simulation study to trade-off between the conflicting objectives of maximising customer service level and minimising Work-In-Process.

Bekker [20] proposed as a computationally economic approach to optimise throughout rate and allocated buffer space, which are the two conflicting objectives of the buffer allocation problem.

Berlec et al. [21] study the calculation of optimal batch quantity using first the basic model, and then the extended model taking into account the tied-up capital in a production, in addition to the costs of changing the batch and storage costs. They implement the study for a case to find out when either of the two models should be used.

Erkan and Can [22] used AHP (Analytic Hierarchy Process) and FAHP (Fuzzy Analytic Hierarchy Process) to decide on Barcode or RFID system to select for a company, in order to collect data for its warehouse. As a result of the study, it is found that AHP produces consistent results with FAHP. Barcode system is selected for the data collection system and FAHP is found to be more sufficient in decision making process due to its fuzziness and vagueness compared to AHP. Unlike the existing studies, we approach to the SBS/RS from a storage rack design and velocity profiles for shuttle carriers and elevators' lifting tables perspective by using simulation modelling.

3. SHUTTLE BASED STORAGE AND RETRIEVAL SYSTEMS

SBS/RSs are composed of elevators with lifting tables that are attached on a mast, shuttle carriers, buffer positions and the storage racks (Fig. 1). The elevators lifting table provides vertical movement for totes to reach the prescribed tier in the system. The elevators lifting table can reach up to 1.5 m/s velocity and more, theoretically. Elevators are usually bottlenecks in the system so that they determine the performance of the whole system [18].

A shuttle carrier is a tier-captive autonomous vehicle with four wheels that transports totes from buffer position to storage locations in the storage rack. It is equipped with telescopic attachment for manipulating totes. The maximal weight of a tote should not exceed 50 kg per shuttle carrier and its dimensions should be in the range of: min. (150 × 200 × 80) mm and max. (600 × 400 × 250) mm. A shuttle carrier can travel up to 4 m/s theoretically.

In SBS/RS, there is usually a single shuttle carrier in each tier of the storage rack (tier-captive system). This assumption can be released if we use a special shuttle elevator at the back of the storage rack, for moving shuttle carriers up and down to the prescribed tier in the storage rack (tier-to-tier system) [18]. There are two buffer positions, each serving one side in storage rack at each tier. These positions are used for buffering totes carried by lifts for storage process and by shuttles for retrieval process. The storage rack is composed of storage Columns (C). By multiplying storage columns C in the horizontal and Tiers (T) in the vertical direction, the length L_{SR} and the height H_{SR} of the Storage Rack (SR) are achieved.

In continuation, the following assumptions and notations are considered in the simulation model of the SBS/RS.

3.1 Main assumptions

- The SBS/RS is divided into two sides in an aisle. Hence, totes can be stored in either side of a tier.
- The I/O location of the SBS/RS is located at the first tier, next to the lift location (Fig. 1).
- The storage rack is divided by columns and tiers. At each tier, there are two buffer positions (left and right) and a single shuttle carrier (aisle-captive system).
- The elevator manipulates two lifting tables independently one of which is located at the left side and the other one is located at the right side of the elevator. Each lifting table can serve one tote at a time (Fig. 1).
- The elevator and the shuttle carrier complete single and/or dual command cycles.
- Drive characteristics (v_y, a_y) of the elevator lifting table as well as the height H_{SR} of the storage rack are known priori.
- Drive characteristics of the shuttle carrier (v_x, a_x) as well as the length L_{SR} of the storage racks are known priori.
- The height H_{SR} and the length L_{SR} of the storage racks are large enough for the elevators lifting table and the shuttle carrier to reach their maximum velocity $v_{\max}$ in the vertical and in the horizontal direction.
- Randomized assignment policy is considered, which means that any available storage position in the SBS/RS is equally likely to be selected for storage or retrieval location to be processed.

Notations

AS/RS	Automated storage and retrieval systems.
CB	Crane based.
S/R	Storage and retrieval.
SR	Storage rack.
CBAS/RS	Crane based automated storage and retrieval systems.
SBS/RS	Shuttle based storage and retrieval systems.
I/O	Input and output.
CO_2	Carbon dioxide.
AVS/RS	Autonomous vehicle storage and retrieval systems.
SC	Single command cycle.
DC	Dual command cycle.
vp	Velocity profile.
AHP	Analytic hierarchy process.
FAHP	Fuzzy analytic hierarchy process.
RFID	Radio frequency identification.
C	Number of columns in the SR.
T	Number of tiers in the SR.
A	Number of aisles in the SR.
L_{SR}	Length of the storage rack.
H_{SR}	Height of the storage rack.
a_y	Acceleration / deceleration of the elevators lifting table in the vertical direction.
a_x	Acceleration / deceleration of the shuttle carrier in the horizontal direction.
v_y	Maximum velocity of the elevators lifting table in the vertical direction.
v_x	Maximum velocity of the shuttle carrier in the horizontal direction.
v_{max}	Maximum velocity.
S	Set of totes to be stored.
R	Set of totes to be retrieved.

s	Open location.
r	Closed location.
T	Time.
$d(T)$	Distance in dependence of time.
t_l	Pickup and delivery time.
$t_{\mathrm{I/O_{tier\,i}},\,S_i}$	Mean travel time of the shuttle carrier for travelling from the I/O location to the storage location in the i^{th} tier of the SR.
$t_{S_i,\,R_i}$	Mean travel time of the shuttle carrier for travelling from the storage location to the retrieval location in the i^{th} tier of the SR.
$t_{R_i,\,\mathrm{I/O_{tier\,i}}}$	Mean travel time of the shuttle carrier for travelling from the retrieval location in to the I/O location in the i^{th} tier of the SR.
$T(\mathrm{DC})_{\mathrm{SCAR}}$	Mean dual command cycle time of the shuttle carrier.
$\lambda(\mathrm{DC})_{\mathrm{SCAR}}$	Throughput performance of the shuttle carrier.
$t_{\mathrm{I/O,\,tier}\,i}$	Mean travel time of the elevators lifting table for hoisting from the I/O location in the first tier of the SR to the buffer position in the i^{th} tier of the SR.
$t_{\mathrm{tier}\,i,\,\mathrm{tier}\,j}$	Mean travel time of the elevators lifting table for hoisting from the buffer position in the i^{th} tier of the SR to the buffer position in the j^{th} tier of the SR.
$t_{\mathrm{tier}\,j,\,\mathrm{I/O}}$	Mean travel time of the elevators lifting table for hoisting from the buffer position in the j^{th} tier of the SR to the I/O location in the first tier of the SR.
$T(\mathrm{DC})_{\mathrm{LIFT}}$	Mean dual command cycle time of the elevators lifting table.
$\lambda(\mathrm{DC})_{\mathrm{LIFT}}$	Throughput performance of the elevators lifting table.
l_{tote}	Length of the tote.
w_{tote}	Width of the tote.
h_{tote}	Height of the tote.
l_{COM}	Length (depth) of the column.
w_{COM}	Width of the column.
h_{COM}	Height of the column.
Q	Total number of storage locations (warehouse volume).
η	Efficiency of the elevators lifting table / shuttle carrier.
τ	Expected bottleneck.
$\lambda(\mathrm{DC})_{\mathrm{aisle}}$	Throughput capacity of SBS/RS in one aisle.
$\lambda(\mathrm{DC})_{\mathrm{SBS/RS}}$	Whole SBS/RS system performance.

3.2 Simulation model of the SBS/RS

To facilitate the performance evaluation of the SBS/RS, discrete event simulation is employed. Our simulation model begins with the process which marks the whole storage locations in the SBS/RS according to the prescribed storage area. After creating the list of free storage locations, enter in the simulation model the first tote, which is situated in the I/O location of the SBS/RS. Further on, the tote receives a sign, which belongs to the buffer position in the i^{th} tier and the storage location in the storage rack of the i^{th} tier. The elevators lifting table picks up the tote from the I/O location and moves to the buffer position in the i^{th} tier. After conducting transport to the buffer location in the i^{th} tier, the elevators lifting table set down the tote, which is waiting to be moved by a shuttle carrier. Next, the shuttle carrier picks up the tote from the buffer position in the i^{th} tier and travels to the storage location, where the tote is set down by a shuttle carrier. For the storage operation, the randomized storage policy has been used. Next, the tote stored is put on the waiting list by a computer (computer data base), where it waits for the retrieval operation. For the retrieval process the random request selection rule has been used.

After the storage operation in the i^{th} tier, the shuttle carrier travels to the retrieval location in the i^{th} tier of the storage rack. The retrieval location is positioned in the same tier (tier-captive system). Next, the shuttle carrier picks up the tote and moves through the tier to the buffer position in the i^{th} tier, where the tote is next picked up by the elevators lifting table.

The average cycle time for the transaction is therefore associated with the travel time of the elevators lifting table and the travel time of the shuttle carrier. As a performance measure for the SBS/RS, the mean Dual Command (DC) cycle time and consequently the throughput capacity have been used. The throughput capacity represents the number of transactions (stores and retrievals) that the system can perform in a given time period. As a note, the throughput capacity is inversely dependent on the average cycle time.

Movement of the elevators lifting table and travelling of the shuttle carrier in the simulation model is based on the real velocity-time dependence. Two types of velocity-time dependences can be distinguished depending on whether the obtained peak velocity $v(t_p)$ is less than v_{max} (type I) or equal to v_{max} (type II). It can be verified that time $T < 2v_{max} / a$ for type I and $T > 2v_{max} / a$ for type II.

Velocity-time dependence for type I

The distance in dependence of time $d(T)$ equals the following expression:

$$d(T) = \int_0^T v(t)dt = \frac{a \cdot T^2}{4} \tag{1}$$

Velocity-time dependence for type II

The distance in dependence of time $d(T)$ equals the following expression:

$$d(T) = \int_0^T v(t)dt = v_{max} \cdot T - \frac{{v_{max}}^2}{a} \tag{2}$$

The definition of the storage strategy

As mentioned before, dual command cycle requests for the storage and retrieval sequence of the elevators lifting table and for the shuttle carrier are based on the random strategy. The detailed procedure of the above mentioned statement for the shuttle carrier and for the elevators lifting table is presented in the continuation.

Algorithm of the logistics for DC of the shuttle carrier

1: Selection of one open storage location in i^{th} tier of the SR for the storage sequence

2: Selection of one closed storage locations in i^{th} tier of the SR for the retrieval sequence

3: Selection of the random storage and the retrieval assignment strategy of the shuttle carrier

4: Performance of the storage and the retrieval assignment of the shuttle carrier under DC

$s_i \in (S_i; i = 1,...,n)$ and $r_i \in (R_i; i = 1,...,n)$

If $|R_i| \geq 1$, then select $s_i \in S_i$ and $r_i \in R_i$ randomly:

$R_i \leftarrow R_i - \{r_i\}$

$S_i \leftarrow S_i - \{s_i\} + \{r_i\}$

Note: One new open location is created in S_i (r_i) and one open location (s_i) is lost.

According to the algorithm of the logistics for DC of the shuttle carrier, mean dual command cycle time $T(\mathrm{DC})_{\mathrm{SCAR}}$ equals: (*i*) mean travel time from the $\mathrm{I/O}_{\mathrm{tier}\ i}$ location of the SR to the random open (storage) location in the SR, (*ii*) mean travel time from random open (storage) location in the SR to the random close (retrieval) location in the SR and (*iii*) finally mean travel time from the random close (retrieval) location of the SR to the $\mathrm{I/O}_{\mathrm{tier}\ i}$ location.

Mean dual command cycle time $T(\mathrm{DC})_{\mathrm{SCAR}}$ is enlarged for all the manipulations related for totes handling (pick up and delivery times, identification time, etc.):

$$T\left(\mathrm{DC}\right)_{\mathrm{SCAR}} = 4 \cdot t_l + t_{\mathrm{I/O}_{\mathrm{tier\ i}},\, S_i} + t_{S_i,\, R_i} + t_{R_i,\, \mathrm{I/O}_{\mathrm{tier\ i}}} \tag{3}$$

By considering eq. (3) the throughput performance of all shuttle carriers in case of DC per hour is calculated by eq. (4):

$$\lambda\left(\mathrm{DC}\right)_{\mathrm{SCAR}} = \frac{3600}{T\left(\mathrm{DC}\right)_{\mathrm{SCAR}}} \cdot k \cdot m \tag{4}$$

where k is 2, due to the DC and $m = T$ due to the application of the tier-captive SBS/RS.

Algorithm of the logistics for DC of the elevators lifting table

1: Selection of one open buffer position at the i^{th} tier of the SR for the storage sequence
2: Selection of one closed buffer position at the j^{th} tier of the SR for the retrieval sequence
3: Selection of the random storage and the retrieval assignment strategy of the elevators lifting table
4: Performance of the storage and the retrieval assignment of the elevators lifting table under DC

$s_i \in \left(S_i; i = 1,...,n\right)$ and $r_i \in \left(R_i; i = 1,...,n\right)$

If $\left|R_i\right| \geq 1$, then select $s_i \in S_i$ and $r_i \in R_i$ randomly:

$R_i \leftarrow R_i - \{r_i\}$

$S_i \leftarrow S_i - \{s_i\} + \{r_i\}$

Note: One new open location is created in S_i (r_i) and one open location (s_i) is lost.

According to the algorithm of the logistics for DC of the elevators lifting table, mean dual command cycle time $T(\mathrm{DC})_{\mathrm{LIFT}}$ equals: (*i*) mean travel time from I/O location to the random open (storage) buffer position in i^{th} tier of the SR, (*ii*) mean travel time from random open (storage) buffer position in i^{th} tier of the SR to the random closed (retrieval) buffer position in j^{th} tier of the SR and (*iii*) finally mean travel time from the random closed (retrieval) buffer position in j^{th} tier of the SR to the I/O location.

Mean dual command cycle time $T(\mathrm{DC})_{\mathrm{LIFT}}$ is enlarged for all the manipulations related for totes handling (pick-up and delivery times, identification time, etc.):

$$T\left(\mathrm{DC}\right)_{\mathrm{LIFT}} = 4 \cdot t_l + t_{\mathrm{I/O,\ tier}\ i} + t_{\mathrm{tier}\ i,\ \mathrm{tier}\ j} + t_{\mathrm{tier}\ j,\ \mathrm{I/O}} \tag{5}$$

By considering eq. (5) the throughput performance of both (two) elevators lifting tables in case of DC per hour is calculated by eq. (6):

$$\lambda\left(\mathrm{DC}\right)_{\mathrm{LIFT}} = \frac{3600}{T\left(\mathrm{DC}\right)_{\mathrm{LIFT}}} \cdot k \cdot n \tag{6}$$

where $k = 2$, due to the DC and $n = 2$ due to the elevator with two lifting tables.

4. SBS/RS CASE STUDY

In this section, main input data for the analysis are provided and discussed. Stock keeping unit represents a tote (plastic container) filled with items with the dimensions: length l_{tote} = 0.6 m, width w_{tote} = 0.4 m and height h_{tote} = 0.24 m. With regard to the tote, the storage location has the following dimensions: length (depth) of the column l_{COM} = 0.6 m, width of the column w_{COM} = 0.5 m and height of the tier h_{COM} = 0.5 m. Dimensions of the SBS/RS storage rack (L_{SR} and H_{SR}) depends on the number of columns C in the horizontal direction and number of tiers T in the vertical direction, respectively. Velocity scenarios of the shuttle carrier and the elevators lifting table are as follows: (vp_1) stands for v_x = 1.5 m/s, $a_x^+ = a_x^- = 1.5$ m/s^2, v_y = 1.5 m/s, $a_y^+ = a_y^- = 1.5$ m/s^2 and (vp_2) stands for v_x = 4.0 m/s, $a_x^+ = a_x^- = 3.0$ m/s^2, v_y = 2.0 m/s, $a_y^+ = a_y^- = 1.5$ m/s^2.

Note: velocity scenarios vp_1 and vp_2 are selected according to the references of material handling equipment producers and practical experiences of the authors.

Pick up and set down times t_l for the shuttle carriers and elevators are set to 3.0 and 1.5 seconds, respectively.

As seen in Table I, nine (9) SBS/RS configurations are analysed based on three values of tiers T (T = 10, T = 15 and T = 20) and three values of aisles A (A = 3, A = 6 and A = 9). Total number of storage locations Q is assumed to be approximately 10,000 storage locations [16].

Table I: SBS/RS configurations.

SBS/RS configuration (RC)	Number of tiers (T)	Number of aisles (A)	Number of columns (C)	Length of the SR (L_{SR})	Height of the SR (H_{SR})	Warehouse volume (Q)
1	10	3	167	83.50	5.00	10,020
2	10	6	84	42.00	5.00	10,080
3	10	9	56	28.00	5.00	10,080
4	15	3	112	56.00	7.50	10,080
5	15	6	56	28.00	7.50	10,080
6	15	9	38	19.00	7.50	10,260
7	20	3	84	42.00	10.00	10,080
8	20	6	42	21.00	10.00	10,080
9	20	9	28	14.00	10.00	10,080

5. ANALYSIS OF RESULTS AND DISCUSSION

Table II summarizes mean dual command cycle time of the elevators lifting table $T(\mathrm{DC})_{\mathrm{LIFT}}$ and the shuttle carrier $T(\mathrm{DC})_{\mathrm{SCAR}}$, the throughput performance of the elevators lifting tables $\lambda(\mathrm{DC})_{\mathrm{LIFT}}$ and shuttle carriers $\lambda(\mathrm{DC})_{\mathrm{SCAR}}$.

Table II: Performance comparison of the SBS/RS.

RCi	Velocity profile vp_1				Velocity profile vp_2			
	Shuttle carrier		Elevators lifting table		Shuttle carrier		Elevators lifting table	
	$T(\mathrm{DC})_{\mathrm{SCAR}}$ (sec.)	$\lambda(\mathrm{DC})_{\mathrm{SCAR}}$ (totes/h)	$T(\mathrm{DC})_{\mathrm{LIFT}}$ (sec.)	$\lambda(\mathrm{DC})_{\mathrm{LIFT}}$ (totes/h)	$T(\mathrm{DC})_{\mathrm{SCAR}}$ (sec.)	$\lambda(\mathrm{DC})_{\mathrm{SCAR}}$ (totes/h)	$T(\mathrm{DC})_{\mathrm{LIFT}}$ (sec.)	$\lambda(\mathrm{DC})_{\mathrm{LIFT}}$ (totes/h)
1	89.70	803	13.20	1091	53.80	1338	12.90	1116
2	52.60	1369	13.20	1091	35.20	2045	12.90	1116
3	40.00	1800	13.20	1091	28.90	2491	12.90	1116
4	64.80	1667	15.40	935	41.40	2609	14.60	986
5	40.00	2700	15.40	935	28.90	3737	14.60	986
6	32.10	3364	15.40	935	24.90	4337	14.60	986
7	52.60	2738	17.80	809	35.20	4091	16.40	878
8	33.90	4248	17.80	809	25.80	5581	16.40	878
9	27.60	5217	17.80	809	22.50	6400	16.40	878

Shuttle based storage and retrieval system performance as a whole is presented on Fig. 2. Because of the SBS/RS is composed of the elevators lifting tables and the tier-captive shuttle carriers that are working independently from each other, the possible bottleneck is required to be found for calculating the SBS/RS system performance.

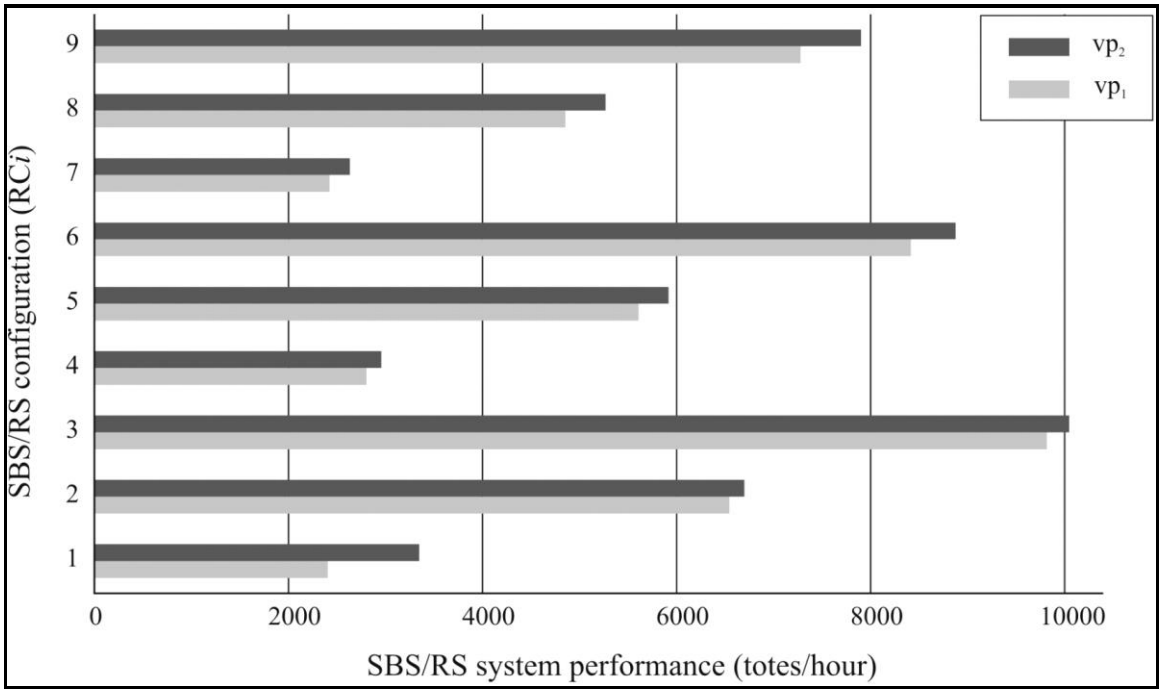

Figure 2: Shuttle based storage and retrieval system performance.

Note: The efficiency of the elevators lifting table and the shuttle carrier is calculated by η = min ($\lambda(DC)_{SCAR}$, $\lambda(DC)_{LIFT}$) / max ($\lambda(DC)_{SCAR}$, $\lambda(DC)_{LIFT}$). The expected bottleneck is calculated by τ = max ($\lambda(DC)_{SCAR}$, $\lambda(DC)_{LIFT}$. The throughput capacity of SBS/RS in one aisle equals $\lambda(DC)_{aisle}$ = min ($\lambda(DC)_{SCAR}$, $\lambda(DC)_{LIFT}$). The whole SBS/RS system performance is calculated by $\lambda(DC)_{SBS/RS} = A \cdot \lambda(DC)_{aisle}$.

5.1 Shuttle carrier

Mean dual command cycle time $T(DC)_{SCAR}$ and consequently the throughput performance $\lambda(DC)_{SCAR}$ depend on the number of columns C, number of aisles A and the velocity profile vp_i (v_x and a_x) of the shuttle carrier. Because the elevators' lifting tables are usually bottlenecks in the SBS/RS, shuttle carriers work with relatively small utilization depending on the vp_i and RC*i*. The fastest double command transactions of shuttle carriers belongs to SBS/RS with relatively small number of columns C (case: A = 9; RC3, RC6 and RC9). This relationship proves to be valid for both selected velocity profiles vp_i of the SBS/RS. The opposite, the slowest double command transactions of shuttle carriers belongs to SBS/RS with relatively large number of columns C (case A = 3; RC1, RC 4 and RC7).

According to the distribution of the $T(DC)_{SCAR}$, velocity profile vp_i has a significant impact on the mean dual command cycle time of the shuttle carrier. A decreasing tendency of $T(DC)_{shut}$ are observed for the velocity profile vp_2 according to vp_1. This relationship shows the influence of horizontal velocity v_x and acceleration a_x^+ in accordance to the length L_{SR} of the SBS/RS. Generally, the best results are achieved by shuttle carriers having fast drivers in the horizontal travelling direction.

Because the throughput capacity $\lambda(DC)_{SCAR}$ is inversly dependent on the mean dual command cycle time $T(DC)_{SCAR}$, the highest throughput capacity $\lambda(DC)_{shut}$ belongs to the

SBS/RS with small number of columns C (CASE A = 9; RC3, RC6 and RC9). On the contrary the lowest throughput capacity $\lambda(DC)_{SCAR}$ belongs to the SBS/RS with large number of columns C (case A = 3; RC1, RC 4 and RC7).

The throughput performance $\lambda(DC)_{aisle}$ of one aisle in the SBS/RS is calculated according to the expected bottleneck of the elevators lifting table or the shuttle carrier. Usually the bottleneck in the SBS/RS is the elevator, except for RC1 at vp_1, where we have the SBS/RS configuration with large number of columns C and small number of tiers T.

5.2 Elevators lifting table

Mean dual command cycle time $T(DC)_{LIFT}$ and consequently the throughput performance $\lambda(DC)_{LIFT}$ depend on the number tiers T and the velocity profile vp_i (v_y and a_y) of the elevators lifting table. Because the elevators lifting tables are usually a bottleneck in the SBS/RS, the elevator works with 100 % efficiency. The fastest double command transactions of the elevators lifting tables belongs to SBS/RS with relatively small storage racks (case: T = 10; RC1, RC2 and RC3). This relationship proves to be valid for both selected velocity profiles vp_i of the SBS/RS. The opposite, the slowest double command transactions of the elevators lifting tables belongs to SBS/RS with relatively high storage racks H_{SR} (case T = 20; RC7, RC8 and RC9).

6. CONCLUSION

In this paper, simulation analysis of the SBS/RS is presented. The simulation model of the SBS/RS is based on the tier-captive system of shuttle carriers that can travel with real velocity-time dependence in the horizontal direction. As well the elevators lifting tables that are attached on the mast are moving with real velocity-time dependence in the vertical direction. In the simulation model of SBS/RS randomized storage assignment policy and the sequencing request selection rule have been applied.

Various elements of the SBS/RS have been examined, such as the rack design of the SBS/RS, velocity of the elevators' lifting tables and the shuttle carriers in order to investigate the efficiency of the SBS/RS.

As a result of this study, we observed that the throughput capacity $\lambda(DC)_{SBS/RS}$ of the SBS/RS significantly depends on the throughput performance of the elevator $\lambda(DC)_{LIFT}$ multiplied by the number of aisles A. Hence, if we decrease the travel time of lifts by decreasing the number of tiers in the system design (i.e., increasing the number of aisles), we can obtain better throughput capacity. These results can be observed in the 3rd scenarios of both velocity profiles (vp_1 and vp_2) in Fig. 2.

Generally, when deciding on a SBS/RS design velocity profile of lifting mechanism, vp_i provides significant benefit in system's efficiency. For example, if we have a SBS/RS with T = 20 and vp_2 (RC7), the throughput capacity of the lift $\lambda(DC)_{LIFT}$ = 878 totes/hour (Table II). Hence the system's throughput capacity depends on this value. However, the same rack design with vp_1, $\lambda(DC)_{LIFT}$ = 809 totes/hour (Table II) which is lower than the previous one. According to the extremly high throughput capacity $\lambda(DC)_{SCAR}$ of shuttle carriers, the assumption that in each tier there is a single shuttle carrier assumption could be released (the application of non tier-captive configuration).

When we have a rack design with extremely large number of colums, this time shuttle carriers may become bottleneck if the velocity profile of them are low (see RC1 of vp_1). This time, the throughput capacity would depend on the throughput rate of the shuttle carriers. Hence, increasing the velocity profile of the shuttle carriers would increase the throughput capacity of the whole system (see RC1 of vp_2 in Table II).

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