RCS/RS under throughput investigation

Georg Kartnig Prof.
Technische Universitaet Wien, georg.kartnig@tuwien.ac.at

Philipp Trost
Technische Universitaet Wien, philipp.trost@tuwien.ac.at

Michael Eder
Technische Universitaet Wien, michael.eder@tuwien.ac.at

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Georg Kartnig
Institute of Engineering Design and Product Development
Technische Universität Wien
Vienna, Austria
https://orcid.org/0000-0001-6780-6146
georg.kartnig@tuwien.ac.at

Philipp Trost
Institute of Engineering Design and Product Development
Technische Universität Wien
Vienna, Austria
https://orcid.org/0000-0002-0419-1612
philipp.trost@tuwien.ac.at

Michael Eder
Institute of Engineering Design and Product Development
Technische Universität Wien
Vienna, Austria
https://orcid.org/0000-0002-4702-6908
michael.eder@tuwien.ac.at

***Abstract*—RCS/RS are fully autonomous by robots from above-operated storage systems. The goods are stored in plastic containers stacked on each other and arranged in a block, which enables high storage densities and low space demand concomitant with the need for relocations to access deeper stored containers. E-commerce, pharmaceutical area, food or spare parts trade are typical application fields for those warehouses. A wide range of parameters, such as the number of robots, the filling degree or the stack height, influences the system's performance. This paper gains insights into the throughput of RCS/R-systems with one operating robot serving one picking station with a discrete event simulation. It presents a parameter variation and a performance estimation forecast for multiple robots.**

Keywords*— *RCS/RS, storage systems, automated small-parts warehouses, goods-to-person-picking, discrete event simulation, logistic simulations, tier-captive autonomous vehicles

I. Introduction

In 2021, only in Germany, more than €100 billion were spent on online shopping. According to the German trade association for E-commerce, this sum is around one-seventh of the total retail sales [1].

Besides the distribution and the delivery to the end customer, which is a huge logistical challenge, the warehouses, the picking process inside and the order assembly before the shipping have to work fast and flawlessly. In most cases, this is only possible by goods-to-person picking processes and automated warehouses such as automated storage and retrieval systems (AS/RS), automatic vehicle- or shuttle-based storage and retrieval systems (AVS/RS, SBS/RS) or robotic compact storage and retrieval systems (RCS/RS).

The selection and design process basically depends on the goods to store, their size and quantity. Small goods can be stored in containers. While SBS/RS enable very high throughputs, RCS/RS distinguish by high storage density, low space utilisation, high redundancy, and easy expandability. Both systems are reliable and energy-efficient.

TABLE I. List of Abbreviations

Abbreviation	***Definition***
AS/RS	Automatic storage and retrieval system
AVS/RS	Automatic vehicle-based storage and retrieval system
DES	Discrete event simulation
FCFS	First come, first served
LIFO	Last in, first out
RCS/RS	Robotic compact storage and retrieval system
SBS/RS	Shuttle-based storage and retrieval system
S/R-machine	Storage and retrieval machine

This research focuses on RCS/RS. Those systems are compact storage systems, where small goods are stored in plastic containers stacked on each other and arranged in a block. Robots operate the warehouse from above. An aluminium or steel profile grid serves as a division for the container stacks as well as an orthogonal railway network for the robots.

The novelty of RCS/RS combined with little market competition and high data secrets are just three reasons for the lack of general statements on the system's performance. Additionally, the science is at least one step behind since the companies do not provide any data besides the sales information on their home pages.

This research aims to investigate the throughput of an RCS/RS with one operating robot serving one picking station at one edge of the grid and to give answers to the following research questions:

- How are RCS/R-systems structured?
- What possible throughput can be achieved by one operating robot, and how big is the influence of the relocations?
- How does the throughput depend on the parameters
  - grid size,
  - stack height, and
  - filling degree?
- Is there a way to forecast the throughput using several robots?

This paper presents all the different systems existing on the market yet (Chapter II), gives a systematic literature review (Chapter III), and provides an extensive description of RCS/R-systems (Chapter IV). Based on this, the simulation model will be depicted in Chapter V to gain insights into possible design variants and operating modes. Chapter VI provides simulation results with a parameter variation and forecasts the throughput using more than one robot.

II. State-of-the-Art

This section shall overview the existing systems, their technologies and design, and their application areas. Currently, there are four leading RCS/RS suppliers on the market:

- AutoStore
- Ocado
- Jungheinrich
- Volume Dive

A. AutoStore

The system was invented twenty to thirty years ago by the Norwegian Ignar Hognaland. His idea to reduce the “air” in the warehouse was further progressed. Nowadays, AutoStore is a joint-stock company with a market capitalisation of $12 billion [2]. Fig. 1 shows an AutoStore warehouse with two picking stations:

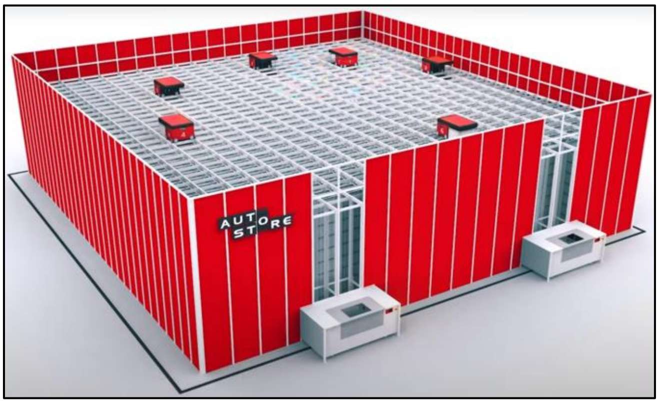

Fig. 1. AutoStore RCS/RS [3]

AutoStore has continuously developed its system and installed over 850 storage systems worldwide. AutoStore promises a self-sorting storage system by return-relocating all the previously relocated containers. This self-sorting effects high throughputs in the case of a distinctive class-based article structure. Standard application fields are retail, third-party logistics, healthcare and industry, and grocery trade [4].

B. Ocado Smart Platform

Ocado was established as a British online grocery trader and is now a hard- and software provider along the whole food supply chain. Analogous to AutoStore, Ocado also stores the goods in stacked plastic containers. The robots are smaller than the ones from AutoStore since they only have a cell dimension of one grid element, as seen in Fig. 2 [5].

Fig. 2. Ocado RCS/RS [5]

While AutoStore advertises its self-sorting effect, Ocado waives the return-relocations due to the usually not existing ABC-article distribution in the field of food trade.

C. Jungheinrich Powercube

Jungheinrich developed an inverse RCS/RS with robots operating on the floor level and storage channels above them called ‘Powercube’. Specially designed claws on the grid profiles hold the containers. The system allows a flexible design upwards and stack heights up to 12 metres (25-30 stacked containers) [6]. Fig. 3 shows the system with the robots under the stacked containers. As can be seen, the robots can transport two containers which is a novelty. This could speed up the relocation process.

Fig. 3. Jungheinrich Powercube RCS/RS [6]

Another significant advantage is the less time required for lifting and lowering since there is always a container direct above the robot, in contrast to AutoStore, where it could also happen that a robot has to lift up a container from the floor level, which takes way longer than lifting the container stored at the top [6].

D. Volume Dive

Volume Dive is also a new RCS/RS on the market. The robots have a 360° rotatable lifting and lowering unit with a gripper. Another innovation is the robot’s turnable wheels which reduce the number of wheels from eight to four compared to the competitors. The system’s stack height is fixed to three containers, resulting in a low demand for relocations. Another big difference compared to AutoStore or Ocado is that retrievals can be done at any position along the edge of the grid [7]. Fig. 4 presents the Volume Dive storage system with three sub-tiers, each storing three containers stacked:

Fig. 4. Volume Dive RCS/RS [7]

Although the stack height is limited to three, the system can reach total heights up to 14 metres since several sub-tiers (Fig. 4) are stacked above. Besides the typical applications such as grocery, e-commerce, retail, wholesale, and, as a speciality, beverage crate warehouses, Volume Dive is suitable for small warehouses due to its very scalable and modular design [7].

III. LITERATURE REVIEW

Based on the State-of-the-Art of Chapter II, this section is supposed to give insights into the literature and scientific publications on this subject. Especially throughput and analytical calculations or simulations of such storage systems were sought.

Scientific research on automatic storage systems (AS/RS) has a long history. It started in the '70s of the last century with AS/RS with one S/R machine. Later on, 3D-AS/RS and AVS/RS with vehicles transporting storage units were under investigation. At the beginning of this millennium, SBS/RS were invented. At this point, RCS/R-systems such as the AutoStore-system were unknown. Nevertheless, RCS/R-systems combine many advantages such as [8,9]:

- 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

Ten Hompel et al. [10,11] were, beside Wehking [12], 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. [13] explored chaotic and sorted warehouse strategies to gain the optimal length-to-weight ratio and stack height. They developed an analytical calculation using a semi-open queuing network and compared the results with those from DES. 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 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, significantly since sorting would reduce the great advantage of the high degree of space utilisation. The sorted system has a considerably higher handling capacity since relocations are minimised or eliminated.

In their research, Beckschäfer et al. [14] focused on warehousing strategies and the question of 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. This was done by using a DES. 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. [15] proposed a roll-out heuristic algorithm to find the optimal order sequencing within an RCS/RS. Tjeerdsma [16] developed a multi-scenario discrete event simulation to redesign an order-processing line for the Dutch post. Hameed et al. [17] developed a numerical performance calculation approach using an optimal path algorithm for robot routing and analysed the impact of a collision avoidance system. For one specific testing scenario, the total throughput decreased by around 10% with the consideration of congestion compared to neglecting them.

Galka et al. [18] 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 were not addressed.

Later, Galka et al. [19] published the most relevant paper for this study, which contains the development of a simulation to determine the influence of the number of robots on the system performance. 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. The stacking height, grid size, robot type, and picking station were regarded as fixed. As expected, the highest throughput rates were achieved with the access probability that required the fewest relocation processes. It could be found that 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. [20] 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. [8] 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 vocabulary definition of the investigated system was made.

IV. SYSTEM DESCRIPTION

RCS/R-systems impress because of their simple design since they are basically built out of four main hardware components:

- Containers
- Grid
- Robot(s)
- Picking Station(s)

Chapter IV presents and describes a typical RCS/RS (e.g. AutoStore, Ocado, Volume Dive with one tier). The goods are stored in plastic containers which are stacked on each other. This enables high storage densities and low space utilisation but also means that not every storage container is accessible direct at any time. Supposing a retrieval order without direct access to the required container, all the other containers stacked above the requested container must be relocated. Each container type has different technically conditioned maximum stacking heights. Usually, the dimensions of the containers are 600 x 400 millimetres. The height varies from 200 to 500 millimetres [8,9].

The stacks are stored next to each other without aisles or tiers, resulting in a block storage layout. A bolted aluminium or steel profile is used as a division between the storage stacks and as an orthogonal rail network for the robots, as seen in Fig. 5. There are no restrictions regarding the grid size or length-to-width ratio. Also, expansion or downsizing is easily possible.

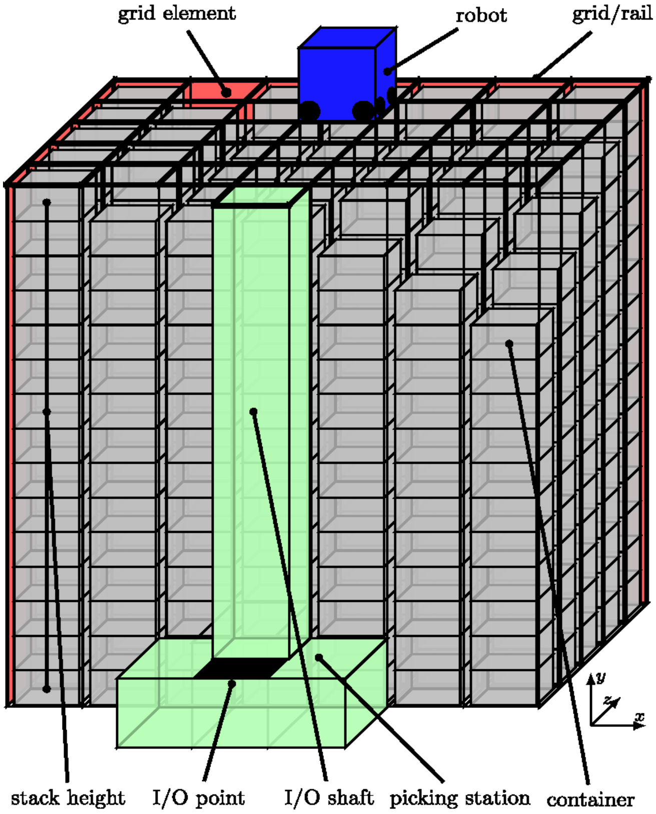

Fig. 5. Definitions for RCS/RS

The storage system is operated fully autonomously by robots from above. The robots are battery-operated. 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, the faster ones must adapt to the slower ones [8,9].

There are also other wheel systems available on the market. While older models must lift or lower their wheels to ride in a specific direction, newer robots can rotate the wheels, reducing the number of wheels from eight to four.

In case of a retrieval, the robot picks up the required container from the corresponding storage location and transports it to the assigned picking station at one edge of the grid. As mentioned, relocations can sometimes be necessary to access the container. 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 minimised. The picking station in front of the warehouse - also known as the port – is connected to the grid level by the I/O-shaft. 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 (dual command cycle).

After the retrieval, some systems, e.g. AutoStore, also carry out return relocations. This means the robot return-relocates the previously relocated containers into the original stacking order. One reason therefore could be a class-based article structure [8,9].

V. Throughput Simulation

The throughput is one of the main criteria for storage systems. A discrete event simulation was built up in the DES program SIMIO (version 15) to gain performance statements. The simulation model shall be described shortly based on the three main processes taking place:

- Storage process
- Retrieval process
- Relocation process

When a new storage unit arrives, it is transported to the grid level by the robot's lifting and lowering mechanism. The robot transports the new container to the assigned stack on the grid level. There, the robot lowers the container down 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.

A robot is assigned to pick it up as soon as a storage unit has to be retrieved. Without direct access, all containers stored above are first moved to neighbouring stacks. The container 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 on one of the wide edges of the grid.

Fig. 6 shows the SIMIO simulation model with a maximum grid size of 50 by 50. The robots wait in front of the storage system because the model was out of order when taking the picture.

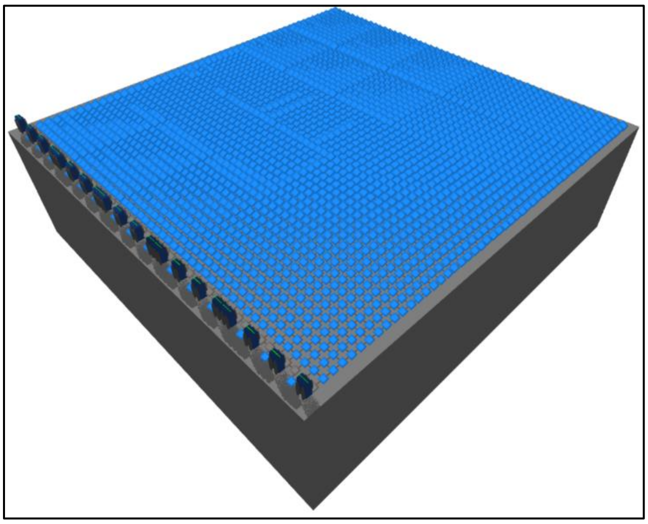

Fig. 6. Simulation model of an RCS/RS (SIMIO)

The simulation is based on the following assumptions:

- The storage strategy within a stack is LIFO.
- An entity is both a container and a stock item.
- The storage is chaotic without pre-sorting or zoning along the grid.
- The order list is generated randomly and evenly distributed.
- The robot works in a dual command cycle under the FCFS rule.
- The robot picks up a new container after retrieving one.
- A relocation entity is relocated to the next available stack.
- The filling degree is limited to a value that ensures that relocations can be done.
- The picking station is always located in the middle of one of the grid's wide edges (x-direction).

TABLE II. presents the kinematic and geometric input data for the simulation.

TABLE II. GEOMETRIC AND KINEMATIC DATA

Input variables		
Parameter	***Symbol***	***Value***
Container dimensions	L_C x W_C x H_C	0.65x0.45x0.33 m
Division x	Δx	0.7 m
Division z	Δz	0.5 m
Exchange time	$t_{Exchange}$	5 s
Filling degree	f	0.1-0.98
Location of the I/O-shaft	k_0	$n_X/2$
Locking and unlocking time	$t_{L/U}$	1 s
Number of I/O-shafts	$n_{I/O}$	1
Number of stacks	n_{Stacks}	100-2,500
Number of stacks along x	n_X	10-50
Number of stacks along z	n_Z	10-50
Robot velocity	v	2 m/s
Robot lift/lower velocity	v_y	1.6 m/s
Stack height	sh	1-25
Wheel exchange time	t_{WE}	1 s

Congestions of the robots in front of the I/O-shaft or anywhere along the grid were not considered since this study investigates the throughput of RCS/RS with one robot serving one picking station. As seen in Fig. 6, the simulation model can also work with more than one robot and more than one picking station, but this will be a matter of further study since this study provides the fundamental analytical approach (see Chapter VII).

Thirty replications were carried out for each simulation scenario. After the start-up phase, a statistical reset was done to avoid data inconsistencies.

VI. RESULTS

As mentioned in Chapter V, the simulation model enables a wide range of parameter variations. A throughput analysis with one operating robot serving one picking will be helpful

- to gain statements on the system's performance
- to create a forecast on the throughput behaviour and,
- to develop an analytical approach to determine the throughput without numerical simulation.

The first part of this chapter shall provide a parameter variation. Therefore, the following parameters will be varied:

- Stack height *sh*
- Filling degree *f*
- Number of stacks n_{Stacks}

Fig. 3 depicts the throughput of an RCS/RS with one robot for different stack heights and filling degrees on a 30 by 30 grid with 900 stacks:

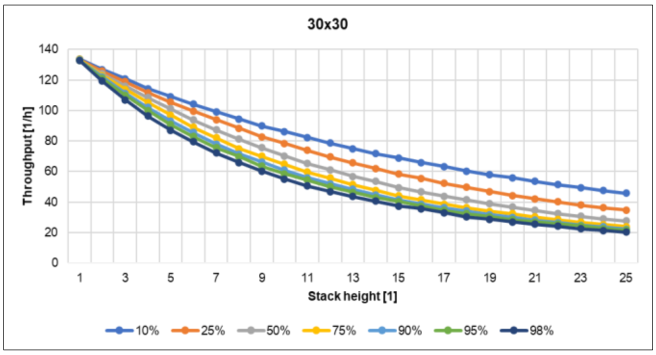

Fig. 7. One robot's throughput depending on the stack height for different filling degrees on a 30x30 grid

As can be seen, 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 higher the filling degree and the higher the containers are stacked, the less throughput can be achieved. This can be attributed to the increased need for relocation processes.

The number of stacks kept constant for the above figure will now be increased from 100 to 2,500. The stack height is therefore set to 16. Moreover, only practical-relevant filling degrees will be considered in Fig. 8:

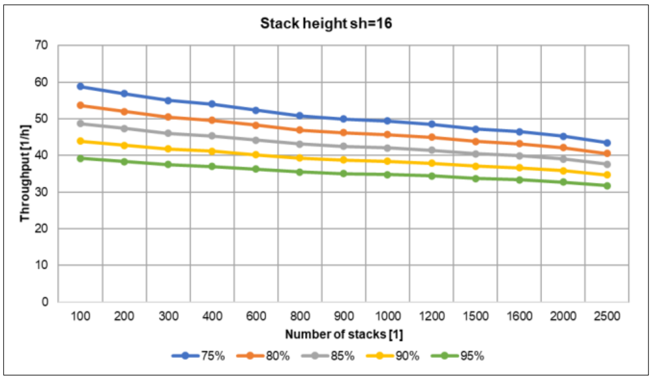

Fig. 8. One robot's throughput depending on the number of stacks for different filling degrees and a stack height of 16

The throughput is nearly constant, especially for the highest filling degrees, which leads to the fact that the impact of the number of stacks and, thus, the effect of the grid size on the throughput is way smaller than the influence of the stack height. One robot retrieves between 45 and 60 containers per hour from the storage system with a 75% filling degree.

To reinforce this argument, Fig. 9 shows the throughput depending on the stack height for different quadratic grid sizes from 10 by 10 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 monotonically falling. The largest grid size has the flattest curve.

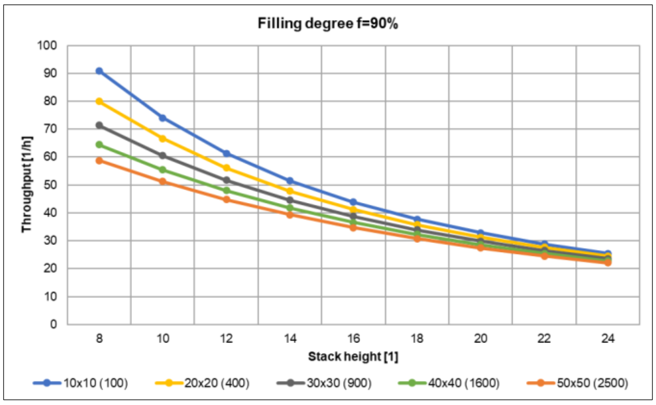

Fig. 9. One robot's throughput depending on the stack height for a different number of stacks and a filling degree of 90%

The stack height influences the throughput noticeably, especially for smaller grid sizes. While, for a stack height of eight, a 10 by 10 grid makes 90 retrievals possible, the throughput of a 50 by 50 system is reduced to nearly 60 orders per hour.

As mentioned, the stack height and the grid size influence the throughput significantly. At this point, the question towards the optimum stack height and grid size for a given number of containers and a given filling degree arises. Therefore, an optimisation example is examined for the parameters as shown in TABLE III. :

TABLE III. REQUIRED PARAMETER SETTING

Input variables		
Storage capacity	*N*	10,000
Stack height	*sh*	10 - 25
Filling degree	*f*	90%

Finding the optima for a storage capacity of 10,000 with a deviation of 10 % and a filling degree of 90 % leads to the following results regarding the throughput and the space demand (TABLE IV.):

TABLE IV. OPTIMISATION EXAMPLE

sh	n_{Stacks}	*N*	ϑ [1/h]	*A* [m²]
25	400	10,000	23,2	140
24	400	9,600	24,5	140
23	400	9,200	25,9	140
12	900	10,800	51,7	315
10	900	9,000	60,5	315

Based on the results of TABLE IV. , the maximum throughput can be achieved using the smallest possible stack height (*sh=10*) combined with a 30 by 30 grid. This scenario also has to largest space demand.

All the figures above depict the throughput of an RCS/RS that can be achieved by one robot serving one I/O-shaft with a picking station. To continue, the performance with more than one robot is another point of interest. Therefore, an application field shall identify the "throughput limits" of such systems. Fig. 10 shows a throughput forecast made by a linear extrapolation with the number of robots along the abscissa. The results of the simulation with one robot are now used for extrapolation. The blue area stands for all possible configurations from small systems with low stack heights, e.g. a 10 by 10 grid with a stack height of 10, up to huge systems with 2,500 stacks and a stack height of 25.

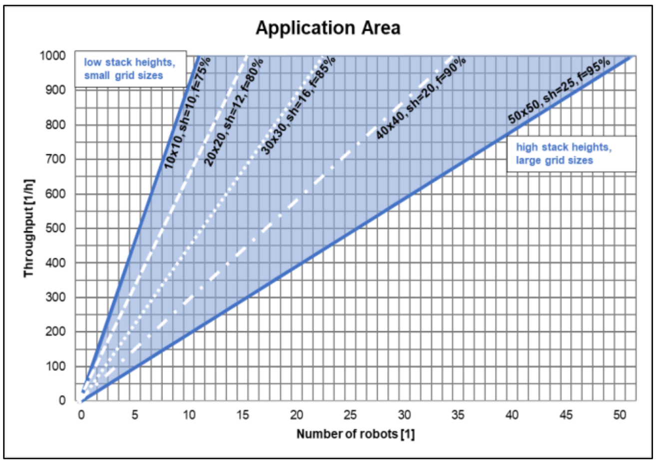

Fig. 10. Application field for throughput forecast

The application field is based on the possible throughput of more than one robot. This works under the assumption that there are enough I/O-shafts with picking stations anywhere along the grid.

Fig. 11 also considers the utilisation of the I/O-shaft and the time required at the picking station to gain the optimal ratio of I/O-shafts to the number of robots for a given scenario.

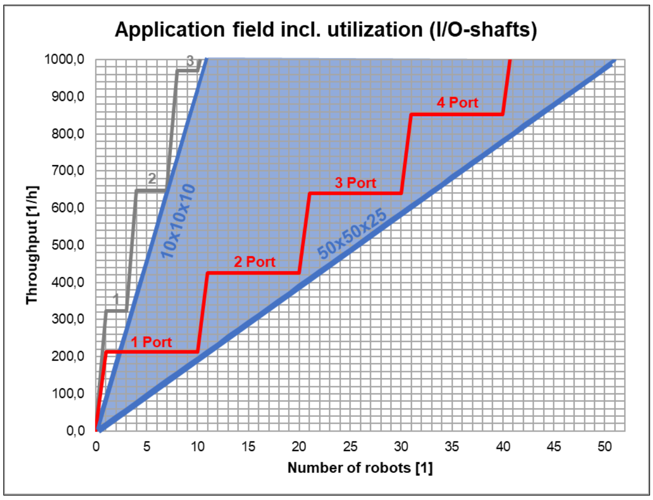

Fig. 11. Application field including the utilisation rate of the picking station

A 10 by 10 grid with a stack height of 10 achieves a throughput of almost 1,000 items per hour by installing three picking stations and using 10 robots. Compared to this, a large storage system such as the one with a 50 by 50 grid and a stack height of 25 would need more than 50 robots serving four to five picking stations to enable 1,000 retrievals. This seems hardly possible since it would lead to congestion and robot queues in front of the I/O-shafts. More I/O-shafts along at least two grid edges could help to remedy this.

VII. Conclusion

The number of RCS/RS suppliers, the number of worldwide installed systems, and the E-commerce trend are increasing. Although, there are hardly any valid and general statements on the system's performance. Since it depends on a various range of parameters and influencing factors, throughput simulation studies bring many different results.

This paper investigates the throughput of a one-robot RCS/RS serving one I/O-shaft with a picking station located at one of the wide edges of the grid. A parameter variation regarding the three most essential system characteristics (stack height, filling degree, and grid size) reveals the system's behaviour. Based on this, a throughput forecast using more robots is given by an application field. The area varies between small systems with low but realistic and practically relevant stack heights and large systems with high stack heights. Moreover, a comparison is given, including the possible throughput of the I/O-shafts and picking stations.

To give an outlook, simulations with optimised robot routings and different storage strategies will be further research topics. Another critical question is the system's behaviour by applying a class-based storage strategy (e.g. such as ABC).

Based on this, an analytical approach to calculate the performance of RCS/RS by using cycle time models and the queuing theory will be developed to, on the one hand, validate and verify the results from numerical simulation and, on the other hand, to gain optimal system settings without the need of powerful computers and the disadvantage of long computing times.

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