Simulationstudy of *Autostore*-systems

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Robot-based compact storage and retrieval systems (RCS/RS) such as the Autostore-system are fully automatically operated by robots from above. The goods are stored in plastic bins that are stacked on top of each other, applying the 'Last-In-First-Out' storage strategy within each stack. This ensures very high degrees of space utilization compared to other storage systems. RCS/R-systems can typically be found in e-commerce or pharmaceutical industry, but also in the food or the spare parts trade. If containers located further down are required, the robots relocate them. Besides the system parameters, there are many other factors, such as the number of used robots or picking stations, that influence the system behavior. With a discrete event simulation (DES) in the Simio simulation program, insights into design variants and operating modes were gained.

Keywords: *RCS/RS, automated small-parts warehouse, goods-to-person-picking, discrete event simulation, tier-captive autonomous vehicle*

1. INTRODUCTION AND PROBLEM DEFINITION

The COVID-19 pandemic and the closing of the stationary trade accelerated the unstoppable rapid trend towards e-commerce [1]. Therefore, the supply chain must interact perfectly in the background. Within a few minutes of the order being placed, the goods have to be picked, packed and dispatched. Especially in the e-commerce sector, but also in the health care or in the food trade, such processes are increasingly being handled with fully automatic small parts storage systems (RCS/RS) as it can be seen in Figure 1 below. These systems are operated fully autonomically by robots from above and store goods in plastic containers stacked onto each other [2,3].

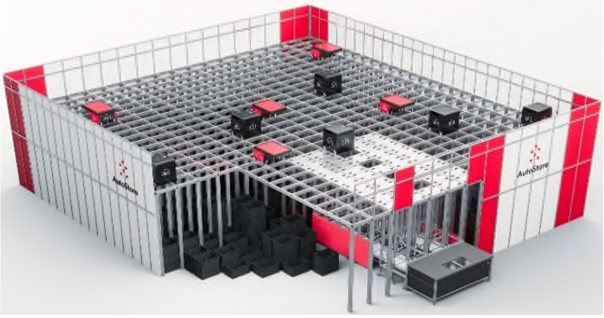

Figure 1: *Autostore*-system [2]

Such storage system were invented 20 years ago. This, on the one hand, explains the very small number of scientific papers about the topic, but, on the other hand, justifies the detailed treatment, especially since over 850 systems are already in operation worldwide [2]. Another reason for the absence of literature is the fact that there are only two manufacturers worldwide – *Autostore* from Norway and *Ocado* from the UK. They both use a similar technology and adhere to a strict secrecy of all data. There is little to no information about the throughput or the cycle time of such systems. Which influencing factors occur and how do they affect each other? How does the number of robots used have an impact on the throughput? When do the robots interfere with each other?

Based on the literature research and the previous scientific examination of such storage systems, there is a research gap regarding a comprehensive, manufacturer-independent investigation of the system. In addition, the behavior of the robots on the storage grid has not been examined in any publication so far in order to calculate or numerically approximate the limit throughput of such systems. This gives rise to the following research questions:

- How are RCS/R-systems structured, which parameters influence the system behavior and how?
- How does the number of robots used for a specific warehouse size affect the throughput?
- What are the interferences between the vehicles on the grid?

This paper aims at giving a literature review (chapter 2) and a functional description of RCS/R-systems (chapter 3). Based on this, in chapter 4, a simulation will be developed in order to gain insights into possible design variants and operating modes to be presented in chapter 5 of this paper.

2. LITERATURE REVIEW

This part will give an overview of the few existing literature and scientific publications on this subject. In particular, investigations into throughput and analytical calculations or simulations of such storage systems were sought.

Ten Hompel et al. [4,5] were, beside Wehking [6], the first who mentioned RCS/R-systems in a relevant logistical volume and gave an overview about the used technology and the advantages such as high efficiency, flexibility and modularity. Zou et al. [7], Beckschäfer et al. [10] and Galka [10,11] all developed a discrete event simulation to gain statements about the system but none of them published general information about RCS/R-systems such as the maximum throughput or maximum number of robots on the grid.

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Zou et al. [7] explored chaotic and sorted warehouse strategies in order to gain the optimal length-to-weight ratio and stack height. They also developed an analytical calculation using a semi-open queuing network (SOQN). This was done under the assumption of numerous simplifications and introducing a "wall parameter". Mutual hindrances of the robots were not further considered since the number of robots was small in relation to the grid. The central statement of the investigation was that the costs for the sorted warehousing - which is atypical for RCS/RS - can be twice as high as with the chaotic strategy, especially since sorting would reduce the great advantage of the high degree of space utilization. The sorted system has a significantly higher handling capacity, since relocations are minimized or entirely eliminated [7].

In their research, Beckschäfer et al. [8] focused on warehousing strategies and whether a new product should be stored in an empty container or an already with the same product partially filled container should be removed from storage in order to store the new stock item. Besides a fixed number of picking stations, only warehouse filling levels of around 50 percent and a constant stacking height of 13 containers were considered [8].

Galka et al. [10] carried out a user study among 64 *Autostore*-system users and provided general results on grid sizes in operation, the number of robots and picking stations used, shift models and order items per hour. Based on this, the authors formed ratios such as the number of robots per grid size or the number of stacks, the number of picking stations per grid size or the number of robots per picking station. Questions about the handling capacity of the systems, the number of relocation processes, warehousing strategies, or robot routing were not addressed [10].

One year later, Galka et al. [11] published the most relevant paper for this study, which contains the development of a simulation in collaboration with a cooperation partner to determine the influence of the robots on the system performance. Different probabilities of access to the stacking levels represented the parameters of the investigation, in addition to the variation in the number of picking stations and robots. The stacking height as well as the grid size, the type of robot and picking station were regarded as fixed. As expected, the highest throughput rates were achieved with the access probability that required the fewest transfer processes. It could be found that the marginal productivity of the vehicles on the grid depends on many factors. In addition, in a specifically defined system, the question of how the help of another robot affects handling performance was investigated. Finally, the authors advised to contact material handling suppliers for further information on system performance because of the great variety of parameters [11].

Another publication that has to be mentioned is from Arnold and Furmans [12]. They deal with the "design of conveyors with several independently operable individual vehicles", such as forklifts, stacker cranes, shuttles or robots on the grid. Their primary target was to find the technically and economically optimal use of these vehicles. As a method for precise analysis, they suggest conducting a numerical simulation, the results of which could be confirmed by an analytical approach using the queuing theory. In any case, increasing the number of vehicles "beyond a level that is compatible with the system concept" leads to obstructions and blockades among the vehicles. If the optimum, as shown in Figure 2, is exceeded, the throughput declines [12].

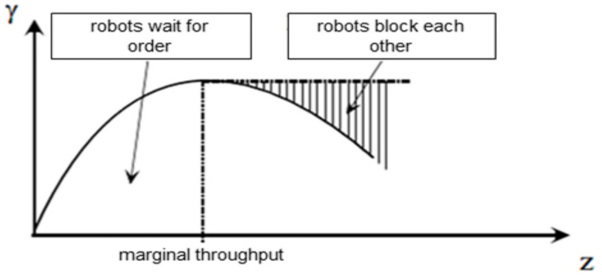

Figure 2: Marginal throughput [12]

3. DETAILED SYSTEM DESCRIPTION

First of all, the advantages of an RCS/R-system shall be explained:

- simple, modular design
- flexible expandability
- high storage density
- high system reliability (high redundancy)
- high energy efficiency
- operated fully autonomously by robots
- goods-to-person picking
- business-independent applicability

3.1 Modules

Beside the controller, RCS/R-systems consist of four main components:

Storage grid:

The grid is built out of bolted aluminium or steel profiles and serves as an orthogonal rail network for the robots and a grid division for the storage containers. There are no restrictions regarding the size of the grid or the length-to-width ratio. The height of the storage grid is based either on the height of the hall or, if the maximum technical height is possible, on the maximum number of plastic containers that may be stacked on top of each other. This depends on the type of the container [2,5].

Robot:

The robot is battery operated and has eight wheels (four in each direction); four of them can be raised or lowered to allow the robot to move in a specific direction. A change of direction takes a certain amount of time. Minimizing the number of direction changes per cycle could be helpful to maximize the throughput. This also minimizes the frequency of acceleration and breaking for each storage cycle. Almost all vehicles available on the market have energy recovery systems [2,3]. To pick up a container, the robot consists of a angle profile frame with four strands of ropes. This mechanism is also used to lower / to raise the container down/up onto/from the stack. The cell dimension of the robot defines the area that the robot itself requires due to its geometry. While the base area of older series usually extends over two storage compartments, newer ones only block one or one and a half grid cells [2,3,5]. In systems which combine different types of robots, the faster ones have to adapt to the slower ones [2].

Container:

Inside the warehouse, the goods to be stored are stacked on top of each other in plastic containers. This results in a technically conditioned maximum stacking height of the containers. The dimensions of the containers are 600 x 400 millimeters. In terms of height, there are variants from 200 to 425 millimeters. This results in filling volumes of around 45 to 100 liters. The containers can also be divided to store different stock keeping units (SKU) [2,3].

Picking station:

The picking station - also known as the port - connects the grid level with the picking area in front of the storage system. In general, a distinction can be made between ports with and without container lift. In the latter system, the container is lowered by the robot with the help of the rope-based lifting mechanism. A picking station can be used only for storage, only for retrieval, but also for storage and retrieval. Some systems are operated at the picking stations in such a way that immediately after a storage item has been removed, another object is stored in the same container [2].

3.2 Functional description

The functional process in an RCS/R-system will now be presented and described from storage to retrieval.

Storage process:

The storage system is operated fully autonomously by the robots from above. If a new tote has to be stored, it is placed in a container at the picking station. As soon as a robot is available, the container is lifted onto the grid level either by the robot itself or by the lift of the picking station. Figure 3 depicts the storage process:

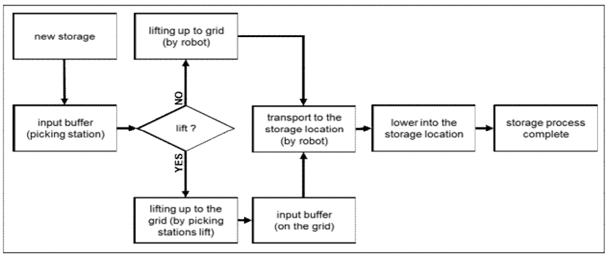

Figure 3: Storage process

After the transport of the container to the assigned storage location has been carried out by the robot, the storage process is complete. Different storage strategies can be used to allocate the storage location. Many systems work with a completely chaotic storage strategy or with the requirement that the next free storage location must be approached. Other strategies could be zoning, partially sorted storage according to certain criteria or same type of totes for each stack.

Retrieval process without relocation:

If a container is required for retrieval and its direct access - without the relocation of other containers - is possible, a robot picks it up from the corresponding storage location and transports it to the assigned picking station. Figure 4 illustrates the process of the relocation:

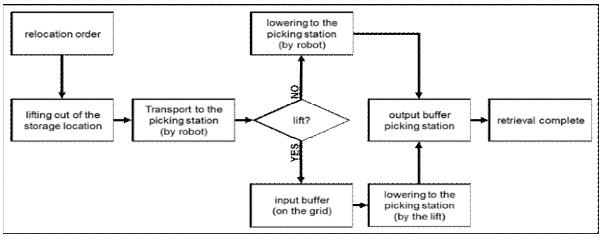

Figure 4: Retrieval process without relocation

Retrieval process with relocation:

In contrast to retrieval with direct access to the required tote, all containers that are stacked above the requested container must be relocated. Figure 5 shows the process of retrieval with necessary relocations:

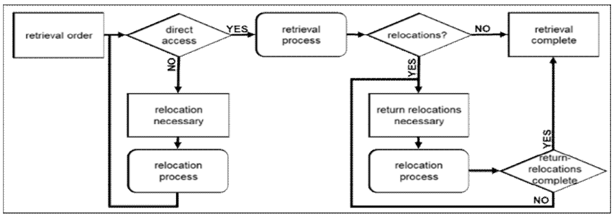

Figure 5: Retrieval process with relocations

The containers to be relocated are moved to the nearest storage locations. The aim should always be that the containers to be relocated can be lowered as quickly as possible, so grid elements with low stacking heights must be excluded. After the retrieval has been completed and the removed container has been stored again after the required storage goods have been removed, there are systems that also carry out return-relocations. This means that one or more robots return-relocate the containers that were previously relocated back into the original stacking order. Among other things, the article distribution and the access structure can influence this.

3.3 Definitions

Based on the system described in chapter 3.1 and 3.2, general definitions for RCS/R systems according to Figure 6 are made below:

- **Article in stock:** The article that is stored “customer-anonymously” in the warehouse and appears in the inventory data [13]
- **Buffer:** Used as equalization storage space, to bridge time or for pre-picking (usually next to the picking station, can speed up multiple picking orders per commission, but minimizes the storage density) [13]
- **Cell dimension:** The area that a *robot* needs for its basic dimensions
- **Container:** Corresponds to the storage unit [13]
- **Container lift:** Lift to lower down/lift up the *containers* from/to the *grid level* to/from the *picking level*; if the *picking station* has a *lift*, it moves in the *I/O shaft*

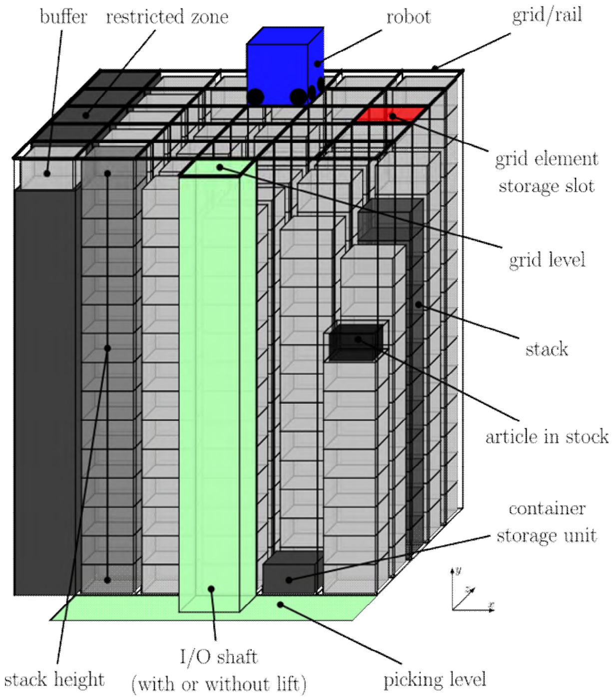

Figure 6: Definitions for RCS-R-systems

- **Grid:** Rail system for the *robots* and the *grid* division for the *containers* of the *stack*
- **Grid level:** *Robot* driving level
- **Grid element:** That sub-element of the *grid* in which the corresponding *container* is stored on the *stack*
- **I/O shaft:** The shaft that connects the *grid level* with the *picking level*; the *robots* can lower or lift the *containers* through this shaft
- **Lifting mechanism:** The angle profile frame lowered by four strands of rope, which can pick up and set down the *containers*
- **Picking station:** Workplace, where the picking takes place
- **Picking level:** The level of the warehouse, where picking takes place
- **Restricted zone:** Those *grid elements*, in which no *containers* may be stored; *robots* are allowed to drive on them (usually in front of the I/O-shaft, prevents blockades, but minimizes the storage density)
- **Robot:** Rail-guided driverless transport vehicle on the *grid*, which can pick up and set down the *containers* with the help of the *lifting mechanism*
- **Stack:** *Stack* of *containers* within a *grid element*
- **Stack height:** Number of *containers* that are stacked on top of each other (within a *grid element*)

4. DISCRETE EVENT SIMULATION

To estimate the maximum throughput of an RCS/R-system with sufficient accuracy, a discrete event simulation was developed in the program Simio. The simulation model (figure 7) represents a system on which up to six robots can store, retrieve and, if necessary, relocate the containers. If a new storage unit arrives, it is transported to the grid level by the lift of the picking station. On the grid level, a free robot takes over the new container and transports it to the assigned stack. There, the robot lowers the container onto the stack, which is implemented in the simulation model by a variable transfer time that depends on the stack height and the lowering speed.

A container to retrieve is generated randomly. As soon as a storage unit has to be retrieved, a robot is assigned to pick it up. If direct access is not possible, all containers stored above are first moved to neighboring stacks. The storage unit to be retrieved is transported to a picking station by the robot and then handed over to the lift, which transports the container down to the pre-storage zone. The robot then picks up a new container that has to be stored. The geometric and kinematic data that are used as input variables in the simulation are listed below:

Grid:

number of stacks ……………….n_{Stacks} = 225
division lateral………………….Δx = 700 mm
division longitudinal…………....Δz = 500 mm
degree of filling………………....f = 10% to 98%
stack height……………………..sh = 10 to 22

Robot:

cell dimension…………………..R_{cell} = 1 cell
number of robots……………….n_{Robots} = 1 to 6
velocity………...……………….$v_{x/z}$ = 4.0 m/s
locking and unlocking time ……$t_{V/E}$ = 1.0 s
lifting speed……..……………….v_y = 1.6 m/s
lowering speed………………..…v_y = 1.6 m/s

Container:

container lenght…………………L_C = 650 mm
container width………………….W_C = 450 mm
container height…………………H_C = 425 mm

Picking station:

number of stations……………….$n_{Station}$ = 1 to 3
buffer grid level………………….$n_{GridBuffer}$ = 1 each
buffer picking station…………….$n_{PickingBuffer}$ = 1 each
exchange time……………………$t_{Exchange}$ = 2 s
lift speed…………………………v_{Lift} = 2.5 m/s

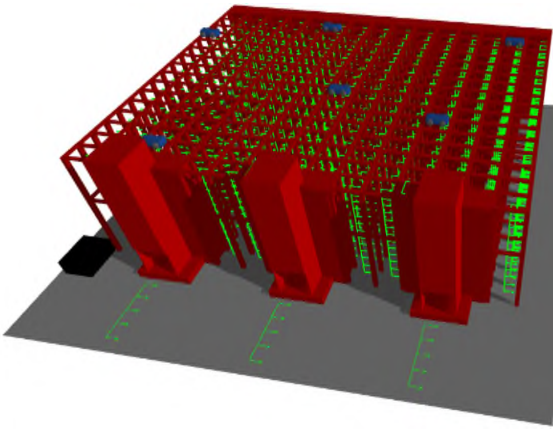

Figure 7: Simulation model of an RCS-R-system

The focus of this paper is on order-related picking operations. Both the robots on the grid and the lifts of the picking stations work in a double command cycle. Thirty replications were carried out for each scenario. The simulation is based on the following assumptions:

- An entity is both a container and a stock item (no item structure, etc.).
- Storage is chaotic; No pre-sorting or zoning is carried out.
- The work done by a picker at the picking port is not subject of this work and not considered.

Different scenarios can be evaluated with this model regarding the following six aspects:

- variation in the number of stacks
- variation in the number of ports
- variation in the number of robots
- variation in stack height
- variation of the degree of filling

5. RESULTS

The simulated system comprises six robots and three picking stations, including a lift working in a double command cycle, and a storage size of 225 stacks (15x15). Figure 8 shows the throughput as a function of stack height (sh) and filling degree (f) of the storage system. The throughput is inversely proportional to the degree of filling and the stack height. It can be seen that for practical filling degrees of 75 to 95 percent, around 100 to 160 containers are stored and retrieved per hour. The fuller the warehouse is and the higher the containers are stacked, the less throughput can be achieved. This can be attributed to the increased need for relocation processes.

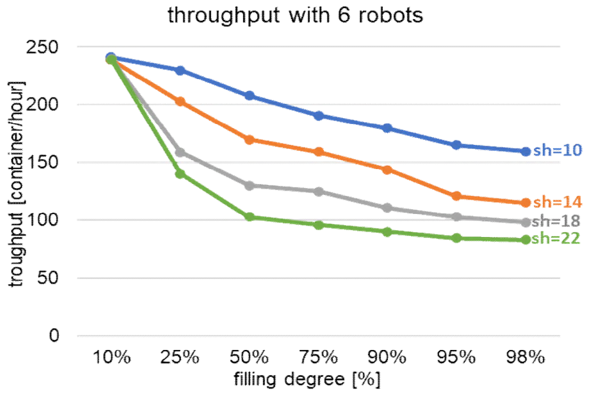

Figure 8: Throughput with 6 robots and 3 stations

The frequency of relocations, therefore, has the greatest influence on the throughput of a system like this. Figure 9 visualizes the number of relocation processes that are necessary to outsource 2,500 containers. As expected, the most relocations are required, when the containers are stacked highest. In very full warehouses, an average of four to twelve containers has to be relocated to retrieve one container, depending on the stack height. In the course of relocations in particular, many robots are often on the move in a very small area of the grid. This may cause obstacles between the robots.

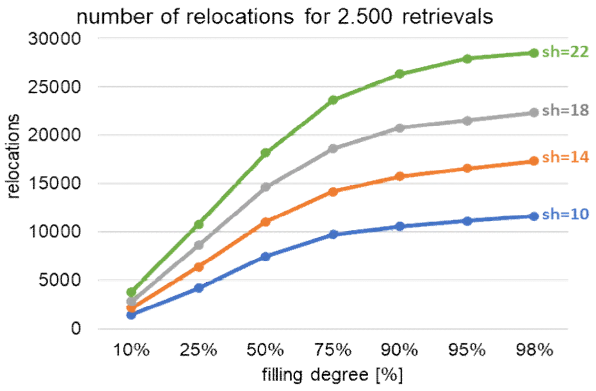

Figure 9: Number of relocations (6 robots, 3 stations)

In the following, based on the described basic model with six robots, the limits of RCS/R-systems will be further explored. For this purpose, the number of robots on the grid is reduced to three. In addition, only the practice-relevant filling levels of 75, 90 and 95 percent are considered. Figure 10 compares the troughput of the system between three and six robots used on the grid:

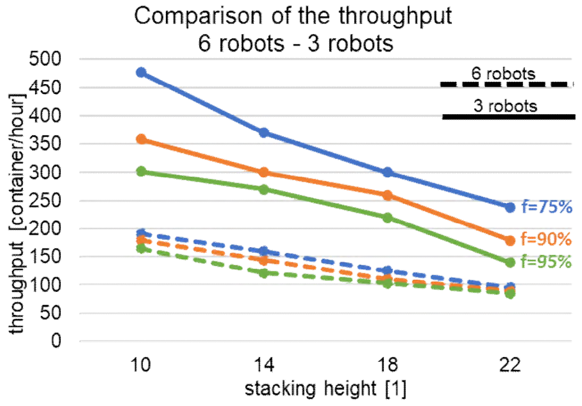

Figure 10: Throughput comparison (3 and 6 robots)

It can be seen that the throughput is more than twice as high with three instead of six robots, which confirms the assumption that - due to a lack of moving space - obstacles between the robots lead to deadlocks and make a higher throughput impossible.

In order to find out how large the optimal number of vehicles used is, it is variied between one and six. Figure 11 confirms qualitatively what was assumed by figure 2 [14]:

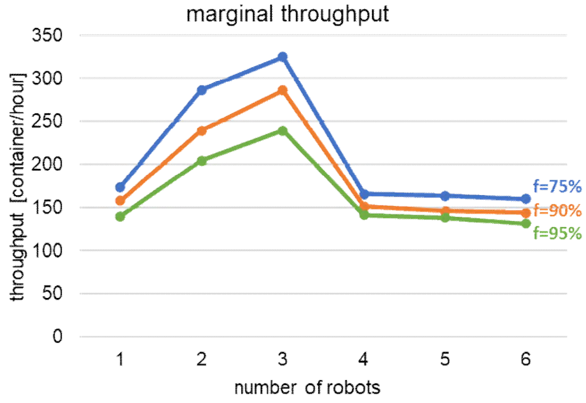

Figure 11: Marginal throughput of RCS/RS

The optimum here is three robots. This confirms the assumption that six robots are too many for this grid size. It should be mentioned at this point that 15 grid elements per direction must be considered as rather small compared to real systems. Regarding the number of robots on the grid, 750 to 1,000 containers or around 75 storage locations per robot should be good benchmarks. This confirms both the study by Galka et al. [12] and a system research carried out by the author of this paper, which is still in progress, according to which a robot serves between 500 and 1,000 containers.

In real operation, maintenance and loading times must also be considered. Depending on the stack height, a robot is used for a grid section of 50 to 100 stacks.

6. CONCLUSION

Expanding online trade and increasing demands on the supply chain are just 2 arguments why RCS/R-systems have been used more and more in recent years. The number of systems worldwide is constantly increasing. There are hardly any valid and general statements on handling performance and cycle time. In the few existing scientific discussions, mostly specific system states were considered, which are either simplified or did not examine all influences independently. This paper provides a lot of parameters and influences that affect the system. It investigates where the maximum throughput for a given grid size is. In addition, a guide value regarding the stacks per robot from empirical system research was confirmed with the help of the discrete event simulation.

Prospectively, simulations with larger grid dimensions and optimized robot routings are to be investigated. Using different article structures or other parameter variations and combinations could provide further insights into the warehousing strategies of RCS/R-systems. In addition, an analytical calculation of RCS/RS to calculate the cycle time and the throughput should be developed to validate the numerical simulation and to identify optimal operating conditions on the one hand, and to be able to make comparisons with other storage systems, such as shuttle systems, on the other hand.

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NOMENCLATURE

Δx	division lateral
Δz	division longitudinal
f	filling degree
$n_{GridBuffer}$	number of buffers grid level
$n_{PickingBuffer}$	number of buffers picking station
n_{Robots}	number of robots
n_{Stacks}	number of stacks
$n_{Station}$	number of pickingstations
R_{Cell}	robot cell dimension
sh	stack height
$t_{Exchange}$	container exchange time
$t_{V/E}$	locking and unlocking time
v_{Lift}	lift speed
$v_{x/z}$	robot speed
v_y	lifting and lowering speed