Simulation Study of *RCS/R*-Systems with Several Robots Serving One Picking Station

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Robot-based compact storage and retrieval systems (RCS/RS) are fully automatic storage systems operated by robots from above. Therein, goods are stored in plastic bins stacked on each other, resulting in a 'Last-In-First-Out' storage strategy within each stack. This ensures very high degrees of space utilization. If containers located further down the stack are required, the robots relocate those stored above the required one. RCS/R-systems can typically be found in e-commerce, the pharmaceutical industry, and food or spare parts trade. Besides the system parameters, many other factors, such as the number of robots or the grid size, influence the system's behavior. This paper focuses on the system's throughput and the optimum number of operating robots. A discrete event simulation (DES) in the SIMIO simulation program gained insights into design variants and operating modes.

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 stationary trade's clo–sing accelerated the unstoppable trend toward e-com–merce [1]. Therefore, the supply chain must function perfectly in the background. The goods must be picked, packed, and dispatched within a few minutes of placing the order. Especially in the e-commerce sector and health care or food trade, such processes are increasingly handled with fully automatic small parts storage systems (RCS/RS), as shown in Figure 1 below. These systems are operated by robots from above, storing goods in plastic containers stacked onto each other [2,3].

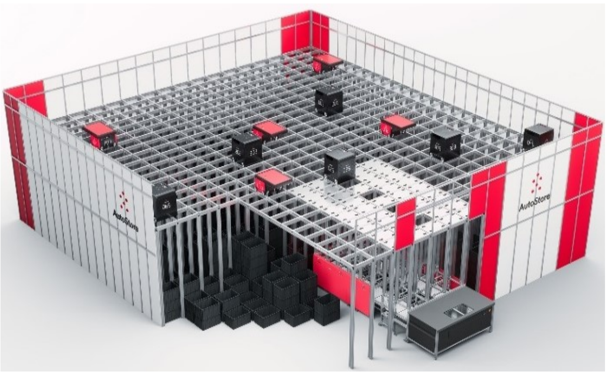

Figure 1. *Autostore*-system [2]

Although such storage systems were invented 20 years ago, there is only a minimal number of scientific papers about the topic. This justifies the detailed treat–ment in this paper, especially since over 850 systems are already in operation worldwide [2]. Another reason for the absence of literature is that there are only two manufacturers worldwide – *Autostore* from Norway and *Ocado* from the UK. They both use similar technology and adhere to strict secrecy of all data. There is little information about such systems' throughput or cycle time. 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 and where do the robots interfere with each other?

Based on the literature research and the previous scientific examination of such storage systems, there needs to be more research regarding a comprehensive, manufacturer-independent system investigation. In addition, the robots' behavior on the storage grid has yet to be examined to calculate or numerically approximate the throughput limit of such systems in any publication so far. This gives rise to the following research ques–tions:

- How are RCS/R-systems structured? Which parameters influence the system behavior and how?
- What can possible throughput be achieved by one operating robot?
- How big is the influence of the relocations?
- How does the throughput depend on the parameters
  - number of operating robots,
  - grid size,
  - stack height and
  - filling degree?

This paper aims to give a systematic literature review (Chapter 2) and a functional description of RCS/R-systems (Chapter 3). Therein, several influences shall be discussed. Based on this, in Chapter 4, a simulation model will be developed to gain insights into possible design variants and operating modes to be presented in Chapter 5 of this paper.

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2. LITERATURE REVIEW

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

Scientific research on automatic storage systems (AS/RS) generally has a long history. It started in the '70s of the last century with AS/RS with one S/R machine. While shuttle-based storage systems (SBS/RS) were first installed at this point, RCS/R-systems such as the Autostore system were unknown. Kartnig et al. [4] did a historical review and discussed megatrends and their impact on the future of storage systems. High performance, good scalability, high redundancy, autonomous vehicles, and high space utilization were just a few attitudes describing a modern storage system. Nevertheless, RCS/R-systems combine all of those advantages mentioned above.

Ten Hompel et al. [5,6] were, beside Wehking [7], the first who mentioned RCS/R-systems in a relevant logistical volume and gave an overview of the used technology and the advantages such as high efficiency, flexibility, and modularity. Zou et al. [8], Beckschäfer et al. [9], and Galka [10,11] all developed a discrete event simulation to gain information about the system. Still, no published general information about RCS/R-systems, such as the maximum throughput or number of robots on the grid.

Zou et al. [8] explored chaotic and sorted warehouse strategies 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 nume–rous 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 size. 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 considerably higher handling capacity since relocations are minimized or eliminated.

In their research, Beckschäfer et al. [9] focused on warehousing strategies and whether a new product should be stored in an empty container or a container that has already been partially filled with the same product should be removed from storage to store the new stock item. Besides a fixed number of picking stations, only warehouse filling levels of around 50% and a constant stacking height of 13 containers were considered.

Ko et al. [12] proposed a roll-out heuristic algorithm to find the optimal order sequencing within an RCS/RS.

Tjeerdsma [13] developed a multi-scenario discrete event simulation to redesign an order-processing line for the Dutch post. Hameed et al. [14] developed a numerical performance calculation approach using an optimal path algorithm for robot routing and analyzed the impact of a collision avoidance system. For one specific testing scenario, the total throughput decreased by around 10% with the consideration of obstacles compared to neglecting them.

Galka et al. [10] conducted 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 maximum number of robots per number of stacks, the number of picking stations per number of stacks, 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 still needed to be addressed.

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 number of robots on the system performance. The stacking height, grid size, robot type, and picking station were regarded as fixed. Different probabilities of access to the stacking levels represented the parameters of the investigation and the variation in the number of picking stations and robots. As expected, the highest throughput rates were achieved with the access probability that required the fewest relocation processes. The marginal productivity of the vehicles on the grid depends on many factors. In addition, in a precisely defined system, the question of how the help of another robot affects handling performance was investigated. Finally, the authors advised contacting material handling suppliers for further information on system performance because of the various parameters.

Chen et al. [15] investigated overhead RCS/RS (ORCS/RS) with overhead cranes ("bridge cranes") using dedicated and shared storage policies within the stacks and zoning within the warehouse by numerical discrete event simulation.

Trost et al. [16] also developed a discrete event simulation to determine the optimal number of robots operating on the grid of an RCS/R-system. The grid size was not varied, and the maximum number of robots was six. Moreover, a precise German definition of the investigated system vocabulary was made.

Since SBS/RS are in some points similar to RCS/RS, the performance calculation for RCS/RS could use at least some approaches from SBS/RS. Kosanic et al. [17] did a comprehensive literature review on SBS/RS and pointed out different performance estimation models and control strategies besides a system description.

Eder et al. [18, 19]developed an analytical approach using the queuing theory to determine the throughput of one aisle of an SBS/RS. Therein, the dynamic interaction between the lift and the shuttles was represented appropriately. His estimation was verified and validated by a numerical simulation (DES).

Besides several SBS/RS performance calculations, Lerher also discussed the effectiveness of storage strategies. Lorenc and Lerher [20]investigated its impact on cycle time.

Rajkovic et al. [21] developed a multi-objective optimization model to minimize the cycle time.

Another publication that has to be mentioned is by Arnold and Furmans [22]. 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 these vehicles' technically and economically optimal use. They suggest conducting a numerical simulation as a method for precise analysis, which could confirm an analytical approach using the queuing theory. In any case, increasing the number of vehicles "beyond a level compatible with the system concept" leads to obstructions and blockades among the vehicles. The throughput declines if the optimum number is exceeded, as shown in Figure 2.

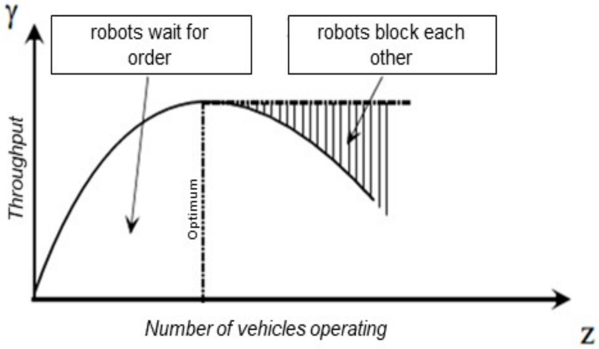

Figure 2. Marginal throughput [22]

As can be seen, the scientific research on RCS/RS just started a few years ago and has multiple open issues. A short excursion to already more investigated SBS/RS shows that the research gap can be split up into three main categories:

- system design
- system performance
- system control

This paper provides a thorough system description and a simulation study determining the system's performance with an extensive parameter variation.

3. DETAILED SYSTEM DESCRIPTION

First of all, the advantages of an RCS/R-system shall be listed [16,23]:

- Simple and modular design
- Scalability
- Flexible expandability
- High storage density
- Low demand for space
- High system reliability (high redundancy)
- High energy efficiency
- Operated fully autonomously by robots
- Goods-to-person picking
- Business-independent applicability
-

3.1 Modules

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

Storage grid:

The grid is built out of bolted aluminum 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 grid size or length-to-width ratio. The height of the storage grid is based either on the height of the hall or on the maximum number of plastic containers that may be stacked on top of each other. This depends on the type of container [16,23].

Robot:

The robot is battery-operated and has eight wheels (four in each direction); four 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 is helpful to maximize the throughput. This also minimizes the frequency of accelerations and brakings for each storage cycle. Almost all vehicles available on the market have energy recovery systems. The robot uses an angle profile frame with four strands of ropes to pick up a container. This mechanism is also used to lower/raise the container down/up onto/from the stack. The robot's cell dimension defines the space the robot requires due to its geometry. While the base measure of older series usually extends over two grid elements, newer ones only block one or one and a half. In systems that combine different types of robots, one must adapt faster to the slower ones [16,23].

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) [16,23].

Picking station:

The picking station in front of the warehouse - also known as the port –is connected to the grid level by the I/O-shaft. There are ports with and without container lifts. 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 so that another object is stored in the same container immediately after a storage item has been removed [16,23].

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 article 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 [16]. Figure 3 depicts the storage process.

After the robot has transported the container to the assigned storage location, 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 require the next free storage location to be approached. Other strategies could be zoning, partially sorted storage according to specific criteria, or the same type of articles for each stack [16,23].

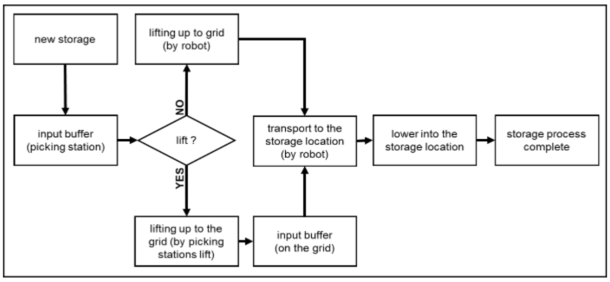

Figure 3. Storage process [23]

Retrieval process without relocation:

Suppose a container is required for retrieval, and its direct access is possible without relocating other contai–ners; a robot picks it up from the corresponding storage location and transports it to the assigned picking station. Figure 4 illustrates the process of retrieval [16,23]:

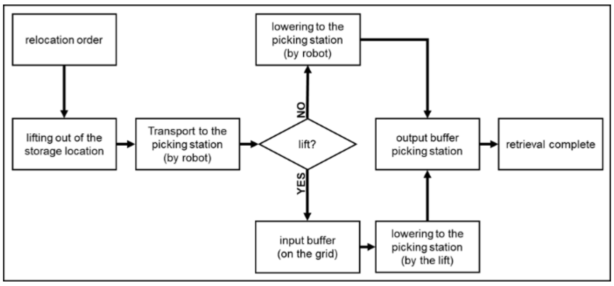

Figure 4. Retrieval process without relocation [23]

Retrieval process with relocation:

In contrast to retrieval with direct access to the re–quired container, all the others stacked above the requ–ested container must be relocated [16,23]. Figure 5 sho–ws the process of retrieval with necessary relocations:

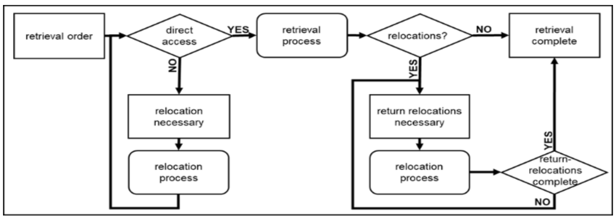

Figure 5. Retrieval process with relocations [23]

The containers to be relocated are moved to other storage locations. Thereby, several strategies can be applied. The aim should always be that the total amount of time required for this is minimized. Thus, each relocation must solve a complex time-window-based optimization problem with the input factors direction, distance, velocity-, acceleration-/ deceleration rate, and wheel-exchange time independently [16,23].

Figure 6 demonstrates the storage, relocation, and retrieval process. The red container in the I/O-shaft located at the front edge has to be stored in the red grid element on the left edge. Therefore, the robot moves to the I/O-shaft, lifts the red container, and transports it to the assigned storage stack. The storage process is finished when the container is lowered onto the stack.

The system assigns the stack on the right side in the second row for relocation. Afterward, the orange conta–iner is required at the picking station because of a newly arrived order to fulfill, so the orange one has to be retrieved and lowered through the I/O-shaft. This can only be done when the yellow container is relocated abo–ve the orange one. Only now can the retrieval be done.

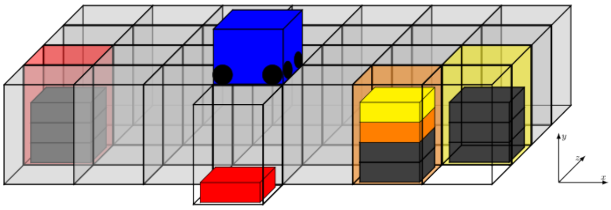

Figure 6. Storage, relocation, and retrieval process

After the retrieval, some systems also carry out return relocations. This means the robot return-relocates the previously relocated containers into the original stacking order. In the case of Figure 6, the yellow container would be return-relocated after retrieving the orange one. Among other aspects, the article distri–bution and access structure can influence the strategic decision of whether return relocations are carried out.

3.3 Definitions

Based on the system described in Chapters 3.1 and 3.2, general term definitions for RCS/R-systems and their components, according to Figure 7, are made in alpha–betic order. It illustrates a small section of an RCS/RS.

- **Buffer:** Used as equalization storage space, to bridge time, or for pre-picking (usually next to the *picking station*). It can speed up multiple picking orders per commission but minimizes the storage density [24].
- **Cell dimension:** The area that a *robot* needs for its basic dimensions.
- **Container:** Plastic vessel which corresponds to the storage unit [24].
- **Container lift:** Lift to lower down/lift 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.*
- **Grid:** Rail system for the *robots* and *grid* division for the *containers* of the *stack.*
- **Grid level:** *Robot*movement level.
- **Grid element:** The 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:** In part of the robot, the angle profile frame is lowered by four strands of a rope, which can pick up and lower 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 can move on them

(usually near the I/O-shaft, which prevents blockades but minimizes the storage density).

- **Robot:** Rail-guided driverless transport vehicle on the grid, which can pick up and lower down the containers with the help of the lifting mechanism.
- **Stack:** Stack of containers within a grid element.
- **Stack height:** Number of containers stacked on top of each other (within a grid element).

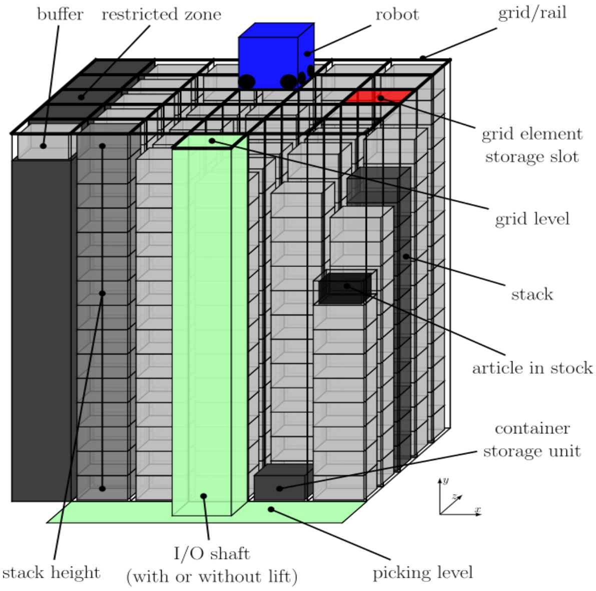

Figure 7. Definitions for RCS/R-systems

3.4 Influencing factors

Based on the description of this section, the throughput of an RCS/RS depends - besides the article distribution - on a large spectrum of influencing factors, which partially also interact with each other.

In general, storage systems are characterized by the following three dimensions:

- Storage capacity
- Warehouse size
- Throughput

It is similar to RCS/RS, as seen in Figure 8. The robots, the picking stations, and the grid size combined with the warehouse strategy and some operation parameters such as the filling degree or the stack height predict the three main variables:

- Storage capacity
- Travel distance
- Cycle time

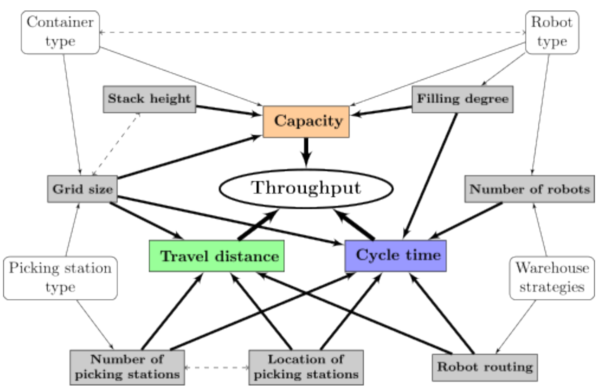

Figure 8. Influencing factors and interaction

The number of picking stations and their location along the edges of the grid has a significant influence on the travel distance and, consequently, on the throughput.

On the one hand, the storage capacity is defined by the grid size and the stack height. Still, on the other hand, the robot types and their container handling and hence the filling degree may reduce the maximum possible storage capacity.

As Figure 8 depicts, many influencing factors, preconditions, and interactions impressively show the complexity of RCS/R-systems.

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 DES program SIMIO. The simulation model (Figure 9) represents a system on which numerous robots can store, retrieve, and, if necessary, relocate the containers. Relating to the functional description (section 3.2), the simulation model imple–mented the processes.

When a new storage unit arrives, it is transported to the grid level by the robot's lifting and lowering mechanism. The robot takes over the new container on the grid level and transports it to the assigned stack. There, the robot lowers the container onto the stack. This is implemented in the simulation model by a variable transfer time that depends on the stack height and the lowering speed.

The order list is generated randomly. A robot is assigned to pick it up as soon as a storage unit has to be retrieved. If direct access is impossible, 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 lowered down through the I/O-shaft to the picking station, where the articles are removed from the container. The robot then picks up a new container that has to be stored. The location of the picking station is always in the middle of one of the wide edges of the grid.

The geometric and kinematic data that are used as input variables in the simulation are listed below:

Grid:

number of stacks ………………n_{Stacks}= 50 to 2,500
number of stacks along x ………n_x = 10 to 50
number of stacks along z ………n_z = 5 to 50
division lateral…………………Δx = 700 mm
division longitudinal…………....Δz = 500 mm
degree of filling………………....f = 10% to 98% (100%)
stack height……………………..sh = 1 to 25

Robot:

cell dimension…………………R_{cell} = 1 cell
number of robots………………n_{Robot}= 1 to 15
velocity………...………………$v_{x/z}$ = 2.0 m/s
locking and unlocking time ……$t_{L/U}$ = 1.0 s
wheel-exchange time …………..t_{WE} = 1.0 s
lifting speed……………………v_y = 1.6 m/s
lowering speed…………………v_y = 1.6 m/s

Container:

container length…………………L_C= 650 mm

container width.....................W_C = 450 mm
container height....................H_C = 330 mm

Picking station:
number of stations..................$n_{Station}$ = 1
location of the station..............k_0=n_x/2
exchange time.......................$t_{Exchange}$ = 5 s

The robots work in a dual command cycle. Thirty replications were carried out for each scenario. The simulation is based on the following assumptions:

- An entity is a container and a stock item (no article structure, etc.).
- Storage is chaotic; no pre-sorting or zoning is carried out.
- Entities to relocate are taken to the closest possible stack with space for another container.
- The work done by a picker at the picking port is not the subject of this work and is not considered.

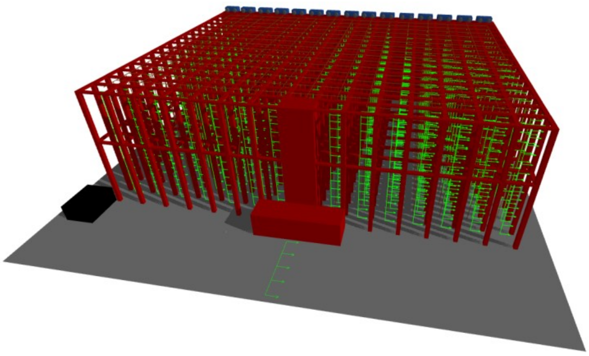

Figure 9. A simulation model of an RCS-R-system

Different scenarios can be evaluated with this model by varying the following parameters:

- number of stacks
- number of robots
- stack height
- filling degree

5. RESULTS

The simulated system comprises up to 15 robots and one picking station with I/O-shaft. The grid size ranges from 50 stacks (10x5) to 2,500 (50x50).

Figure 10 shows the throughput as a function of stack height (*sh*) and filling degree (*f*) of the storage system with one operating robot on a 25 by 25 grid (625 stacks).

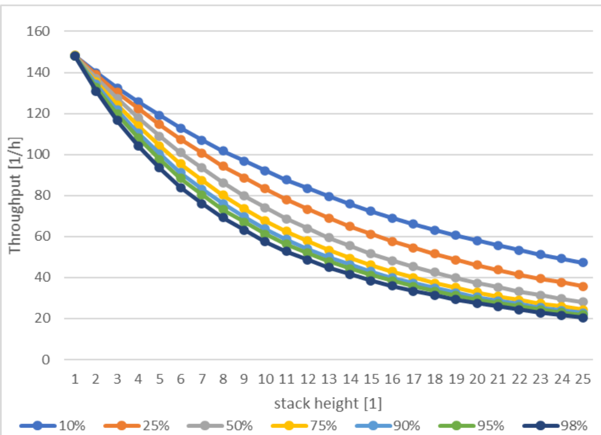

Figure 10. Throughput of one robot depending on the stack height for different filling degrees (grid 25x25)

The throughput is inversely proportional to the filling degree and the stack height. For storage heights between 15 and 25 and practical filling degrees of 75 to 95%, around 20 to 45 containers are retrieved per hour. The larger the warehouse and the higher the containers are stacked, the less throughput can be achieved. This can be attributed to the increased need for relocation processes.

Therefore, the frequency of relocations has the greatest influence on the throughput of a system like this. Figure 11 visualizes the number of relocations that have to be done to retrieve one container.

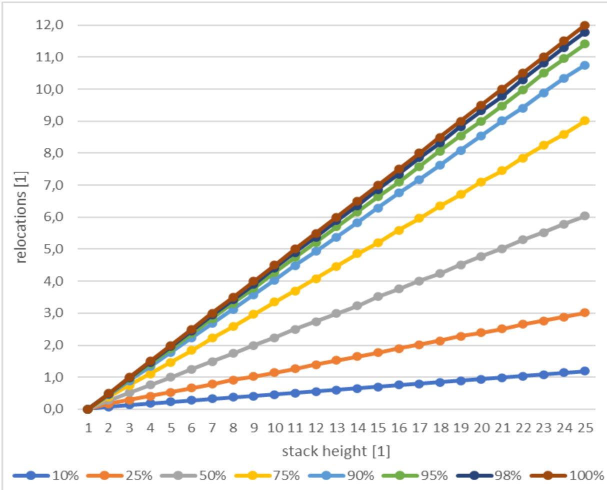

Figure 11. Relocations necessary to retrieve one container depending on the stack height for different filling degrees

As expected, most relocations are required when the containers are stacked highest. The 100% filling degree is plotted theoretically, although some empty storage locations are necessary for relocations. During reloca–tions, many robots are often on the move in a tiny area of the grid. This may cause obstructions between the robots.

In the following, the limits of RCS/R-systems will be further explored based on the described model with one robot. For this purpose, the stack height is set to the value of *sh=16,* and the number of stacks $n_{\ Stacks}$ is between 100 and 2,500. In addition, only the practice-relevant filling levels from 75 to 95% are considered. Figure 12 compares the throughput for different filling degrees in dependence on the number of stacks:

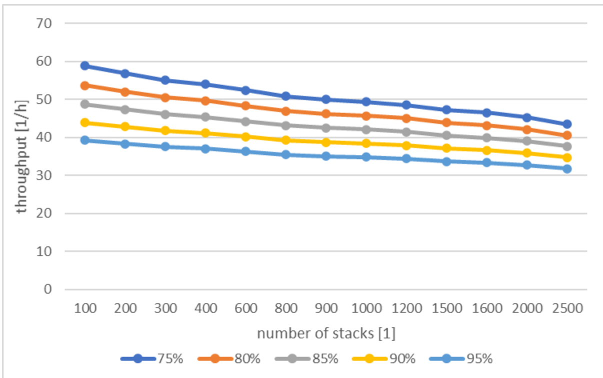

Figure 12. Throughput of one robot depending on the grid size for different filling degrees (sh=16)

It can be seen that the throughput is nearly constant, especially for the highest filling degrees, which leads to the impact of the number of stacks and, thus, the impact of the grid size on the throughput is way smaller than the influence of the stack height. One robot can retrieve between 30 and 40 containers per hour from the storage system with a 95% filling degree.

To reinforce this argument, Figure 13 shows the throughput depending on the stack height for different quadratic grid sizes from 10 by 10 up to 50 by 50. Therefore, the system's filling degree is set to a constant value of *f=90%*. As can be seen, all curves are monoto–nically falling. The largest grid size has the flattest curve.

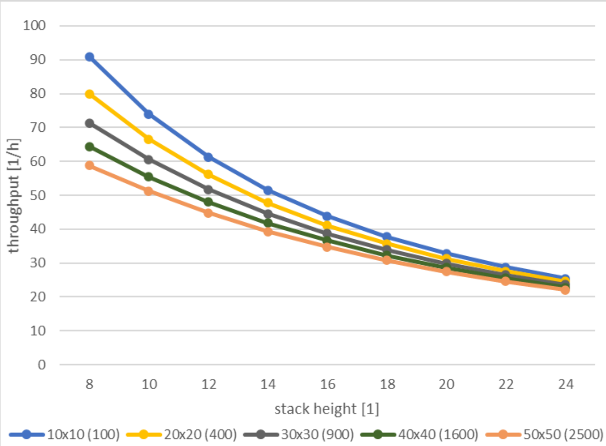

Figure 13. Throughput of one robot depending on the stack height for different quadratic grid sizes (f=90%)

As mentioned above, the stack height influences the throughput noticeably, especially for smaller grid sizes. For example, a stack height of *sh=8* combined with a 10 by 10 grid makes a throughput of 90 totes per hour and a robot theoretically possible.

Figure 14 shows, analogous to Figure 13, the thro–ughput in dependence on the stack height for rectan–gular grid sizes:

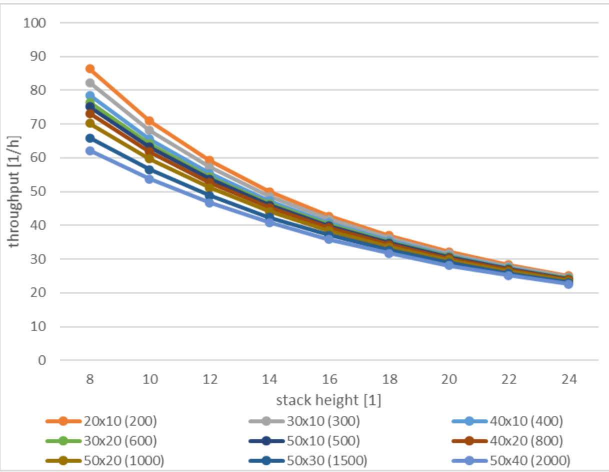

Figure 14. Throughput of one robot depending on the stack height for different rectangular grid sizes (f=90%)

The above diagram's values compared to those from Figure 13 also depict that quadratic grid sizes enable a little higher throughputs for identical stack numbers. As can be seen, the deviation of the through–put between the 40 by 10 grid (Figure 14) compared to the 20 by 20 grid (Figure 13) is about 2 container re-trievals per hour (for a stack height of *sh=8*). This effect is also reduced with increasing stack height due to the influence of the relocations.

All the previous plots displayed the throughput of RCS/R-systems with one robot operating on the grid. The number of robots operating is now increasing. The grid size is fixed to 625 stacks (25x25), with the filling degree to*f=90%*. Figure 15 shows the throughput of an RCS/RS with one picking station and an increasing number of robots for different selected stack heights between 1 and 25.

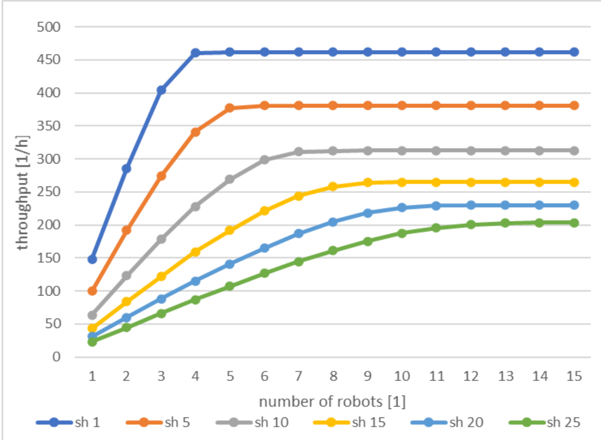

Figure 15. Throughput depending on the number of robots for different stack heights (grid 25x25, f=90%)

Figure 15 depicts that the throughput increases with the number of robots and converges towards a limit value. The limit is given by the time a robot requires at the I/O-shaft. For this paper, the time at the I/O-shaft – also called service time – is the sum of the time for lifting and lowering the container through the shaft, the time for locking and unlocking the old and the new container, and the time for the container exchange (e.g., via a conveyor). This also explains the different limits since the stack height defines the vertical length of the I/O-shaft and hence the required time.

Accompanying this, the question of how extensive the utilization of every single robot arises. Figure 16 exhibits the throughput per robot depending on the number of robots used:

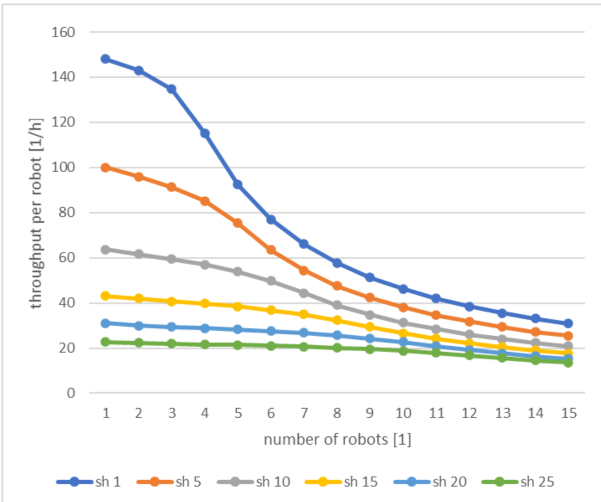

Figure 16. Throughput per robot depending on the number of robots for different stack heights (grid 25x25, f=90%)

As shown in Figure 16, the throughput for all stack heights is monotonically decreasing. It is different and nearly constant for larger stack heights as long as the limit is not reached. This can be explained again by the high number of necessary relocations.

The stack height will be set to a constant and prac–tical realistic value of *sh=25*, and the grid size shall be varied. Figure 17 shows the throughput depending on the number of robots for four different quadratic grid sizes:

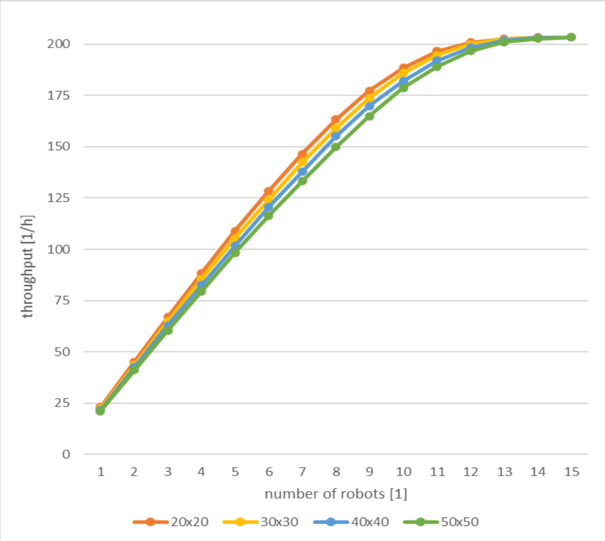

Figure 17. Throughput depending on the number of robots for different quadratic grid sizes (sh=25, f=90%)

As expected, the smallest grid size enables the high-est throughputs, but the deviation between the grid sizes could be much bigger. It can be seen that with 13 to 14 robots operating, a theoretical maximum due to the utilization of the picking station and the I/O-shaft is reached. Adding one more robot to the grid can not increase the throughput. For small grid sizes, it could lead to an obstacle, a blockade, or a dead-lock situation.

Analogous to Figure 17 for quadratic grid sizes, the throughput depending on the number of robots for some rectangular grid sizes are depicted in Figure 18:

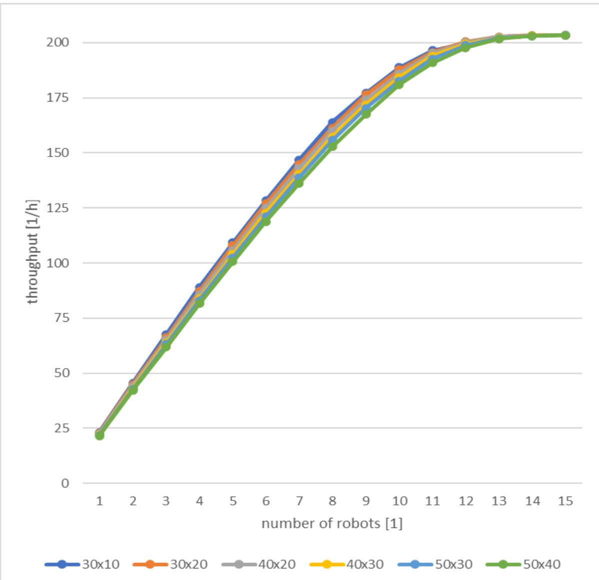

Figure 18. Throughput depending on the number of robots for different rectangular grid sizes (sh=25, f=90%)

Figure 18 shows similar results as Figure 17. The deviation between different grid sizes is marginal.

To close this section, a great variety of applications shall be discussed. Therefore, Figure 19 presents a fore–cast using several picking stations. The blue area repre-sents all the possible configurations between the two limit lines, which describe the throughput depen–ding on the number of robots of a small grid with a low stack height and a large grid with a high stack height.

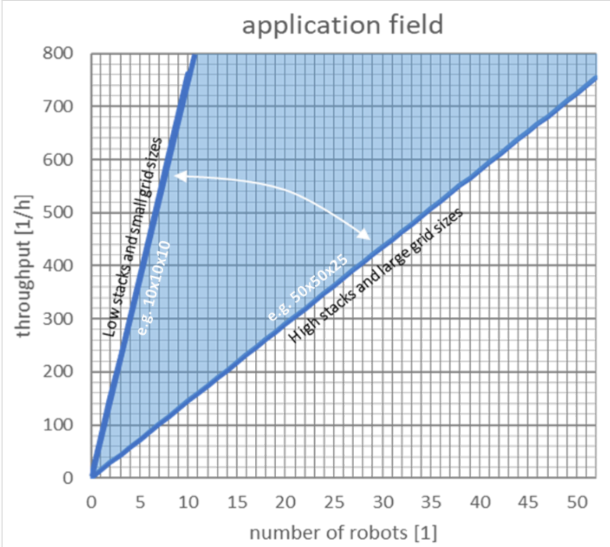

Figure 19. Throughput forecast

6. CONCLUSION

The number of systems worldwide is constantly gro–wing. Expanding online trade and increasing demand on the supply chain are just two reasons RCS/R-systems have been used more and more in recent years. There are no valid general statements on handling perfor–mance and cycle time. In the few existing scientific discussions, mostly specific system states were consi–dered, either simplified or did not examine all influ–ences independently. This paper provides many para–meters and influences that affect the system and eva–luates how they interact. The optimal number of operat-ing robots was determined for different grid sizes, fill-ing degrees, stack heights, and width-to-length ratios. Last, a forecast and a first application field were pre–sented in order to give easy and fast answers to the question of what performance is possible for a specific demand of storage locations.

Prospectively, simulations with optimized robot routings and different storage strategies will be investi–gated. Different class-based storage strategies shall also be tested, and other parameter variations/combinations could provide further insights into warehousing with RCS/R-systems. Also, other but very similar systems shall be investigated to discover their advantages re-garding performance.

An analytical approach of RCS/R-systems to calcu–late the cycle time and the throughput will 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
H_C	container height
L_C	container length
k_0	picking station position
n_{Robot}	number of robots
n_{Stacks}	number of stacks
$n_{Station}$	number of picking stations
n_x	number of stacks along x
n_z	number of stacks along z
R_{Cell}	robot cell dimension
sh	stack height
$t_{Exchange}$	container exchange time
$t_{L/U}$	locking and unlocking time
t_{WE}	wheel-exchange time
W_C	container width
v_{Lift}	lift speed
$v_{x/z}$	robot speed
v_y	lifting and lowering speed

СИМУЛАЦИЈСКА СТУДИЈА РЦС/Р-СИСТЕМА СА НЕКОЛИКО РОБОТА КОЈИ ОПСЛУЖУЈУ ЈЕДНУ БРАНУ СТАНИЦУ

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Компактни системи за складиштење и проналажење засновани на роботима (РЦС/РС) су потпуно аутоматски системи за складиштење којима управљају роботи одозго. При томе се роба складишти у пластичне канте наслагане једна на другу, што резултира стратегијом складиштења 'последњи-први-изишао' унутар сваке гомилице. Ово обезбеђује веома висок степен искоришћења простора. Ако су потребни контејнери који се налазе даље од наслага, роботи премештају оне ускладиштене изнад потребног. РЦС/Р-системи се обично могу наћи у е-трговини, фармацеутској индустрији и трговини храном или резервним деловима. Поред параметара система, многи други фактори, као што је број робота или величина мреже, утичу на понашање система. Овај рад се фокусира на пропусност система и оптималан број робота који раде. Симулација дискретних догађаја (ДЕС) у СИМИО симулационом програму стекла је увид у варијанте дизајна и режиме рада.