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THE DESIGN AND INVESTIGATION OF TWO STORAGE/RETRIEVAL MECHANISMS OF THE CYLINDRICAL AUTOMATED STORAGE AND RETRIEVAL SYSTEM

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Abstract. The objective of this research is to propose and investigate a new design of the Cylindrical Automated Storage and Retrieval System (C-AS/RS) and provide a performance comparison of the two types of Storage/Retrieval Mechanisms (SRM I and SRM II) for the system configurations with different input/output location numbers and positions. Although the better performance is expected from of the system with SRM II, because it contains the vertically independent moving load handling devices (LHDs) compared to the interconnected LHDs used in SRM I, the vertically independent movement requires more sophisticated equipment which should be considered by the system designers. Hence, the performance investigation is required to identify the differences between the two types of the SRMs for different C-AS/RS configurations. For this purpose, the detailed simulation model of the C-AS/RS was developed, investigated for various combinations of system parameters and the multiple regression models for predicting system performance measures were developed (adjusted R-square greater than 0.83 for all models). The differences of the performance measures were evaluated and showed that SRM II achieved 7÷20% higher load retrieval rates compared to SRM I for all investigated parameter combinations. The investigation also showed that the number and position of the input/output locations had a significant impact on the system performance.

Keywords: cylindrical automated storage and retrieval system, order picking system, automated warehouse, simulation, regression analysis.

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Introduction

The automation of warehouse processes usually reduces labour costs and increases system accuracy, reliability and performance. Since automated warehouse systems require high investment and usually have a fixed layout and controls, many design issues should be solved in the most optimal way to provide substantial automation benefit (Roodbergen, Vis 2009). The most modern warehouses include Automated Storage and Retrieval System (AS/RS), which have been already investigated by the majority of the researchers (Gu *et al.* 2010). Traditional one-aisle single-shuttle AS/RS contains the rack structure, storage/retrieval crane with a single load handling device (shuttle) which serves rack locations, the connection to the other system in the warehouse via input/output conveyors and the control system which schedules the AS/RS operations.

The increasing number of AS/RS applications in warehousing has lead to the development of the various modifications to traditional AS/RS. The multi-shuttle AS/RS, containing a number of load handling devices on a single crane, demonstrated significant improvement in system performance compared to single-shuttle systems (Guo, Liu 2008). The split-platform AS/RS has separated the combined vertical and horizontal movement of the traditional crane into a vertically moving platform serving rack levels and a horizontally moving platform serving locations in each level (Vasili *et al.* 2006). The independent mechanisms for vertical and horizontal movement can operate at higher speeds and handle more loads at a time. The autonomous vehicle AS/RS operates similarly to split-platform AS/RS, but uses vertically moving lifts to transport horizontally moving vehicles to the required levels, where each vehicle accesses

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its destination location (Fukunari, Malmborg 2008). This type of system provides a complete independence of the horizontally moving vehicle which can access any storage location in any level and aisle.

All afore mentioned types of AS/RS are widely used in goods-to-person order picking systems where product totes containing items of the single stock keeping unit are retrieved from storage and transported to the order picking workstation to fulfil active customer orders (Andriansyah *et al.* 2011). The workstation operator picks the required amount of items from the product tote and puts them into the active order tote, hence the sequenced flow of product totes from AS/RS merges with the sequenced flow of active order totes at the workstation. The typical goods-to-person system has a single AS/RS aisle directly connected to a single workstation, but as the order picking process has a significantly high impact on warehouse operation costs, it has been shown that having a single workstation connected to the multiple AS/RS aisles is much more effective considerating labour cost (Koh *et al.* 2005). However, in the multi-aisle system, the product tote sequence from the AS/RS might be violated, because each AS/RS aisle processes the totes in parallel and independently, so having no additional sequence control might result in the operator receiving product totes which do not match the currently active order totes in the picking station. Any type of product tote sequence control from AS/RS to workstations will decrease the system performance compared to unsequenced flow, so the sequence control level should be reduced to a minimum.

The objective of this research is to propose and investigate a new design of Cylindrical Automated Storage and Retrieval System (C-AS/RS), which is a supplement for goods-to-person order picking system, used for the sequencing of product totes or the active order totes locally at the workstation. The C-AS/RS contains a new type of storage/retrieval mechanism (SRM), which has a number of vertically moving and rotating Load Handling Devices (LHDs), and is placed in the centre of the octagonal shape rack (Janilionis, Bazaras 2011). The system is designed to operate as a short-term buffer providing the high rate processing of the storage and retrieval requests. The novelty of this research is the first combined investigation of the two types of SRMs of the C-AS/RS, which have different mechanical and control designs.

The design of C-ASRS requires solving the same fundamental problem classes as for any other type of the AS/RS: system physical configuration, storage assignment, order batching, SRM operations sequencing and dwell point selection (Manzini *et al.* 2006). Although all classes are related, primarily the system's physical configuration should be considered, which defines the storage rack capacity and layout, the type of SRM with its motion parameters, number of system Input/Output (I/O) locations, to name but a few. The storage rack configuration, number of LHDs on the SRM, velocity and acceleration parameters of the SRM, the number of I/O locations and their position in the system have a significant impact on the system performance (Gagliardi *et al.* 2012; Potrč *et al.* 2004).

This paper follows the previous research by the same authors, who have already investigated the impact of I/O positions to the C-AS/RS performance with independent vertically moving LHDs (Janilionis, Bazaras 2012a) and the impact of I/O positions together with a number of LHDs on the SRM to the system performance with interconnected vertically moving LHDs (Janilionis, Bazaras 2012b). This research will focus on the performance investigations of two SRM types of the C-AS/RS with a different number of I/O locations and different I/O positions. The simultaneous movement and rotation of the SRM complicates the development of analytical performance estimation models for C-AS/RS, hence the simulation model for the system investigation will be developed (Basile *et al.* 2012). Compared with previous research, the detailed C-AS/RS operation model and the fully parameterized simulation model, which includes the functionality of both SRM types, are introduced in this research. In addition to previous designs of the C-AS/RS, this research also considers the system I/O locations positioned in the same level, allowing the SRM to pick and drop loads simultaneously at the I/O. For the model development and experiment results analysis, the discrete event simulation software AutoMod (LeBaron, Jacobsen 2007) was integrated with the statistical analysis software SPSS (Norušis 2012).

1. C-AS/RS Design

The C-AS/RS system offers modular and integrated design which is dedicated for warehouses with order picking systems. The main components of the C-AS/RS are shown in Fig. 1: storage rack, LHD(-s), SRM and I/O locations.

The storage rack has a number of storage columns and levels arranged in a cylindrical octagonal shape, which allows each LHD of the SRM to access any rack location during the operation cycle. The system is scalable level-wise, each storage location has a capacity for a single load and a number of locations in the rack are used as I/O locations, which are blocked for storage. The flexibility of the system design allows a required number of I/O locations positioned at any level and column.

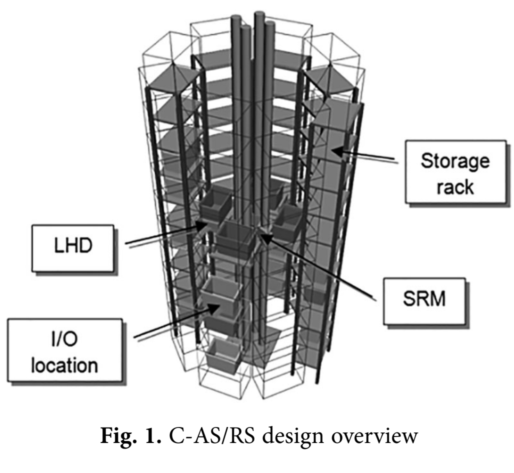

Fig. 1. C-AS/RS design overview

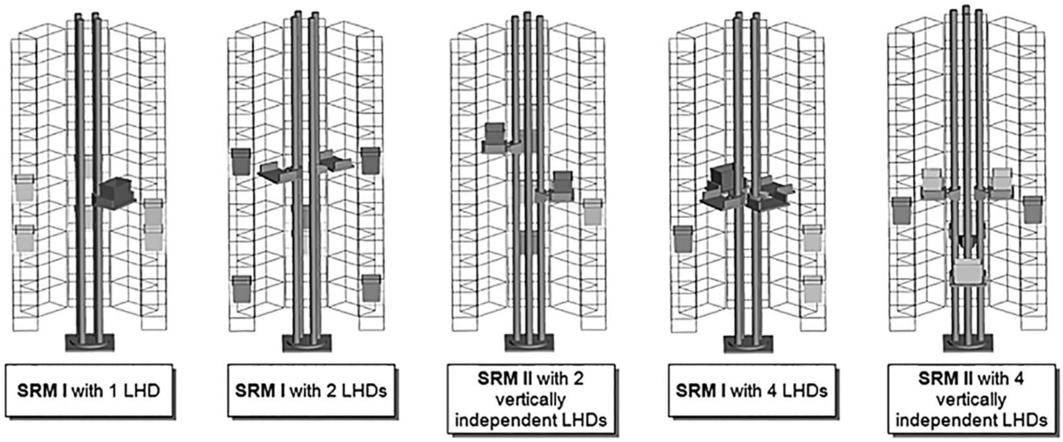

Fig. 2. C-AS/RS configurations with SRM I–II and 1–4 LHDs

The C-AS/RS should be connected to the other systems in the warehouse via conveyors placed in the I/O locations. The SRM has a number of LHDs, where each of them has a capacity for a single load, therefore, the system is also scalable with regard to LHD and the number of LHDs can be selected depending on the required performance. Fig. 2 shows two SRM design types considered in this research with a different number of LHDs and movement functionality.

SRM I can rotate and move all the LHDs simultaneously as a single unit, while the SRM II rotates the LHDs as a single unit, but they can move vertically independently.

2. C-AS/RS Operation and Simulation Models

The C-AS/RS operation model provides the specification of the storage/retrieval cycle of the SRM. Before specifying the cycle, the operation environment parameters should be defined. The SRM operates inside the cylindrical octagonal shape rack structure which has L levels and C columns, hence the total number of rack locations is $L \times C$. Fig. 3 shows the top view of the sample rack level 1 with 3 types of rack locations defined: I – system input location; O – system output location and z – storage location.

Any type of location is positioned in level l_i, $i = 1,\ldots,L$ and column c_j, $j = 1,\ldots,C$ – e.g. storage location z_{l_i,c_j}. The layout of I/O locations is configured so that the SRM could pick and drop loads at the I/O level with minimum possible time.

The SRM moves vertically at velocity v_{vert} (m/s) with acceleration a_{vert} (m/s^2), rotates at velocity a_{rot} (m/s) with acceleration a_{rot} (deg/s^2), and LHD load transfer on/off time is t_{tr} (s). The SRM rotates by $\pm d_{c_{j1},c_{j2}}$ degrees between columns c_{j1} and c_{j2} in time $t_{c_{j1},c_{j2}}$ and each LHD of the SRM moves vertical distance $d_{l_{i1},l_{i2}}$ between levels l_{i1} and l_{i2} in time $t_{l_{i1},l_{i2}}$, so considering the ability of the SRM to move and rotate simultaneously, the time required to move from storage location $z_1 = z_{l_{i1},c_{j1}}$ to $z_2 = z_{l_{i2},c_{j2}}$ is $t_{z_1,z_2} = \begin{cases} t_{c_{j1},c_{j2}} \geq t_{l_{i1},l_{i2}}, \ t_{c_{j1},c_{j2}}; \\ t_{l_{i1},l_{i2}}. \end{cases}$

Fig. 4 shows the flow diagram of the sequence of the C-AS/RS operations, which is based on the standard SRM cycle principle applied for any other type of AS/RS, where the SRM with a certain number of LHDs performs a defined number of storage and retrieval operations in a cycle (Potrč *et al.* 2004).

The system initialize operation sets up all necessary parameters of the C-AS/RS which are used throughout the system operations: SRM type, vertical velocity v_{vert}

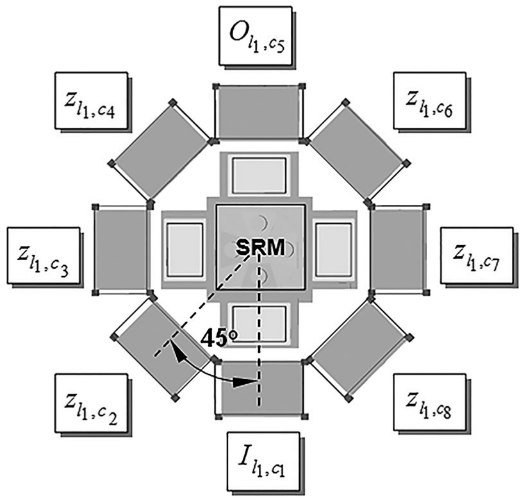

Fig. 3. C-AS/RS operation environment

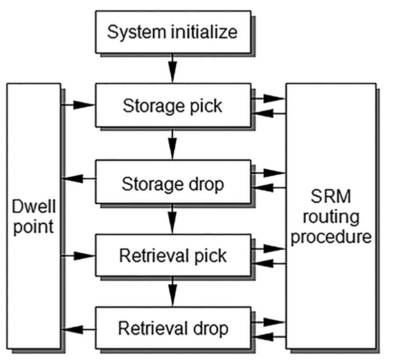

Fig. 4. C-AS/RS operation flow diagram

and acceleration a_{vert}, rotation velocity v_{rot} and acceleration a_{rot}, LHD load transfer on/off time t_{tr}, number of active LHDs N_{LHD}, number of active storage levels N_L, number of I/O locations N_{IO} and the I/O position l_{IO}. The dwell point defines the location of the SRM where it travels after completing the last operation if there is no following operation available.

The key element in C-AS/RS control is the SRM routing procedure, which is called every time before the SRM starts any type of movement. The procedure receives the current position of the SRM and the location set of the target loads to be processed as an input. Based on the required operation type (storage pick, storage drop, retrieval pick or retrieval drop), the procedure estimates the time required to execute different routing scenarios which in turn process the set of target loads completely and the procedure then selects the scenario with minimum execution time. This research defines the application of the SRM routing procedure output based on the optimal branch and bound routing algorithm, which determines the minimum travel time between the rack locations, but is not specified in this paper (Farahani, Tari 2002). The procedure provides the following output: the SRM rotation sequence set $D = \left\{ \pm d_{c_{j1}, c_{j2}}(k) : 1 \le k \le N_{LHD} \right\}$, which defines the rotation sequence the SRM needs to follow to process all target loads and the set of active LHDs in each rotation $S_{LHD}(D)$, which defines the subsets of active LHDs and their target locations during rotation $\pm d_{c_{j1}, c_{j2}}(k)$, $1 \le k \le N_{LHD}$. Fig. 5 shows the application of the SRM routing procedure output to the actual operation execution.

During storage and retrieval operations, the C-AS/RS exchanges information with the routing procedure in order to define the efficient movement of the SRM.

For the storage operation, the system input location set $S_I = \left\{ I_k : 1 \le k \le N_{LHD}, I_k = I_{l_i, c_j} \right\}$, where target loads are currently located, is created and passed to the SRM routing procedure. After receiving procedure output, the SRM is routed from the position of the last operation to the system input locations I_k to pick the target loads. Having storage loads on board, the closest available storage location in the rack is selected for each load, thus storage location set $S_z = \left\{ z_k : 1 \le k \le N_{LHD}, z_k = z_{l_i, c_j} \right\}$ is created and passed to the routing procedure. The SRM then travels from the system input position to the target storage locations z_k and drops the loads.

At the following similar steps, the retrieval operation can be specified. The target retrieval loads are processed using First In First Out (FIFO) rule and the storage location set S_z is created and passed to the routing procedure. The SRM travels from the position of the last operation to the storage locations z_k and picks the target retrieval loads, which are assigned to the closest available system output locations and the created output location set $S_O = \left\{ O_k : 1 \le k \le N_{LHD}, O_k = O_{l_i, c_j} \right\}$

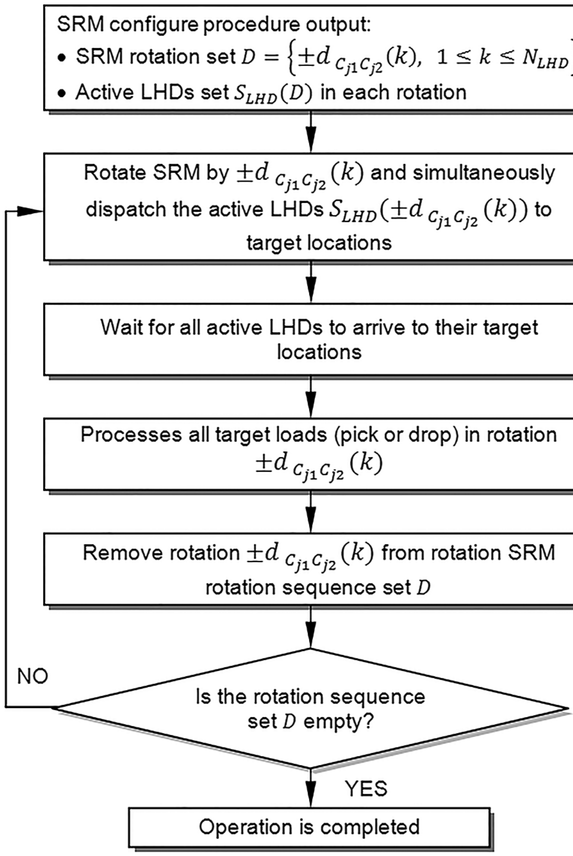

Fig. 5. Application of the SRM routing procedure output

is passed to the routing procedure. The SRM is routed from the current position to the system output locations O_k to drop the loads.

The parameterized C-AS/RS simulation model was developed based on the system design and operation principles described above using the true-to-scale 3-D simulation software AutoMod (*http://www.automod.com*). Fig. 6 shows the flow diagram of the simulation model proposed in this research.

The simulation starts with the system parameters initialization, which is used throughout the model run, and the storage rack filling with loads up to the desired occupancy. After some time, the retrieval flow from the storage rack to the system output queue Q_{out} is generated at the exponentially distributed rate of λ_{out} loads/hour. The detailed order picking process is not considered in this research, so any available load in the Q_{Rack} is randomly selected for retrieval and waits for the SRM to deliver it to the system output queue Q_{out}. The C-AS/RS simulation model functions as a 'pull system', where each retrieval load immediately generates the storage load. The generated flow of storage loads arrives in the system input queue Q_{in} and waits for the SRM to deliver loads to the rack storage locations Q_{rack}. The SRM processes all loads on a FIFO basis and follows operation rules described previously. In case of being idle, the SRM uses the 'stay dwell' rule and remains idle at the position of the last operation.

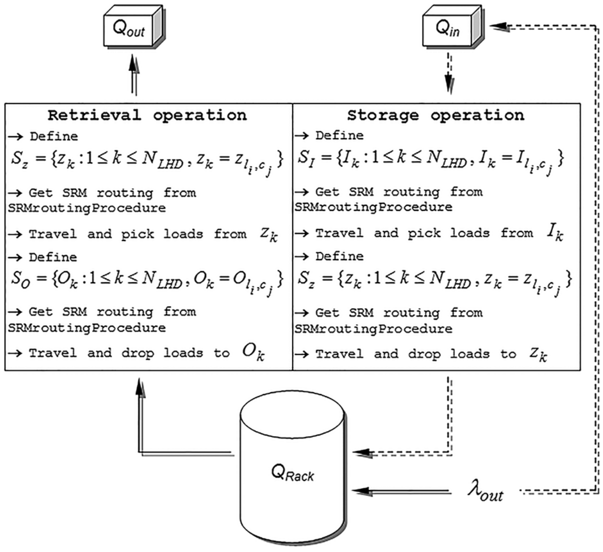

Fig. 6. C-AS/RS simulation model flow diagram

This research proposes two performance measures such as equipment utilization U_{SRM} and the average load input to the system time $\overline{T}_{load}^{in}$ (seconds) for comparisons of the systems with different combinations of the parameters.

3. Results

Simulation results were generated from multiple model runs using the AutoMod statistical analysis module AutoStat (*http://www.automod.com*), which was combined with advanced statistical analysis software SPSS (*http://www.ibm.com/software/analytics/spss*) for the result analysis. The key objective is to provide the comparative performance analysis of two proposed SRM types of the C-AS/RS for the experimental parameters such as SRM type, retrieval rate λ_{out}, the number and positions of I/O locations N_{IO} and l_{IO} and evaluate system performance measures such as equipment utilization U_{SRM} and average load input to the system time $\overline{T}_{load}^{in}$. U_{SRM} shows the proportion of time the SRM was doing at any kind of movement action. For normal system operation mode, the value of U_{SRM} should be $U_{SRM} \le 0.9$ and the objective is to achieve the required retrieval rate λ_{out} with the minimum possible value of U_{SRM} (Fukunari, Malmborg 2009). $\overline{T}_{load}^{in}$ is measured from the time moment the storage load enters the system input queue Q_{in} to the moment it is put to the rack location in the queue Q_{Rack}. Similarly, the average load output from the system time $\overline{T}_{load}^{out}$, measured from the moment of the load retrieval request creation in the rack queue Q_{Rack} to the moment load arrives in the system output queue Q_{out}, follows the same interpretation as the measure $\overline{T}_{load}^{in}$, so it is not discussed in the results section.

The two sets of fixed and varied model parameters are considered in this research. The fixed parameters are: rack dimensions $L \times C$ – 8×11, rack filling level – 90%, SRM rotation velocity v_{rot} = 90 deg/s (with acceleration a_{rot} = 180 deg/s^2), LHD vertical velocity v_{vert} = 3 m/s (with acceleration a_{vert} = 5 m/s^2), number of active LHDs N_{LHD} = 4 and LHD load transfer on/off time t_{tr} = 1 s. All loads in the model are of the same type and equally handled by the SRM. The varied parameters are: hourly retrieval rate $\lambda_{out} \in \left[425, 925\right]$ (loads/hour), number of I/O locations $N_{IO} \in \left\{2, 4\right\}$, I/O positions $l_{IO} \in \left\{0101, 0102, 0111, 0506, 0606\right\}$ and the SRM type $SRM \in \{1, 2\}$. The combination of parameters N_{IO} and l_{IO} specifies the number and position of the system I/O locations, e.g. C-AS/RS with $N_{IO} = 2$ and $l_{IO} = 0102$ has 2 input conveyors located at rack level 1 and 2 output conveyors at rack level 2. For the systems with I/O locations in the same level, e.g. $l_{IO} = 0101$, the SRM has a new feature to pick and drop loads simultaneously at the I/O level.

Fig. 7 shows 95% Confidence Intervals (CI) of the mean U_{SRM} for the two SRM types with different I/O numbers and positions. The SRM II achieves significantly higher retrieval rates for all simulated scenarios, because the LHDs can move vertically independently, while SRM I rotates and moves all the LHDs simultaneously as a single unit. However, vertically independently movement requires more sophisticated equipment, so system designers should consider it when choosing the SRM type. The direct comparison between the two SRM types can only be done for the systems, which achieve the target retrieval rate λ_{out} at the utilization $U_{SRM} \le 0.9$. Systems with low utilizations ($U_{SRM} < 0.5$) were simulated but not presented in this paper, because changing the SRM type and I/O parameters did not show significant differences in the system performance measures and the required retrieval rate λ_{out} was achieved for any given system configuration.

The best system I/O position is $l_{IO} = 0606$, where I/O locations are positioned in the same middle rack level: SRM I achieves retrieval rate $\lambda_{out} = 615$ with $N_{IO} = 2$ and $\lambda_{out} = 700$ with $N_{IO} = 4$ at $U_{SRM} = 0.9$, while SRM II respectively shows utilizations $U_{SRM} = 0.77$ ($N_{IO} = 2$) and $U_{SRM} = 0.75$ ($N_{IO} = 4$) for the same λ_{out} values. Systems with SRM II and $l_{IO} = 0606$ achieve significantly higher retrieval rates of $\lambda_{out} = 765$ for $N_{IO} = 2$ and $\lambda_{out} = 900$ for $N_{IO} = 4$ at $U_{SRM} = 0.9$.

The achievable retrieval rate reduces significantly for the worst system I/O position $l_{IO} = 0111$ where input is positioned in the bottom rack level and output in the top level. In this case, the SRM I is expected to achieve $\lambda_{out} = 510$ for $N_{IO} = 2$ and $\lambda_{out} = 640$ for $N_{IO} = 4$ at $U_{SRM} = 0.9$, while SRM II respectively shows utilizations $U_{SRM} = 0.79$ ($N_{IO} = 2$) and $U_{SRM} = 0.79$ ($N_{IO} = 4$) for the same λ_{out} values. C-AS/RS with SRM II can further operate to the retrieval rate $\lambda_{out} = 600$ for $N_{IO} = 2$ and $\lambda_{out} = 775$ for $N_{IO} = 4$ at $U_{SRM} = 0.9$.

For the other I/O positions, the C-AS/RS achieves intermediate retrieval rates between the best and worst cases: the second best I/O position is $l_{IO} = 0101$, where both SRM types demonstrate 1÷6% worse results com-

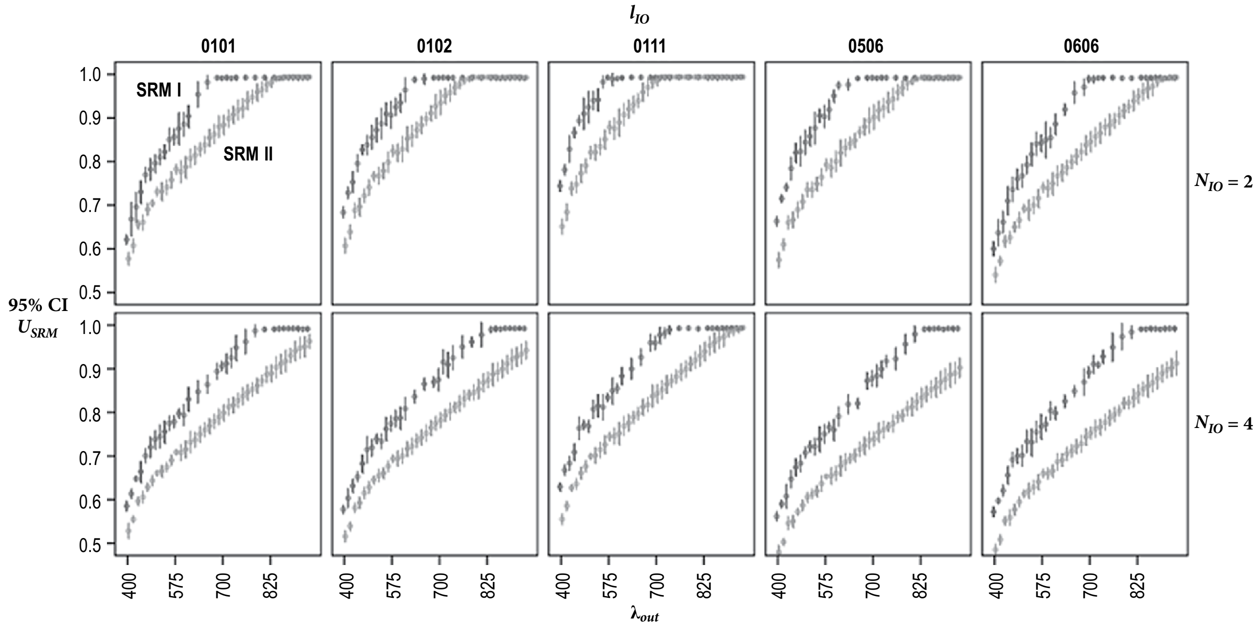

Fig. 7. 95% CI of the mean U_{SRM} for $SRM \in \{1, 2\}$, $l_{IO} \in \{0101, 0102, 0111, 0506, 0606\}$, $N_{IO} \in \{2, 4\}$ and $\lambda_{out} \in \{425, 925\}$

pared to the $l_{IO} = 0606$ and the U_{SRM} increases by 7÷15% for $l_{IO} = 0506$ and 9÷20% for $l_{IO} = 0102$ compared to $l_{IO} = 0606$ for the same λ_{out} values. In general, simulation results indicated that SRM II always achieves 7÷20% higher retrieval rates λ_{out} compared to SRM I for all given parameter combinations. Since the results can be classified by l_{IO} into 3 main categories representing the best $l_{IO} \in \{0606, 0101\}$, medium $l_{IO} \in \{0506, 0102\}$ and the worst $l_{IO} = 0111$ cases, only the best member of each group $l_{IO} \in \{0606, 0506, 0111\}$ can be further considered. Table shows the utilization results summary for different system parameters combinations.

Fig. 8 shows graphical analysis results of the $\overline{T}_{load}^{in}$ for the two SRM types with I/O numbers $N_{IO} \in \{2, 4\}$ and positions $l_{IO} \in \{0506, 0606, 0111\}$. The values of

Table. SRM utilization U_{SRM} and average load input to the system time $\overline{T}_{load}^{in}$ for combinations of parameters l_{IO}, N_{IO} and λ_{out}

N_{IO}	λ_{out}	$l_{IO} = 0506$				$l_{IO} = 0111$				$l_{IO} = 0606$			
		SRM I		SRM II		SRM I		SRM II		SRM I		SRM II	
		U_{SRM}	$\overline{T}_{load}^{in}$	U_{SRM}	$\overline{T}_{load}^{in}$	U_{SRM}	$\overline{T}_{load}^{in}$	U_{SRM}	$\overline{T}_{load}^{in}$	U_{SRM}	$\overline{T}_{load}^{in}$	U_{SRM}	$\overline{T}_{load}^{in}$
2	425	0.72	33.32	0.61	26.19	0.78	40.04	0.68	30.92	0.64	28.52	0.57	24.00
	450	0.74	33.68	0.66	27.28	0.83	43.57	0.74	30.05	0.66	28.64	0.62	24.65
	510	0.81	36.22	0.7	27.15	0.90	55.09	0.79	33.20	0.76	31.15	0.66	24.28
	550	0.88	42.91	0.75	28.24	0.94	69.07	0.84	34.57	0.82	34.21	0.7	24.77
	600	0.93	54.07	0.80	29.37	0.99		0.89	39.76	0.85	36.68	0.75	25.21
	615	0.97	122.09	0.82	29.98	0.99		0.91	41.20	0.89	42.37	0.77	25.75
	690	0.99		0.89	35.94	0.99		0.98	130.75	0.97	94.86	0.84	28.32
	765	0.99		0.96	61.95	0.99		0.99		0.99		0.89	33.28
4	550	0.72	25.43	0.62	19.93	0.81	32.24	0.71	24.25	0.73	26.13	0.63	20.41
	600	0.77	26.70	0.66	20.02	0.87	36.30	0.75	24.67	0.79	27.48	0.67	20.51
	640	0.82	28.39	0.69	20.30	0.89	40.23	0.79	25.56	0.83	29.47	0.7	20.83
	700	0.87	32.52	0.74	20.69	0.96	71.09	0.84	27.81	0.89	33.82	0.75	21.64
	725	0.89	38.45	0.76	21.09	0.98	96.85	0.86	32.30	0.91	36.63	0.77	21.29
	775	0.93	124.23	0.79	21.69	0.99		0.89	33.08	0.95	156.12	0.8	22.22
	850	0.99		0.85	23.75	0.99		0.96	54.26	0.99		0.86	24.61
	910	0.99		0.90	26.14	0.99		0.99	131.19	0.99		0.89	27.93

$\overline{T}_{load}^{in}$ are increasing together with the values of the retrieval rate λ_{out} and the differences of the $\overline{T}_{load}^{in}$ between the two SRM types are increasing as well. The comparison of the $\overline{T}_{load}^{in}$ between the two SRM types can be done only for retrieval rates λ_{out} where both systems operate at normal mode with $U_{SRM} \leq 0.9$. For the worst I/O position $l_{IO} = 0111$, $N_{IO} = 2$ and $\lambda_{out} \in [350, 510]$, the differences of $\overline{T}_{load}^{in}$ between the SRM types increases from 17% to 66% and 15÷57% for $N_{IO} = 4$ and $\lambda_{out} \in [350, 640]$. Similar differences are achieved with the best I/O position $l_{IO} = 0606$: 14÷65% for $N_{IO} = 2$ and $\lambda_{out} \in [350, 615]$ and 16÷56% for $N_{IO} = 4$ and $\lambda_{out} \in [350, 765]$. Table shows that the overall $\overline{T}_{load}^{in}$ differences between the two SRM types vary from 14% to 66% depending on the system configuration and the retrieval rate λ_{out} where systems operate at $U_{SRM} \leq 0.9$.

The multiple regression models for the system performance measures are also developed in this research. In order to satisfy regression requirements the additional binary parameters are defined:

- $bN_{IO} = 0 \cdot (N_{IO} = 2) + 1 \cdot (N_{IO} = 4)$ for number of I/O locations;
- $bSRM = 0 \cdot (SRM = 1) + 1 \cdot (SRM = 2)$ for SRM type;
- $bd_1 = 1 \cdot ((l_{IO} = 0102)\ OR\ (N_{IO} = 0506))$, $bd_{10} = 1 \cdot (l_{IO} = 0111)$ and $l_{IO} \in \{0101, 0606\}$ when $bd_1 = 0$ and $bd_{10} = 0$ for I/O position.

The best fit combined regression models for predicting performance measures U_{SRM} and $\overline{T}_{load}^{in}$ of the systems with both SRM types can be developed for λ_{out} range where systems operate at $U_{SRM} \leq 0.85$ and achieve retrieval rates $\lambda_{out} \leq 600$:

$$\ln \overline{T}_{load}^{in} = 0.72 + 1.005 \cdot bN_{IO} + 1.430 \cdot bSRM + 0.03 \cdot bd_{10} \cdot \ln\lambda_{out} + 0.449 \cdot \ln\lambda_{out} - 0.266 \cdot bSRM \cdot \ln\lambda_{out} + 0.038 \cdot bd_1 - 0.204 \cdot bN_{IO} \cdot \ln\lambda_{out},\ R_{adj}^2 = 0.89;$$

$$U_{SRM} = -2.775 + 0.571 \cdot \ln\lambda_{out} + 0.16 \cdot bN_{IO} - 0.054 \cdot bSRM \cdot \ln\lambda_{out} + 0.08 \cdot bd_{10} + 0.016 \cdot bd_1 + 0.254 \cdot bSRM - 0.041 \cdot bN_{IO} \cdot \ln\lambda_{out},\ R_{adj}^2 = 0.92.$$

Systems with SRM II can achieve higher retrieval rates, hence separate regression models are developed for $SRM = 2$, $\lambda_{out} \leq 900$ and $U_{SRM} \leq 0.85$:

$$\ln \overline{T}_{load}^{in} = 2.077 + 0.194 \cdot \ln\lambda_{out} + 0.522 \cdot bd_1 - 0.079 \cdot bd_1 \cdot \ln\lambda_{out} - 0.04 \cdot bN_{IO} \cdot \ln\lambda_{out} + 0.179 \cdot bd_{10},\ R_{adj}^2 = 0.83;$$

$$U_{SRM} = -2.425 + 0.501 \cdot \ln\lambda_{out} - 0.015 \cdot bN_{IO} \cdot \ln\lambda_{out} + 0.012 \cdot bd_{10} \cdot \ln\lambda_{out} + 0.179 \cdot bd_1 - 0.027 \cdot bd_1 \cdot \ln\lambda_{out},\ R_{adj}^2 = 0.93.$$

All models have values of adjusted R-Square R_{adj}^2 greater than 83%, satisfy regression assumptions and show the best fit for adjusted R-square and Mallows $C(p)$ statistics (Norušis 2012).

Conclusions

This research proposed and investigated a new design of the C-AS/RS with two types of SRMs with its new feature to pick and drop loads simultaneously at the I/O level. The proposed system is applied as a supplement for goods-to-person order picking systems to sequence the product

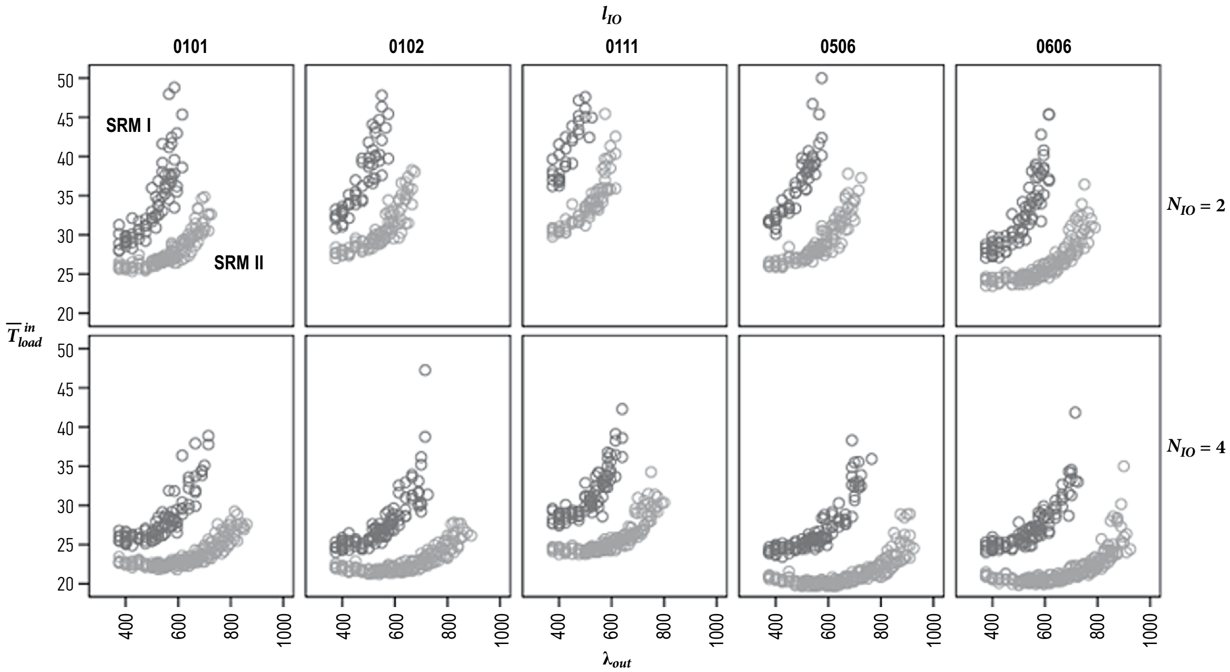

Fig. 8. Average load input to the system time $\overline{T}_{load}^{in}$ (s) for $SRM \in \{1, 2\}$, $l_{IO} \in \{0101, 0102, 0111, 0506, 0606\}$, $N_{IO} \in \{2, 4\}$ and λ_{out} where $U_{SRM} \leq 0.9$

totes or the active order totes locally at the workstation. In addition, the detailed C-AS/RS operation model and the fully parameterized simulation model, which includes the functionality of both SRM types, were introduced and compared to the previous C-AS/RS researches carried-out by authors. The developed simulation model in the AutoMod environment was investigated using the AutoStat module by generating multiple model runs and providing analysis with SPSS software. The performance comparisons by SRM utilization and the average load input to the system time considered different combinations of system parameters – SRM type, retrieval rate, the number of I/O locations and the I/O positions.

Analysis of the U_{SRM} showed that SRM II always achieves 7÷20% higher retrieval rates compared to SRM I for all given combinations of parameters λ_{out}, N_{IO} and l_{IO}. The two SRM types can be compared for retrieval rates λ_{out}, where systems operate at a normal mode with $U_{SRM} \leq 0.9$. The biggest difference of 200 loads/hour between the SRMs and the highest retrieval rates at $U_{SRM} = 0.9$ for both SRM types were achieved for system configurations with 4 I/O locations positioned in the same middle rack level ($l_{IO} = 0606$, $N_{IO} = 4$): SRM I achieved $\lambda_{out} = 700$ and SRM II $\lambda_{out} = 900$. The smallest difference of 90 loads/hour between the values of λ_{out} at $U_{SRM} = 0.9$ was achieved for system configurations with 2 I/O locations positioned at the opposite ends of the rack ($l_{IO} = 0111$, $N_{IO} = 2$): SRM I achieved $\lambda_{out} = 510$ and SRM II $\lambda_{out} = 600$. It has been also shown that there are no significant differences in performance measures for I/O positions $l_{IO} = 0606$ and $l_{IO} = 0101$, and similarly for $l_{IO} = 0506$ and $l_{IO} = 0102$ for both SRMs. The systems with low utilizations ($\lambda_{out} < 425$ and $U_{SRM} < 0.5$) were also investigated, but changing the SRM type and I/O parameters did not show significant differences in the performance measures.

The values of $\overline{T}^{in}_{load}$ showed an increasing differences between the two SRM types together with an increasing retrieval rate λ_{out}. The overall $\overline{T}^{in}_{load}$ differences between the two SRM types varied from 14% to 66% depending on the system configuration and the retrieval rate λ_{out} where systems operate at $U_{SRM} \leq 0.9$.

In addition to the performance analysis, the multiple regression models for system performance measures $\overline{T}^{in}_{load}$ and U_{SRM} were developed in this research, which showed the best fit for the regression criteria (for all regression models $R^2_{adj} > 0.83$) and satisfied regression assumptions. Models provide a tool for system designers, which allows the prediction of performance measures for different combinations of parameters SRM, l_{IO}, N_{IO} and λ_{out}.

The investigations presented in this paper showed that the number and position of the I/O locations have a significant impact on the C-AS/RS performance and suggested that the research should be extended by considering more system parameters. It is essential to investigate the impact of the vertical motion and rotation parameters, LHD load transfer on/off time, number of LHDs on the SRM, rack size and SRM routing algorithms on the system performance as the next stage of the research.

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