cylindrical AS/RS; automated warehouse; simulation; statistical analysis

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PERFORMANCE COMPARISON OF CYLINDRICAL AS/RS WITH SINGLE AND MULTI LOAD HANDLING DEVICES

Summary. This paper proposes the concept of a new type of Cylindrical Automated Storage and Retrieval system (C-AS/RS), which consists of the octagonal shape rack, system input/output (I/O) positions, load storage and retrieval mechanism (SRM), which rotates and moves simultaneously and contains a number of load handling devices (LHDs). Physical structure of the single and multi-LHD systems, control algorithms and the performance measures were presented. Simulation modelling techniques, descriptive statistics and analysis of variance were used in this research to identify the effects of different location of I/O positions, the number of LHDs on the SRM and the retrieval request rates to the performance of the C-AS/RS system.

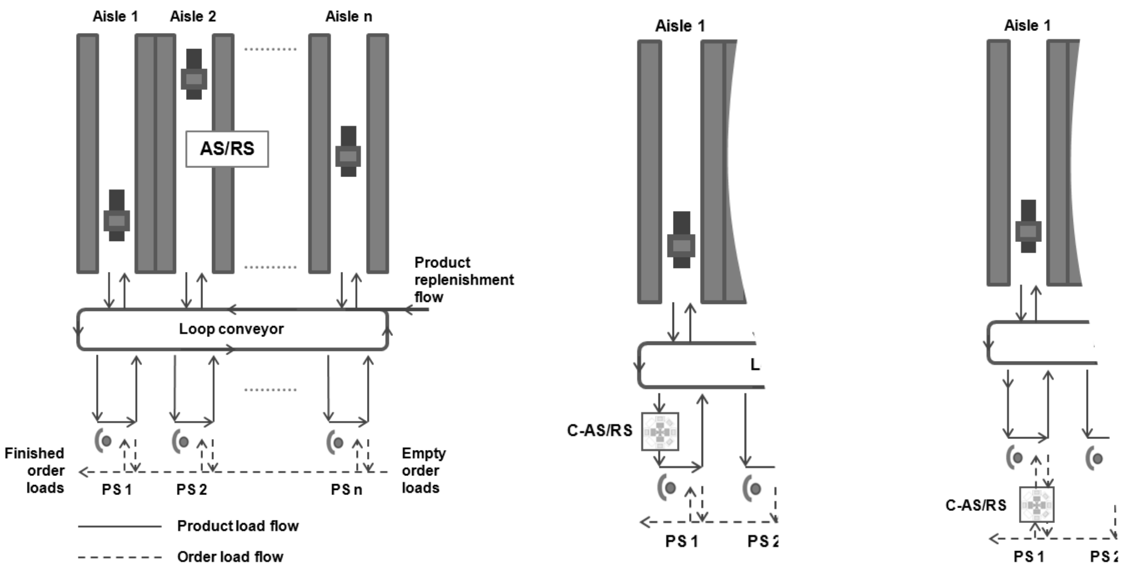
СРАВНЕНИЕ РАБОТЫ АВТОМАТИЗИРОВАННЫХ ЦИЛИНДРИЧЕСКИХ СИСТЕМ СКЛАДИРОВАНИЯ C-AS/RS С РАЗНЫМИ ПОГРУЗОЧНО-РАЗГРУЗОЧНЫМИ УСТРОЙСТВАМИ

Резюме. В данной работе описывается концепция автоматизированных цилиндрических систем складирования нового типа (англ. Cylindrical Automated Storage and Retrieval Systems - C-AS/RS), которая состоит из стеллажа восьмиугольной формы, системы локализации ввода / вывода (англ. input/output-I / O), механизма сбора и хранения груза (англ. Storage Retrieval Mechanism - SRM), который вращается и движется одновременно и содержит ряд погрузочно-разгрузочных устройств (англ. Load Handling Device - LHD). Также была представленф физическая структура моно и мульти-LHD системы, алгоритмы управления и показатели эффективности. В данном исследовании были использованы методы иммитационного моделирования, дискриптивной статистики и дисперсионного анализа для определения влияния различных I/O локализаций, количества LHDs на SRM и интенсивности потока выбора груза на производительность системы C-AS/RS.

1. INTRODUCTION

The level of warehouse processes automation is increasing in modern companies and logistics service providers as it enhances productivity and reduces order delivery time to the customer. One of the key elements of the automated warehouse is the automated storage and retrieval system (AS/RS) [1]. The manual goods storage and retrieval operation is based on a person-driven storage/retrieval mechanism (e.g. forklift) moving in the middle of the aisle and delivering loads to the storage locations and picking the requested loads of an order from the rack. The AS/RS replaces the manual storage/retrieval mechanism by the automated stacker crane which simultaneously moves horizontally and vertically in the middle of aisle and delivers loads from the system input/output positions (I/O) to the storage locations and picks the requested order loads from the rack and transports them to the I/O. The main advantages of AS/RS are reduced labour costs, human error rates, increased system performance and storage capacity [2]. The types of AS/RS include: pallet, mini-load, split-platform, autonomous vehicle AS/RS, etc. [3]. The flexibility of the AS/RS allows to select the optimal system design which satisfies different industry requirements, so AS/RS are widely used in automotive, distribution and manufacturing industries.

One of the most popular applications of the AS/RS is the order picking system (OPS), where the product items are retrieved from the storage in order to fulfil required customer orders. AS/RS integration in OPS is the example of part-to-picker OPS, where product items from the storage locations in the warehouse are transported to the order picking stations by automated transport devices [4].



a b c

Fig. 1. a) End-of-aisle OPS; C-AS/RS integration into end-of-aisle OPS, b) option 1, c) option 2
Рис. 1. а) Система сбора груза, находящегося в конце ряда стелажов складирования; интегрирование C-AS/RS в систему сбора грузов, b) вариант 1, c) вариант 2

Fig. 1a shows the typical configuration of the end-of-aisle OPS, which was investigated in [5]. The multi-aisle connection to the number of picking stations requires sequencing of the load flow from the storage to the picking stations, because the picker works on a single order at a time and required product items are arriving from any storage aisle. Picker receives the storage loads from the AS/RS and picks the required number of product items to the order load and repeats this process until the order load is completed, then it can continue on the next one. The sequencing restriction of the product loads limits the performance of the AS/RS and the linking conveyor system, because the product loads of one order cannot overtake or mix with the product loads of the next order for the same picking station. Ideally, the AS/RS and conveyor should operate at the best possible rate without any sequencing restrictions, so the improvements of the end-of-aisle OPS are required to achieve the optimum efficiency of the automated material handling equipment and the pickers. This paper presents the new design of the AS/RS – the cylindrical automated storage and retrieval system (C-AS/RS), which can be integrated into the OPS and reduce the sequencing restriction for the product load flow to the minimum. Fig. 1b shows the application of C-AS/RS for product load sequencing locally in the picking station. All arriving product loads are consolidated in the C-AS/RS and as soon as all loads for an order are available, they are retrieved and transported to the picker. Another application is showed in Fig 1c: multiple orders are processed in parallel but the picker only works on a single order load at a time since the C-AS/RS delivers the required order load based on the arrival sequence of the product loads to the station.

The proposed C-AS/RS consists of the octagonal shape rack and a new type of storage retrieval mechanism (SRM) with up to 4 load handling devices (LHDs), which moves vertically and rotates simultaneously [6]. For AS/RS designer it is very important to know the system capabilities and limitations for different physical configurations and control algorithms. This research will identify the impact of the different I/O positions locations, number of LHDs on the SRM and different retrieval requests rates to the system performance measures. Simulation analysis techniques, simulation software AutoMod [7], descriptive statistics, analysis of variance (ANOVA) and statistical analysis software SAS 9.3 [8] were used for developing C-AS/RS simulation model, preparing simulation scenarios and result analysis.

2. SYSTEM DESIGN AND CONTROLS

The C-AS/RS is an integrated system, which comprises of octagonal shape rack, SRM, I/O positions and control software (Fig. 2a). The C-AS/RS is designed to function in connection with other automated systems in the warehouse and exchange loads via I/O positions. Rack shape allows to have the I/O positions in any level and location, so the C-AS/RS can be used in different operational environments. The SRM stores arriving loads from the other systems to the rack locations and retrieves them on request and sends to the other system (Fig. 2b). The mechanism performs moving and rotating actions simultaneously and each LHD is able to access any storage location and I/O position.

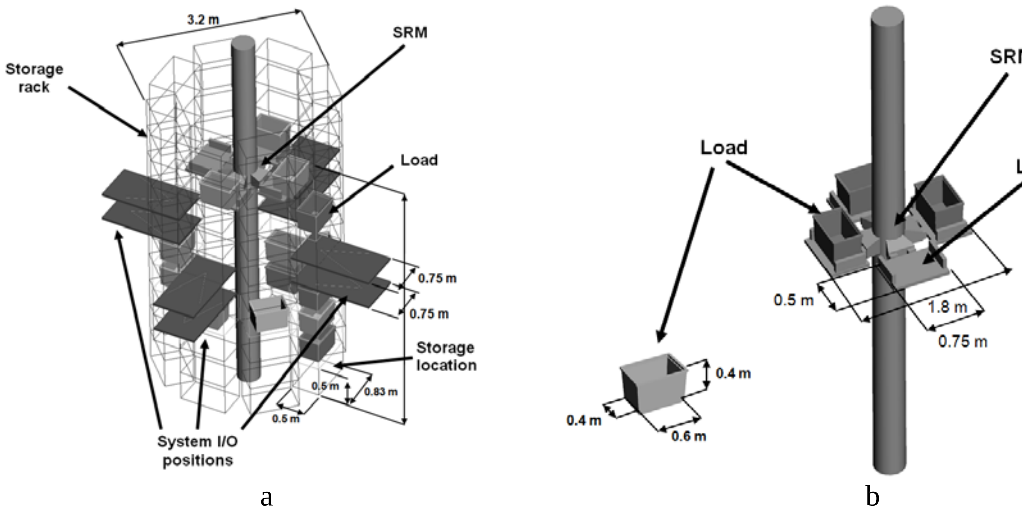


Fig. 2. a) C-AS/RS system view, b) SRM
Рис. 2. a) конструкция системы C-AS/RS, b) SRM

The control software tracks the contents of each storage location and finds the optimal routing scenario for every storage or retrieval operation. The C-AS/RS controls includes the following operations:

- **Idle state**. The SRM stays in the idle state if there are no storage or retrieval requests available, and is activated when at least one request is sent to the control software. The SRM operates on "stay dwell" rule in the case of the idle state, where the mechanism stays at the location of the last completed operation until next operation is available.

- **Storage operation**. The storage load arrives at one of the system input positions and is put on the active storage load list, where it waits for the SRM to pick up. The size of the storage load list is less or equal to the number of LHDs on the SRM. The control software tracks the active status of the SRM and starts the storage operation immediately after the retrieval operation or invokes the mechanism from the idle state. The software configures the sequence of movements and rotations of the SRM for the storage load pick operation so that the total operation time to process all storage loads is minimized and dispatches the SRM to the input positions to pick the loads. After having the storage loads on board, the control software selects the closest available storage locations so that the time of the storage load drop operation is minimized. The SRM transports loads to the rack locations and completes the storage operation.
- **Retrieval operation**. When the retrieval load is activated, it is put on the active retrieval load list, where it waits for the SRM to pick up. The size of the retrieval load list is less or equal to the number of LHDs on the SRM. The control software tracks the active status of the SRM and starts the retrieval operation immediately after the storage operation or invokes the mechanism from the idle state. The software configures the sequence of movements and rotations of the SRM for the retrieval load pick operation so that the total operation time to process all retrieval loads is minimized and dispatch the SRM to the rack locations to pick the loads. After having the retrieval loads on board, the control software configures the SRM for the retrieval load drop operation to the system output positions with minimized operation time. The SRM transports the loads to the system output positions and completes the retrieval operation.

The previous researches [9, 10] had shown the benefits of multi-shuttle AS/RS systems over the single-shuttle systems and compared different operational scenarios. Fig. 3 shows the C-AS/RS configurations with different number of LHDs considered in this research. The single LHD system is expected to demonstrate the lower performance compared with multi-LHD systems, because it processes less loads per operation cycle. However, it is very important to know the expected performance of different system configurations, so that designers could make the optimal system configuration selection for the specific design case.

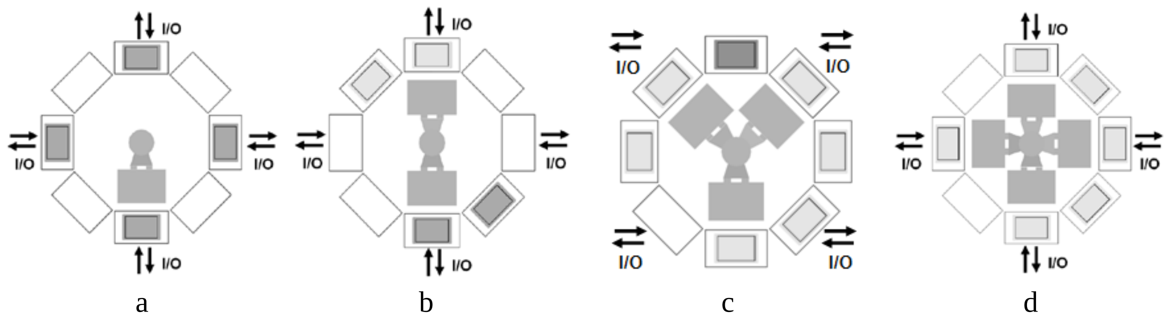


Fig. 3. C-AS/RS configurations with 4 I/O positions: a) 1 LHD; b) 2 LHD; c) 3 LHD; d) 4 LHD
Рис. 3. Конфигурации системы C-AS/RS с 4 I/O позициями: a) 1 LHD; b) 2 LHD; c) 3 LHD; d) 4 LHD

All C-AS/RS configurations showed in Fig. 3 follows the same sequence of storage and retrieval control rules and the control software always searches for the minimized operation time.

3. RESEARCH DESIGN

The simulation model of the C-AS/RS showed in Fig. 4 is based on AutoMod software, which provides tools for the developing detailed and precise simulation models of the automation systems. The main model assumptions are the following:

- At the start of the simulation experiment, the storage rack is filled up to 90% filling level.
- Retrieval requests are generated at the rate of λ_{out} loads/hour.
- Each retrieval request selects the random storage load for the retrieval operation.
- As soon as the retrieval request is created, the new storage load is generated and sent to the system at the same time.
- The system input position for the storage load is selected randomly while the closest output position is selected for the retrieval loads.
- Each storage load is stored in the closest available rack location.

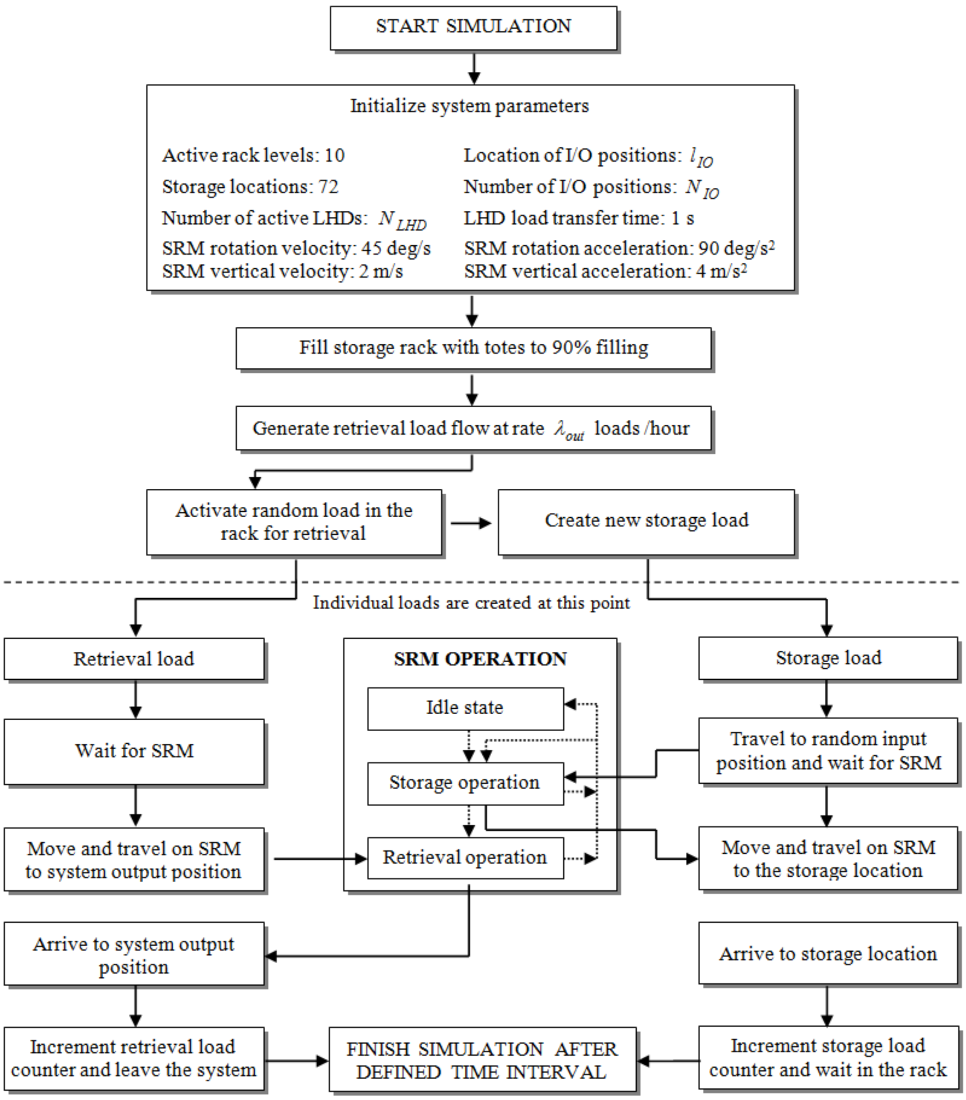


Fig. 4. C-AS/RS simulation model
Рис. 4. Иммитационная модель C-AS/RS

The main experimental parameters of the model are specified in Fig. 4 with defined values for the fixed parameters. The varied experimental parameters are:

- hourly retrieval request rate $\lambda_{out} \in (100,150,200,225,250,275,300,325,350,400,425,450,500,525,550,600,625,650,700)$,
- location of the I/O positions $l_{IO} \in (0102, 0304, 0506, 0105, 0110)$ (e.g. $l_{IO} = 0102$ - input is located at rack level 1 and output at level 2),
- number of LHDs on SRM $N_{LHD} \in (1,2,3,4)$,

which are used to set up different simulation scenarios and evaluate the effect of the following system performance measures:

- T_{tr} - average percent of time each LHD spent in transferring loads on/off $(T_{tr} \cdot 100\%)$,
- T_{move} - average percent of time each LHD spent in movement and rotation $(T_{move} \cdot 100\%)$,
- T_{idle} - average percent of time each LHD was idle with no operations $(T_{idle} \cdot 100\%)$,
- T_{wait} - average percent of time each LHD was waiting due to other LHD (-s) transferring the load (-s) on/off $(T_{wait} \cdot 100\%)$,

where $(T_{wait} + T_{move} + T_{idle} + T_{wait}) \cdot 100\% = 100\%$. The number of I/O positions is assumed to be equal to the number of LHDs on the SRM ($N_{IO} = N_{LHD}$), because it allows the SRM to operate in the most optimum way - pick and drop all required loads at the I/O positions simultaneously. This paper investigates the effects of different I/O positions locations, the number of LHDs on the SRM and the load retrieval request rates to the performance measures of the C-AS/RS system.

4. RESULTS

Simulation results were compared for all different combinations of experimental parameters specified in section 3: retrieval rate λ_{out}, location of I/O positions l_{IO} and the number of LHDs on the SRM N_{LHD}. Statistical analysis software SAS 9.3 was used for result analysis. The system performance is significantly affected by the number of LHDs on the SRM, so different system configurations achieve the saturation level with the maximum performance limit (100% equipment utilization) at different values of the retrieval request rate λ_{out}.

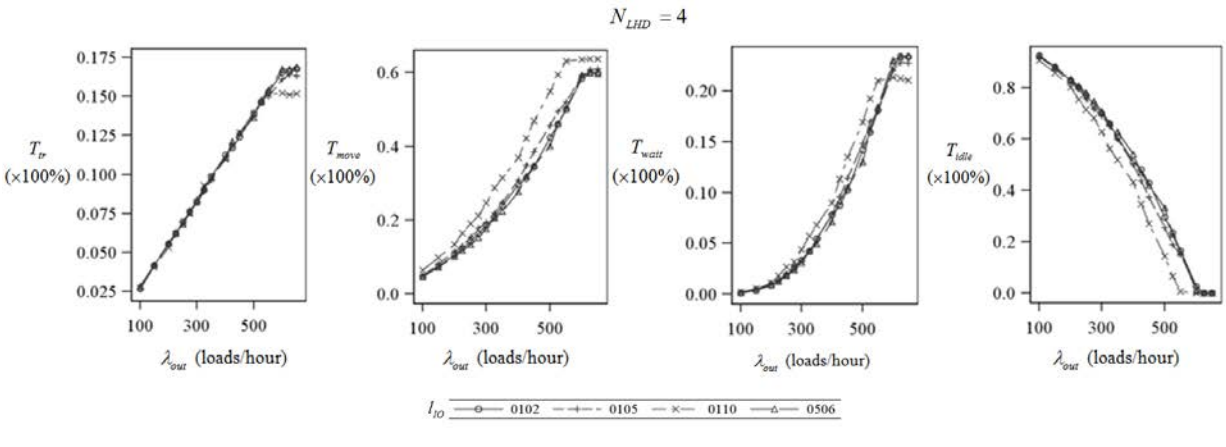


Fig. 5. Multi-LHD system performance measures for different values of l_{IO} and λ_{out}

Рис. 5. Показатели эффективности мульти-LHD системы при различных l_{IO} и λ_{out} значениях.

Fig. 5 shows graphical analysis results of performance measures for the C-AS/RS with 4 LHDs and different locations of I/O positions l_{io} and retrieval request rates λ_{out}. The performance measures T_{tr} and T_{wait} are not significantly dependent on the locations of the I/O positions and the variations of the measure values do not exceed 3% for different values of λ_{out}. The greatest differences can be seen for the performance measures T_{idle} and T_{move} for different values of l_{IO} and λ_{out}. It is assumed that system saturates if the value of T_{idle} drops below 15% (average LHD utilization $U_{lhd} = (1 - T_{idle})$ exceeds 85%), so the maximum achievable retrieval request rate for the system with $N_{LHD} = 4$ is $\lambda_{out} = 550$ loads/hour ($T_{idle} = 16.5\%$) when system I/O positions are located close to each other and at the bottom levels of the rack ($l_{IO} = 0102$). The T_{idle} reduces slightly to 15% for $\lambda_{out} = 550$ if the input positions are located at the level 1 and output positions are separated and located at level 5 (e.g. $l_{IO} = 0105$). The value of T_{idle} drops significantly to 0.7% if the I/O positions are located at the opposite vertical ends from the physical rack centre ($l_{IO} = 0110$).

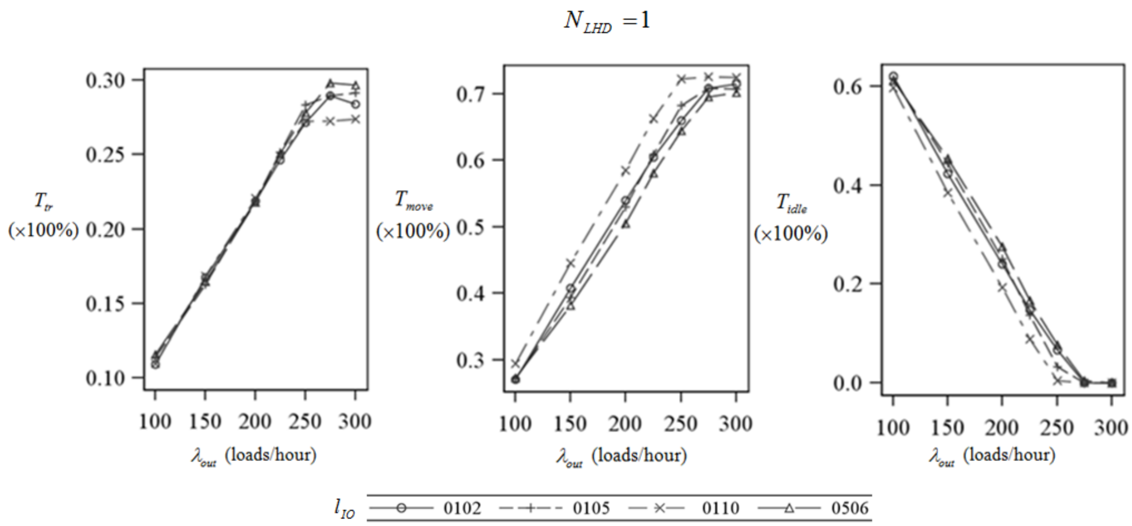


Fig. 6. Single-LHD system performance measures for different values of l_{IO} and λ_{out}

Рис. 6. Показатели эффективности моно-LHD системы при различных l_{IO} и λ_{out} значениях

Fig. 6 shows results for the single-LHD system ($N_{LHD} = 1$): measure T_{tr} is not significantly dependent on the location of the I/O positions l_{IO}, while the values of T_{idle} and T_{move} are affected by different values of this parameter. T_{wait} is not considered in this experiment, because there is no interaction between different LHDs. The maximum achievable retrieval request rate for the system with 1 LHD is $\lambda_{out} = 225$ ($T_{idle} = 16.7\%$) when system I/O positions are located close to each other and as close as possible to the physical rack centre ($l_{io} = 0506$). The T_{idle} reduces slightly to 13.8% for $\lambda_{out} = 225$ in the case of $l_{IO} = 0105$ and T_{idle} drops significantly to 8.8% if the I/O positions are located at the opposite ends from the physical rack centre ($l_{IO} = 0110$).

The one-way analysis of variance with means comparisons and Tukey's test [8] was applied to find the homogeneous groups of factor levels (I/O positions locations - l_{IO}) for different hourly retrieval request rates λ_{out}. It is an all pair-wise comparison test, which compares the mean of each T_{idle} to every other mean T_{idle} for different values of l_{IO}, and identifies where the difference between two means is significant. The Tukey's test was performed (with 95 % confidence) for system performance measure T_{idle} and the assumptions of Tukey's test were satisfactory.

Table 1 shows ANOVA results of the sorted list of factor level combinations in decreasing order in terms of mean T_{idle}. In each homogenous group of factor levels l_{IO}, the value of mean T_{idle} does not differ statistically significant. The gray colour in Table 1 indicates the best homogeneous group for different combinations of N_{LHD} and highest values of retrieval request rate λ_{out}. Results showed that for all different retrieval request rates λ_{out}, the values of T_{idle} were significantly lower if the I/O positions were located at the opposite ends from the physical rack centre ($l_{IO} = 0110$). For the highest values of λ_{out} and $l_{IO} = 0110$, the values of T_{idle} were approx. 5-15% smaller compared to the other I/O positions locations.

Table 1

Homogeneous subsets of factor level l_{IO} combinations for system performance measure T_{idle} (Tukey comparison)

$N_{LHD} = 1$						$N_{LHD} = 2$					
$\lambda_{out} = 150$		$\lambda_{out} = 200$		$\lambda_{out} = 225$		$\lambda_{out} = 275$		$\lambda_{out} = 300$		$\lambda_{out} = 325$	
Factor levels	**Mean** T_{idle}	**Factor levels**	**Mean** T_{idle}	**Factor levels**	**Mean** T_{idle}	**Factor levels**	**Mean** T_{idle}	**Factor levels**	**Mean** T_{idle}	**Factor levels**	**Mean** T_{idle}
0506	0.453	0506	0.276	0506	0.167	0304	0.359	0304	0.285	0304	0.133
0105	0.443	0105	0.250	0102	0.148	0506	0.336	0506	0.262	0506	0.128
0304	0.429	0304	0.247	0105	0.138	0102	0.305	0102	0.203	0105	0.102
0102	0.423	0102	0.240	0304	0.131	0105	0.303	0105	0.174	0102	0.091
0110	0.385	0110	0.192	0110	0.088	0110	0.208	0110	0.094	0110	0.001
$N_{LHD} = 3$						$N_{LHD} = 4$					
$\lambda_{out} = 400$		$\lambda_{out} = 425$		$\lambda_{out} = 450$		$\lambda_{out} = 500$		$\lambda_{out} = 525$		$\lambda_{out} = 550$	
Factor levels	**Mean** T_{idle}	**Factor levels**	**Mean** T_{idle}	**Factor levels**	**Mean** T_{idle}	**Factor levels**	**Mean** T_{idle}	**Factor levels**	**Mean** T_{idle}	**Factor levels**	**Mean** T_{idle}
0304	0.321	0304	0.275	0105	0.157	0506	0.332	0304	0.251	0102	0.164
0102	0.294	0506	0.226	0304	0.136	0304	0.312	0102	0.235	0506	0.159
0506	0.290	0105	0.212	0102	0.135	0102	0.295	0506	0.228	0304	0.158
0105	0.278	0102	0.194	0506	0.130	0105	0.255	0105	0.188	0105	0.150
0110	0.215	0110	0.154	0110	0.097	0110	0.142	0110	0.067	0110	0.007

Performance measures for the multi-LHD systems and λ_{out} for one of the most optimal I/O positions location $l_{IO} = 0506$ are showed in Fig. 7.

The maximum achievable retrieval request rate for the system with 3 LHDs is $\lambda_{out} = 450$ ($T_{idle} = 15.7\%$) and $\lambda_{out} = 325$ ($T_{idle} = 13.33\%$) for the system with 2 LHDs. So, the system designer can expect about 31% increase in the achievable request rate for the 2 LHD system compared to 1 LHD, 50% for 3 LHD and 60% for 4 LHD systems if the I/O positions are located close to each other and as close as possible to the physical rack centre ($l_{IO} = 0506$).

The multiple regression models for predicting retrieval request rate λ_{out} were developed for system configurations with $N_{IO} = N_{LHD}$ and for all values of l_{IO} in this research and the model of the most optimal I/O positions location $l_{IO} = 0506$ is presented in this paper. The following additional binary parameters were defined in order to satisfy the regression requirements:

- $bN_2 = 1 \times ((N_{IO} = 2)\ AND\ (N_{LHD} = 2))$,
- $bN_3 = 1 \times ((N_{IO} = 3)\ AND\ (N_{LHD} = 3))$,

- $bN_4 = 1 \times ((N_{IO} = 4)\ AND\ (N_{LHD} = 4))$,
- $bN_2 = 0$, $bN_3 = 0$ and $bN_4 = 0$ for system configuration with $N_{IO} = 1$ and $N_{LHD} = 1$.

The regression model for predicting λ_{out} when $l_{IO} = 0506$, was developed for $T_{idle} \in (0.05, 0.7)$:

$$\hat{\lambda}_{out} = 284.02 - 252.45 \times T_{idle} - 42.78 \times T_{idle}^2 + 177.41 \times bN_2 + 243.72 \times bN_3 + \\ + 315.63 \times bN_4 - 150.12 \times bN_2 \times T_{idle}^2 - 135.75 \times bN_3 \times T_{idle}^2 - 193.77 \times bN_4 \times T_{idle}^2 \quad (1)$$

The regression model (1) satisfies regression assumptions and showed very good fit (adjusted R-Square $R_{adj}^2 = 0.99$). Regression models can be used by the system designers to predict the target system retrieval request rate for selected system configuration and required utilization.

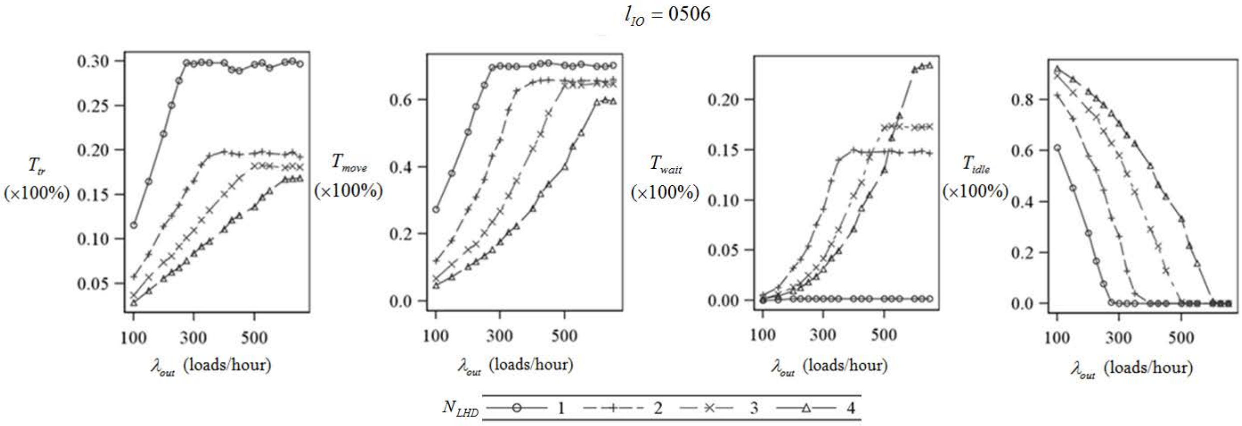


Fig. 7. System performance measures for different values of N_{LHD} and λ_{out} when $l_{IO} = 0506$

Рис. 7. Показатели еффективности системы при различных N_{LHD} и λ_{out} значениях, когда $l_{IO} = 0506$

5. CONCLUSIONS

In this paper the physical structure of the new type of multi-LHD cylindrical automated storage and retrieval system together with control algorithms and the performance measures were presented. Using the AutoMod software, the C-AS/RS simulation model was created and used for the investigation of the impact of different I/O positions locations l_{IO} and number of LHDs on the SRM N_{LHD} to the performance measures of C-AS/RS – the average percent of time the LHD spent transferring loads on/off T_{tr}, the average percent of time the LHD spent in vertical movement and rotation T_{move}, average percent of time each LHD was waiting due to other LHD (-s) transferring the load (-s) on/off T_{wait} and the average percent of time each LHD was idle with no operations T_{idle}.

Simulation result analysis was done with SAS 9.3 software and the maximum achievable retrieval request rates for the C-AS/RS configurations with different number of LHDs were identified. Assuming that the system saturates if the value of T_{idle} drops below 15%, the maximum achieved retrieval request rates λ_{out} for systems with different number of LHDs were as follows: 1 LHD - $\lambda_{out} = 225$ ($T_{idle} = 16.7\%$), 2 LHDs - $\lambda_{out} = 325$ ($T_{idle} = 13.3\%$), 3 LHDs - $\lambda_{out} = 450$ ($T_{idle} = 15.7\%$) and 4 LHDs - $\lambda_{out} = 550$ ($T_{idle} = 16.4\%$). Hence, the expected improvement in achievable request rate is about 31% compared 1 LHD system to the 2 LHD system, 50% for 3 LHD and 60% for 4 LHD systems.

The one-way analysis of variance and Tukey's test was applied to find out the homogeneous groups of locations of the I/O positions for different hourly retrieval request rates λ_{out}. Results showed that for all different retrieval request rates, the values of T_{idle} were statistically significant lower if the I/O positions were located at the opposite ends from the physical rack centre ($l_{IO} = 0110$). For the highest values of λ_{out} and $l_{IO} = 0110$, the values of mean T_{idle} were approx. 5-15% smaller compared to the other I/O locations positions.

Multiple regression models for predicting system retrieval request rate λ_{out} were developed in this research and the model for $l_{IO} = 0506$ was presented which showed the very good fit ($R^2_{adj} = 0.99$) and satisfied regression assumptions. Models provide a tool for system designers to predict the target system retrieval request rate for different values of N_{LHD}, N_{IO} and T_{idle}.

The C-AS/RS analysis presented in this paper showed the significant impact of the considered experimental parameters to the system performance measures and implies that further investigations of the SRM motion parameters, LHD transfer time, I/O configuration and rack size are required. In addition, the proposed options of the C-AS/RS integration into OPS should be investigated for different number of AS/RS aisles, number of picking stations and order profiles.

Acknowledgements

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