Int. j. simul. model. 5 (2006) 1, 25-36
ISSN 1726-4529 Original scientific paper

DESIGN AND EVALUATION OF THE CLASS-BASED MULTI-AISLE AS/RS

Lerher, T.
University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, SI-2000 Maribor, Slovenia
E-Mail: tone.lerher@uni-mb.si

Abstract
In this paper, the design and evaluation of the multi-aisle automated storage and retrieval systems (AS/RS) is presented. In comparison with the well known single-aisle systems, the multi-aisle systems, where the storage and retrieval machine serves more than one picking aisle, can substantially reduce the investment cost. The objective of this study is to exploit the benefits of the class-based multi-aisle system for reducing the average travel time for a transaction and consequently to increase the throughput capacity. For the storage operation, the random location assignment policy was applied, while for the retrieval operation the "first come first served" and "nearest neighbour" request selection rules were applied. The performance comparison of the single-class and class-based multi-aisle systems is contrasted with the alternative combination of the storage rack configuration and the number of picking aisles. The results show that class-based multi-aisle systems are effective in reducing the average travel time and also show large improvements in throughput capacities.
(Received in August 2005, accepted in December 2005. This paper was with the author 2 months for 2 revisions.)

Key Words: Warehouse, Multi-Aisle Automated Storage and Retrieval Systems, Class-Based Storage Policy, Simulation and Performance Analysis

1. INTRODUCTION

Automated storage and retrieval systems (AS/RS) are major material handling systems which have been widely used in automated factories and distribution centers. AS/RS consist of storage racks (SR) erected along aisles, storage and retrieval machines (S/R machines), conveyors, input/output stations (I/O stations), buffers, etc. The major advantages of AS/RS in comparison with the conventional warehouses are: high throughput capacity (*Pf*), efficient utilization of warehouse volume (*Q*), high reliability and better control of inventory, better workforce utilization, improved safety conditions and decrease in damage and shortages. On the other hand, AS/RS are rather expensive and inflexible in future changes. Therefore, a careful design is crucial for the success of such systems. The performance of the AS/RS is most often measured by average travel time per single (SC) and dual (DC) command cycles that the S/R machine can perform in a given time period.

Reducing the average travel time taken per transaction and thus increasing the *Pf* has been the subject of many researches. Hausman *at al.* [1] are one of the first ones who consider the request sequencing with SC for the square-in-time (SIT) SR only. According to the assignment of incoming transport unit loads (TUL) to storage locations, they compared the performances of three storage assignment policies: class-based storage, randomized storage and dedicated storage. The class-based storage policy distributes TUL, based on their demand rates, among a number of classes and it reserves a region within the SR for each class. Randomized and dedicated storages are in fact extreme cases of the class-based storage policy. The randomized storage considers a single class for the whole TUL´s; meanwhile the dedicated storage considers one class for each TUL [2]. The class-based storage model by [1] produced higher *Pf* results over other scheduling techniques by taking the advantage of storage according to the product turnover frequency, where the most demanded TUL are stored closer to the I/O location. Graves *et al.* [3] extended their models to more efficient DC with different storage assignment policies for SIT racks. Analytical models of SC and DC for the non-SIT rack (racks of general shapes) have been developed by Bozer and White [4]. Their analytical models are based on the randomized storage with different input and output configurations of the input queue. A common practice in sequencing storage and retrieval requests is that both requests are processed in the "First Come First Served" (FCFS) policy, which is also the assumption made in analytical models of Bozer and White. Han *at al.* [5] have shown that the *Pf* can be increased by replacing the FCFS retrieval sequencing with a new "Nearest Neighbour" (NN) heuristics policy. According to their observation, a decrease of 50 % or more in the interleave time for DC leads in an increase of 10 – 15 % in the *Pf*. Such an increase in the *Pf* could help handle peak demand in the operation phase or even eliminate the aisle, which would lead to considerable savings.

The majority of researchers have restricted their studies to the single-aisle AS/RS only. It must be emphasized that S/R machines alone represent approximately 40 % or more of the costs [6]. A measure to reduce the initial investment cost is the application of the multi-aisle AS/RS. Many producers of the warehouse equipment like *Siemens Dematic* [7], *Stoecklin* [8] and *Dambach* [9] have begun to offer such systems served by automatic curve-going or automatic aisle-transferring S/R machines. In order to evaluate the minimal number of S/R machines in the multi-aisle AS/RS, the *Pf* of those systems has to be determined. A study of multi-aisle AS/RS served by the single S/R machine has been presented by authors Hwang *et al.* [10]. Their study is based on travel time models considering only the average uniform velocity. The weakness of this model [10] lies in the consideration of only average uniform velocity, which is far from being optimal from the practical point of view. Newly modified analytical travel time models of the multi-aisle AS/RS, which consider the real operational characteristics of the S/R machine, have been presented by authors Lerher *at al.* [11], [12]. The newly modified models satisfactorily deal with the single-class randomized storage, under the condition that the storage and retrieval operation can occur randomly in the m^{th} and n^{th} picking aisle. The weakness of the abovementioned model [11], [12] is in the lack of using class-based storage.

The purpose of this research is to use simulation in order to evaluate the performance of the class-based multi-aisle AS/RS. The simulation is necessary for adequate models of the multi-aisle AS/RS, since the existing analytical models apply only to class-based single-aisle AS/RS. In our research, several aspects of controlling the multi-aisle AS/RS have been studied. According to the location assignment of incoming TUL, the class-based storage policy and the calculation of the storage classes in the multi-aisle AS/RS have been considered. The second aspect of the multi-aisle AS/RS is the sequencing of the storage request based on the random storage. Further on, the retrieval request is based on (*i*) FCFS and (*ii*) NN request selection rules. The performance of the class-based multi-aisle AS/RS is the response time, which is expressed by the system throughput capacity.

The remainder of the paper is organized as follows. In chapter 2, the design of the class-based multi-aisle AS/RS along with the design algorithm is presented. Analyses of simulation results and detailed discussion as well as comparisons are presented in chapter 3. Finally, in chapter 4 the main conclusions are given.

2. DESIGN OF THE CLASS-BASED MULTI-AISLE AS/RS

In continuation the following assumptions and notations are made concerning the design and simulation study of the class-based multi-aisle AS/RS.

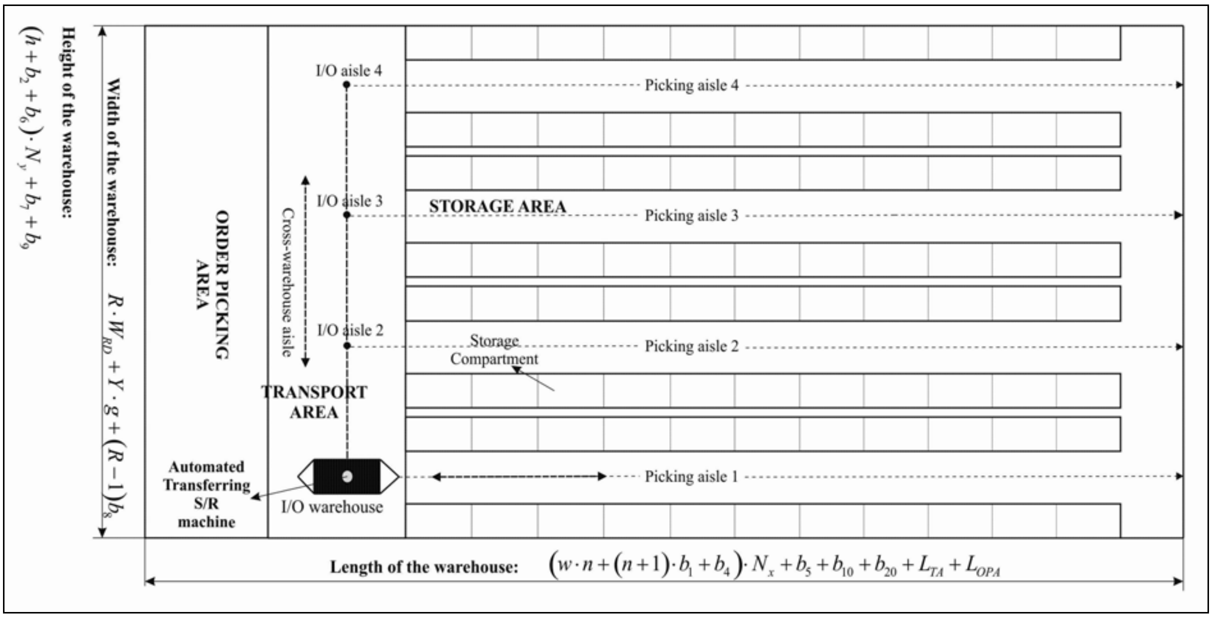


Figure 1: The layout of the multi-aisle AS/RS.

- The warehouse is divided into picking aisles with SR on both sides; therefore there are double SR between the picking aisle and single SR along the warehouse walls. The I/O location of the warehouse is located on the lower left side of the warehouse (Fig. 1).
- An estimated turnover frequency Pf_i of each TUL is known in order to group TUL into different storage classes j (j = 1, 2, 3).
- The number of S/R machines is lower than or equal to the number of picking aisles ($S \leq R$). The S/R machine travels in the cross aisle on the transferring vehicle, which enables access to the adjacent picking aisle i ($i = 1, \ldots, m-1, m, m+1, \ldots, n-1, n$).
- The real drive characteristics of the S/R machine (velocity v, acceleration a^+ and deceleration a^-) as well as the length L and height H of the SR are known.
- The S/R machine enables the operation of SC and DC, to which a variable share of travel time for travelling in the cross aisle ($S \leq R$) must be added.
- When performing the operation of the DC ($S \leq R$), two different cases have been used: (*i*) the storage and retrieval operation is performed in the same picking aisle i and (*ii*) the storage and retrieval operation is performed in two randomly picking aisles m and n.
- The sequencing of the storage request of TUL is performed according to the random strategy; meanwhile for the retrieval request the sequencing (*i*) FCFS and (*ii*) NN strategies are used in the case of retrieval TUL from the SR.

Notations

S	–	the set of all TUL to be stored,
R	–	the set of all TUL to be retrieved,
TUL	–	the combination of the palette and items on the palette,
$R_{i,j}$	–	the set of all TUL in the retrieval list (closed locations) from SR_i ($i = 1, 2, \ldots, m-1, m, m+1, \ldots, n-1, n$) and from class j (j = 1, 2, 3),
$S_{i,j}$	–	the set of all TUL in the storage list (open locations) from SR_i ($i = 1, 2, \ldots, m-1, m, m+1, \ldots, n-1, n$) and from class j (j = 1, 2, 3),
s_i	–	the open location for storing the TUL,
r_i	–	the retrieval assignment of the TUL.

2.1 Model for the design of the class-based multi-aisle AS/RS

The model for the design of the class-based multi-aisle AS/RS is based on the structured approach [13] and [14], where all parameters influencing the design of the storage and transport area, design of classes and discrete event simulation for determination of performance measures, are taken into account. The algorithm of the design model with the following main modulus is presented in the Fig. 2:

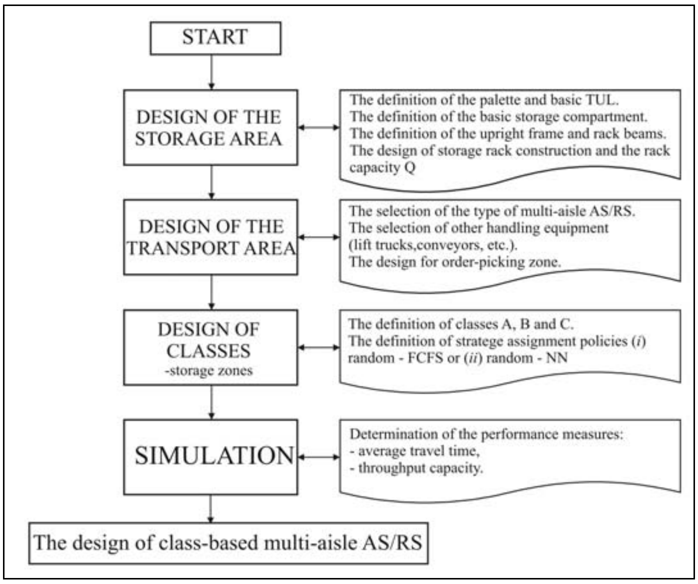


Figure 2: The algorithm of the design model.

- ***Design of the storage area:***

It includes the choice of the palette and the building of the basic TUL. The definition of the storage compartment, which represents a foundation for the storage system, is to come after. Next, the design of SR structure (upright frames and rack beams) depends on the weight of TUL and arrangement of TUL in the horizontal x and vertical y direction. Finally, with regard to the warehouse volume Q, the geometry and type of SR as well as the configuration of the storage area can be determined as follows:

- Length of the storage area:

$$L_{SA} = \left(w \cdot n + (n+1) \cdot b_1 + b_4\right) \cdot N_x + b_5 + b_{10} + b_{20} \tag{1}$$

where N_x is the number of storage compartments in the horizontal direction; w [mm] indicates the width of the palette/TUL; n is the number of TUL in the storage compartment; b_1, b_4, b_5, b_{10}, b_{20} [mm] stand for a safety addition to the width of the storage compartment; width of the upright frame; thickness of the upright frame; the addition to the width of the palette at input buffer; the addition to the end of the warehouse.

- Height of the storage area:

$$H_{SA} = \left(h + b_2 + b_6\right) \cdot N_y + b_7 + b_9 \tag{2}$$

where N_y is the number of storage compartments in the vertical direction; h [mm] indicates the height of the TUL; b_2, b_6, b_7, b_9 [mm] indicate the safety addition to the height of the storage compartment; the height of rack beams; the deviation of the storage compartment from the floor; the safety addition to the height of the warehouse.

- Width of the storage area:

$$W_{SA} = A \cdot W_{RD} + Y \cdot g + \left(A-1\right) b_8 \tag{3}$$

where A and Y stand for the number of picking aisles and the number of SR; W_{RD} [mm] stands for the working area of the S/R machine; g [mm] stands for the length of the pallet.

- ***Design of the transport area:***

It considers selection of the material handling equipment, which mainly depends on the SR geometry, Pf and Q. Generally, two systems of handling equipment are possible: (*i*) the automatic aisle-transferring S/R machine and (*ii*) the curve going S/R machine. For manipulating the TUL to the storage area, lift trucks or accumulating conveyors can be used. Depending on the combination of the material handling equipment, the dimensions of the transport area can be determined as follows:

- Length of the transport area (the combination of the aisle-transferring S/R machine and lift trucks):

$$L_{TA} = \left(W_{S/R\ mac.} + 2 \cdot b_{13}\right) + \left(2 \cdot W_{LT} + 2 \cdot b_{11} + b_{14} + b_{16}\right) \tag{4}$$

where $W_{S/R\ mac.}$ and W_{LT} [mm] refer to the working area of the S/R machine and to the working area of the lift truck; b_{11}, b_{13}, b_{14}, b_{16} [mm] indicate the safety addition to the width of the lift truck; the safety addition to the width of the S/R machine; the safety addition to the parallel meeting of two lift trucks simultaneously; the safety addition to turning the lift truck. The height H_{TA} and width W_{TC} of the transport area equal the dimensions of the storage area.

The order-picking area: length L_{OPA}, height H_{OPA} and width W_{OPA} are determined as a percentage of the storage area.

- ***Design of classes (storage zones):***

The essence of the class-based storage policy is the turnover frequency of TUL. The turnover frequency is defined as the amount of time the TUL requires to be stored and retrieved in a certain time period. Thus, the SR is partitioned into classes – storage zones of TUL based on their average turnover frequency. TUL with the highest turnover frequency are stored in classes nearest to the I/O location in order to minimize travel time. TUL of the same class are stored randomly within their assigned class area in the SR. The area assigned to every single class is proportional to its demand and the percentage of the warehouse. The turnover frequency is based on the *activity based costing* (ABC) analysis for warehouses. The ABC analysis means that a relatively small percentage of TUL in the warehouse presents a large percentage of the total product demand [15]. The ABC analysis simply classifies TUL in three classes [16]:

- Class A deals with a small fraction of TUL, which account for most of the warehouse activity. Usually, there are 5 to 10 % of different TUL, which account for 70 to 80 % of the warehouse activity. For example, the distribution 5/70 means that 5 % of TUL in the warehouse represent 70 % of the total demand.
- Class B deals with moderately important TUL. Usually there are 20 to 30 % of different TUL in the warehouse, which account for 20 to 30 % of the warehouse activity.

- Class C represents a very high volume of TUL, which only have a small portion of the activity. Usually we have 50 to 70 % of different TUL in the warehouse, which account for 5 to 10 % of the warehouse activity.

Based on the ABC analysis of all TUL in the warehouse and their turnover frequencies (Pf_A, Pf_B and Pf_C), the required volume for all three classes Q_A, Q_B and Q_C is determined. Further on, due to classes Q_A, Q_B and Q_C, the dimensions (L and H) for classes A, B and C can be determined [11].

- **The definition of storage strategies**

As mentioned before, SC and DC requests are performed and the random storage strategy is used for sequencing storages request of TUL in the SR. As for the retrieval sequencing request selection rule, the (*i*) FCFS and (*ii*) NN rules are used. Based on the random storage and the turnover frequency of TUL, the storage and retrieval request can occur in the same class C_j (j = 1, 2, 3) or in the combination of classes. The detailed procedure of the abovementioned statement is presented in the following section [11], [15].

- **CASE 1:** $s_i \in \left(S_{i,1}; i=1,...,n\right)$ and $r_i \in \left(R_{i,j}; i=1,...,n,\ j=1,2,3\right)$

If $\left|R_{i,j}\right| \geq 1$, then select $s_i \in S_i$ randomly and the $r_i \in R_i$ on the (*i*) FCFS or (*ii*) NN basis:

a) Perform the storage in s_i (class C_1) and the retrieval assignment in r_i (class C_1):

$$\begin{aligned} R_{i,1} &\leftarrow R_{i,1} - \{r_i\} \\ S_{i,1} &\leftarrow S_{i,1} - \{s_i\} + \{r_i\} \end{aligned} \tag{5}$$

(One new open location is created in $S_{i,1}$ (r_i) and one open location (s_i) is lost.)

b) Perform the storage in s_i (class C_1) and the retrieval assignment in r_i (class C_2):

$$\begin{aligned} R_{i,2} &\leftarrow R_{i,2} - \{r_i\} \\ S_{i,1} &\leftarrow S_{i,1} - \{s_i\} + \{r_i\} \end{aligned} \tag{6}$$

c) Perform the storage in s_i (class C_1) and the retrieval assignment in r_i (class C_3):

$$\begin{aligned} R_{i,3} &\leftarrow R_{i,3} - \{r_i\} \\ S_{i,1} &\leftarrow S_{i,1} - \{s_i\} + \{r_i\} \end{aligned} \tag{7}$$

- **CASE 2:** $s_i \in \left(S_{i,2}; i=1,...,n\right)$ and $r_i \in \left(R_{i,j}; i=1,...,n,\ j=1,2,3\right)$

If $\left|R_{i,j}\right| \geq 1$, then select $s_i \in S_i$ randomly and the $r_i \in R_i$ on the (*i*) FCFS or (*ii*) NN basis:

a) Perform the storage in s_i (class C_2) and the retrieval assignment in r_i in (class C_1):

$$\begin{aligned} R_{i,1} &\leftarrow R_{i,1} - \{r_i\} \\ S_{i,2} &\leftarrow S_{i,2} - \{s_i\} + \{r_i\} \end{aligned} \tag{8}$$

b) Perform the storage in s_i in (class C_2) and the retrieval assignment in r_i (class C_2):

$$\begin{aligned} R_{i,2} &\leftarrow R_{i,2} - \{r_i\} \\ S_{i,2} &\leftarrow S_{i,2} - \{s_i\} + \{r_i\} \end{aligned} \tag{9}$$

c) Perform the storage in s_i (class C_2) and the retrieval assignment in r_i (class C_3):

$$\begin{aligned} R_{i,3} &\leftarrow R_{i,3} - \{r_i\} \\ S_{i,2} &\leftarrow S_{i,2} - \{s_i\} + \{r_i\} \end{aligned} \tag{10}$$

- CASE 3: $s_i \in \left(S_{i,3}; i = 1,...,n\right)$ and $r_i \in \left(R_{i,j}; i = 1,...,n,\ j = 1,2,3\right)$

If $\left|R_{i,j}\right| \geq 1$, then select $s_i \in S_i$ randomly and the $r_i \in R_i$ on the (*i*) FCFS or (*ii*) NN basis:

a) Perform the storage in s_i (class C_3) and the retrieval assignment in r_i (class C_1):

$$\begin{aligned} R_{i,1} &\leftarrow R_{i,1} - \{r_i\} \\ S_{i,3} &\leftarrow S_{i,3} - \{s_i\} + \{r_i\} \end{aligned} \tag{11}$$

b) Perform the storage in s_i (class C_3) and the retrieval assignment in r_i (class C_2):

$$\begin{aligned} R_{i,2} &\leftarrow R_{i,2} - \{r_i\} \\ S_{i,3} &\leftarrow S_{i,3} - \{s_i\} + \{r_i\} \end{aligned} \tag{12}$$

c) Perform the storage in s_i (class C_3) and the retrieval assignment in r_i (class C_3):

$$\begin{aligned} R_{i,3} &\leftarrow R_{i,3} - \{r_i\} \\ S_{i,3} &\leftarrow S_{i,3} - \{s_i\} + \{r_i\} \end{aligned} \tag{13}$$

- **Simulation**

To facilitate the performance evaluation and comparison of the single-class and class-based multi-aisle AS/RS, the discrete event simulation was employed. Our simulation model begins with the process which marks the whole storage compartments in the warehouse according to the prescribed storage area. After creating the list of free storage locations, enter in the simulation model the first TUL, which is situated in the I/O warehouse location and lies in the lower left-hand corner of the leftmost picking aisle (see Fig. 1). Further on, the TUL receives a sign, which belongs to the i^{th} picking aisle and storage location in j^{th} classes A, B or C. The S/R machine picks up the TUL from the I/O warehouse location, loads it into the shuttle, and moves through the cross-aisle to the i^{th} picking aisle. After conducting transport to the i^{th} picking aisle, the S/R machine moves from the I/O aisle i location simultaneously in the horizontal and vertical direction to the storage location in j^{th} classes A, B or C. For the storage operation, the randomized storage policy has been used in a selected class. Next, the TUL that has been 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 FCFS and NN request selection rules have been used. After the storage operation in the i^{th} picking aisle and storage location in j^{th} classes A, B or C, the S/R machine travels to the retrieval location. The retrieval location can be positioned in the same aisle ($m = n$) or in the adjacent aisle ($m \neq n$), with regard to the class procedure, discussed in detail in the previous section. Next, the S/R machine loads TUL into the shuttle and moves through the picking and cross aisle to the I/O warehouse location, where the TUL departs the system. The average travel time for the cycle is therefore associated with the travel of the S/R machine through the cross-aisle and picking aisle. As a performance measure for the class-based multi-aisle AS/RS, the average travel time and consequently the *Pf* has been used. The *Pf* represents the number of transactions (stores and retrievals) that the S/R machine can perform in a given time period. The *Pf* is inversely dependent on the average travel time. In the DC, the storage and retrieval operation is performed for a total of two transactions. Therefore the average *Pf* for the SC and DC is given as follows [11]:

$$Pf = \frac{2 \cdot T}{rT(DC) + 2\left(1-r\right)T(SC) + 2T_0} \cdot \eta \tag{14}$$

where r is the proportion between SC and DC; T [h] is the time for one shift; T_0, [m] is the shuttle time for loading and unloading the TUL; η stands for the efficiency of the S/R machine.

Based on the proposed algorithm and discussed modules, the class-based multi-aisle AS/RS with the simulation model for the performance evaluation has been programmed in the computer software Visual Basic NET [17].

2.2 The class-based multi-aisle AS/RS under study

According to literature and practical experiences, it has been established that different layouts of the SR, the efficiency of the S/R machine and control policies have a tremendous influence on the average travel time and consequently on the throughput capacity. Therefore, three different layouts of the SR of the multi-aisle AS/RS have been used in simulation analyses: (*i*) SR 30/6, (*ii*) SR 60/13 and (*iii*) SR 80/20 [18]. According to the efficiency of the S/R machine, *Stoecklin* automated aisle-transferring S/R machine [8] was used for serving multiple picking aisles. It must be emphasized that beside the velocity v, the acceleration a^+ and deceleration a^- of the S/R machine have been considered as well. Like the layout of the SR and the efficiency of the S/R machine, the control policy also has a significant influence on the average travel time. For the single-class multi-aisle AS/RS, the randomized storage policy and FCFS retrieval assignment policy were applied. Meanwhile, for the class-based multi-aisle AS/RS the randomized storage policy and (*i*) the FCFS retrieval sequencing and (ii) the NN retrieval sequencing have been applied. Based on the turnover frequency of TUL (Pf_A = 80, Pf_B = 15, Pf_C = 5), the proposed size of classes (Q_A = 25, Q_B = 50 and Q_C = 25) has been applied (Table I) [11].

Table I: The turnover frequency Pf_i and the size of classes Q_i.

ABC (Pf_j) – 80/15/5 ABC (Q_j) – 25/50/25	Class	N_x	N_x	L_i (mm)	H_i (mm)
SR 30/6	A	4	3	11680	3486
	B	8	5	23360	5810
	C	10	5	29200	5810
SR 60/13	A	9	6	26280	6972
	B	16	11	46720	12782
	C	20	11	58400	12782
SR 80/20	A	13	9	37960	10458
	B	23	15	67160	17430
	C	27	17	78840	19754

Additional data corresponding to the design model are summarized as follows: w = 800 mm, g = 1200 mm, h = 800 mm, m = 1000 kg, n = 3, N_x and N_y are defined according to the Table I., *Stoecklin AT RBG 0-Q*: $W_{S/R\ mac.}$ = 1400 mm, $H_{S/R\ mac.}$ = 22 000 mm, G_{RD} = 1250 kg, v_x = 3 m/s, v_y = 0,8 m/s, v_i = 0,6 m/s, a_x = 0,5 m/s^2, a_y = 0,8 m/s^2, a_i = 0,4 m/s^2, W_{LT} = 1400 mm, b_1 = 100 mm, b_2 = 200 mm, b_4 = 120 mm, b_5 = 65 mm, b_6 = 162 mm, b_7 = 300 mm, b_8 = 200 mm, b_9 = 1000 mm, b_{10} = 0 mm, b_{11} = 300 mm, b_{13} = 800 mm, b_{14} = 500 mm and b_{16} = 1800 mm [11].

3. ANALYSIS OF RESULTS AND DISCUSSION

Average dual command travel times (in continuation: average travel times) and throughput capacities for multi-aisle AS/RS, which are presented in the following Table and Figures, are given on the basis of the performed simulation analyses. Analyses have been conducted for three different layouts of the SR [18] according to the single-class and class-based storage policy, under the condition that the storage and retrieval request can occur (*i*) in the m^{th} picking aisle only or (*ii*) in the m^{th} and n^{th} picking aisle [11].

Table II: The average dual command travel time for the class-based multi-aisle AS/RS.

T(DC) – sec. (classes correspond to Table II)								
A*i*	SR 30/6 (random – FCFS)				SR 60/13 (random – FCFS)			
	I/O_L warehouse[1]		I/O_M warehouse[2]		I/O_L warehouse		I/O_M warehouse	
	$m = n$	$m \neq n$	$m = n$	$m \neq n$	$m = n$	$m \neq n$	$m = n$	$m \neq n$
1	23,04	23,04	23,04	23,04	34,15	34,15	34,15	34,15
2	31,37	40,17	32,86	41,62	42,51	53,55	43,99	55,04
3	38,68	52,00	34,15	47,43	49,85	66,13	45,27	61,53
4	45,79	62,46	39,72	56,37	56,93	76,95	50,86	70,82
5	52,77	72,38	41,84	61,44	63,92	87,1	52,96	73,13

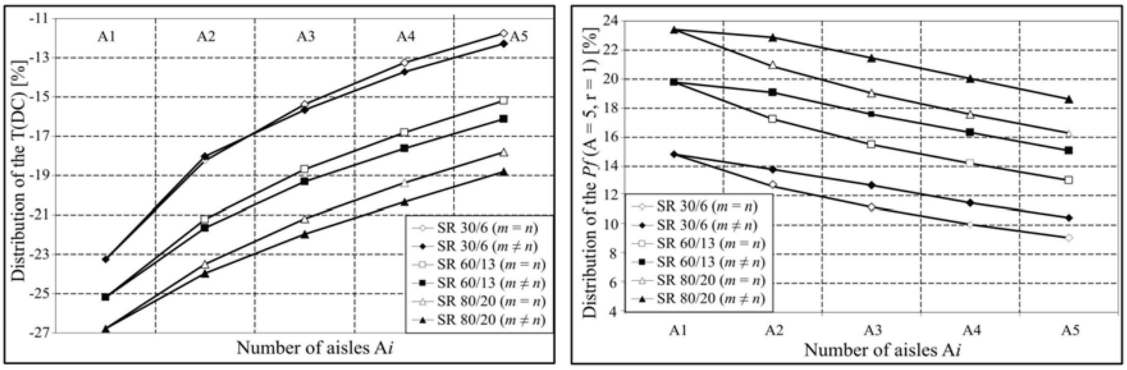
A*i*	SR 80/20 (random – FCFS)				SR 30/6 (random – NN)
	I/O_L warehouse		I/O_M warehouse		I/O_L warehouse
	$m = n$	$m \neq n$	$m = n$	$m \neq n$	$m = n$ and $m \neq n$
1	42,55	42,55	42.55	42.55	17.61
2	50,85	63,71	52.34	65.12	27.54
3	58,18	76,80	53.61	72.26	28.75
4	65,25	87,90	59.18	81.84	34.35
5	72,23	98,23	61.32	87.3	36.43

A*i*	SR 60/13 (random – NN)	SR 80/20 (random – NN)
	I/O_L warehouse	I/O_L warehouse
	$m = n$ and $m \neq n$	$m = n$ and $m \neq n$
1	25,45	31,41
2	35,35	41,21
3	36,52	43,21
4	42,20	48,80
5	44,27	50,93

[1] I/O_L warehouse means that the I/O location is located on the lower left side of the warehouse.
[2] I/O_M warehouse means that the I/O location is located in the middle of the cross aisle.

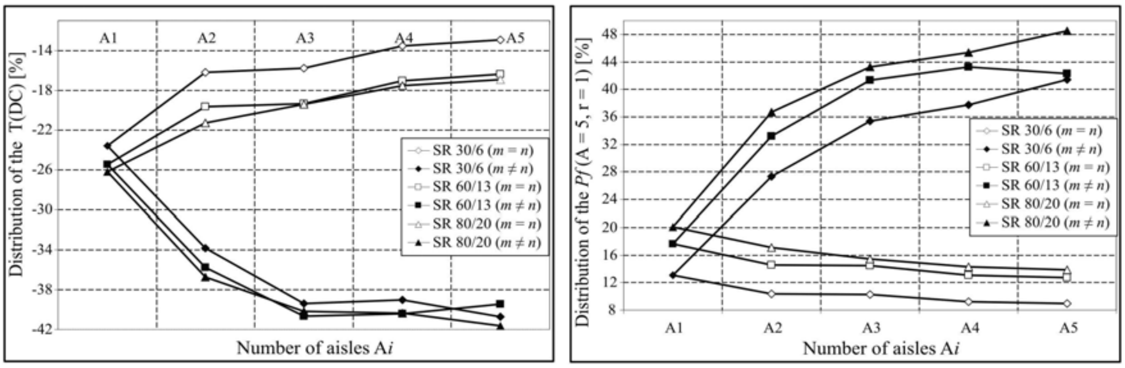
According to the distribution of average travel times for three different layouts of the SR, it is obvious that the layout of the SR and the number of picking aisles have a tremendous impact on the average travel time. Therefore, in determination of the type of multi-aisle AS/RS, the SR geometry represents a very significant piece of information. Another significant piece of information that influences the performance of the multi-aisle AS/RS is the efficiency of the S/R machine. The most effective multi-aisle AS/RS is represented with SIT storage rack. Therefore, in order to increase the efficiency even more, the application of the efficient storage policy is necessary. Because the objective of this study is concerned with the performance improvements utilizing the class-based multi-aisle AS/RS, the simulation results of average travel times for different combinations of sequencing storage and retrieval requests are presented in Table II.

In order to receive the best representative average for the travel time, the simulation results presented in Table II correspond to 1 million runs for every single case of combination of the storage policy. According to the simulation results presented in Table II, the performance comparison between the single-class and class-based multi-aisle AS/RS is presented on the following figures.



a) Average travel time b) Throughput capacities

Figure 3: The comparison of the T(DC) and *Pf* in utilizing the class-based storage policy and FCFS retrieval sequencing (I/O_L warehouse) with the single-class multi-aisle AS/RS.



a) Average travel time b) Throughput capacities

Figure 4: The comparison of the T(DC) and *Pf* in utilizing the class-based storage policy and NN retrieval sequencing with the class-based multi-aisle AS/RS (random – FCFS).

- The comparison of the average travel time according to the class-based storage policy

The diagrams on Fig. 3a and 4a represent distributions of contributions of the average travel time, in comparison with the number of picking aisles A*i*, according to: (*i*) the combination of the class-based storage policy with the random storage and the FCFS retrieval sequencing and (*ii*) the combination of the class-based storage policy with the random storage and NN retrieval sequencing. The basis for the performance comparison are the results of single-class system for the random storage and FCFS retrieval sequencing according to the I/O_M warehouse [11].

Utilizing the random storage policy and the FCFS retrieval sequencing according to the I/O_L warehouse, the biggest contributions can be noticed by the first picking aisle A1 (refers to both conditions $m = n$ and $m \neq n$). The biggest contribution is presented by the multi-aisle AS/RS with SR 80/20 followed by the SR 60/13 and SR/30/6, which indicates a significant influence on the SR geometry. With regard to the increased number of picking aisles A*i*, the expressive decreasing trend of the contributions of the average travel time can be noticed. This can be explained with the increasing length of the cross-warehouse aisle. The time for traveling of the S/R machine in the cross-aisle is getting more influenced due to the high travel time in the picking aisle and thus reduces the significance of the class-based storage policy. The abovementioned dependency refers to all three types of multi-aisle AS/RS and conditions $m = n$ and $m \neq n$. A completely different distribution of contributions of the average travel time utilizing the random storage policy and the NN retrieval request sequencing according to the I/O_L warehouse can be noticed. The basis for the performance comparison are the results of class-based system for the random storage and FCFS retrieval sequencing according to the I/O_M warehouse, presented in Table II. According to the condition $m = n$ and the increasing number of picking aisles, the tendency of contributions of the average travel time slightly decreases. The opposite holds true for the condition $m \neq n$, where contributions of the travel time in interdependence with the increasing number of the picking aisles increase and are in the range of 38 to 42 %. The abovementioned dependency can be explained with the utilization of the class-based storage policy and the NN retrieval sequencing method. For the analyzed example of the class-based multi-aisle AS/RS, the utilization of the abovementioned strategy has proved to be most suitable [11].

- The comparison of the throughput capacity according to the class-based storage policy

The diagrams on Fig. 3b and 4b represent distributions of contributions of the throughput capacities in comparison with the number of picking aisles A*i* according to: (*i*) the combination of the class-based storage policy with the random storage and (*i*) FCFS retrieval sequencing and (*ii*) the combination of the class-based storage policy with the random storage and the NN retrieval sequencing. Because of the strong dependence (inversely proportional) with average travel time, distributions of contributions of the throughput capacities represent similar dependencies like the abovementioned travel times [11].

4. CONCLUSION

In this paper, performance improvements of the class-based multi-aisle AS/RS are presented. The design model of the class-based multi-aisle AS/RS is based on the structured approach [13], [14] and corresponds to the design of the storage and transport area, design of classes and the simulation module for the determination of performance measures. Various elements of the multi-aisle AS/RS have been examined, such as the layout of the SR, the efficiency of the S/R machine and the control policy, in order to investigate the efficiency of the class-based multi-aisle AS/RS in comparison with the single-class multi-aisle AS/RS [11]. For the single-class multi-aisle AS/RS, the randomized storage assignment policy and FCFS sequencing request selection rule have been used. For the class-based multi-aisle AS/RS, the randomized storage assignment policy and (*i*) FCFS and (*ii*) NN request sequencing selection rule have been applied.

It has been established that according to the relationship of different layouts of the SR in comparison with the number of picking aisles the SR geometry has a significant influence on the average travel time. Further on, the maximal contributions have been noticed in the case of class-based storage policy with the random storage and NN retrieval sequencing method under the condition $m \neq n$. Throughput improvements in the range up to 48 % for the class-based multi-aisle AS/RS based on (random – NN) could be achieved, in comparison with class-based multi-aisle AS/RS, which based on (random – FCFS) request sequencing [11]. Therefore, our results could be of help to professionals in practice when making decisions in the early stage of the design project and when deciding which type of storage policy of multi-aisle AS/RS will be the most promising. In spite of the increased throughput capacity of the class-based multi-aisle AS/RS, an additional economic analysis is recommended.

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