Shuttle-based or robotic compact storage and retrieval system?

Philipp Trost
University Assistant
Technische Universität Wien
Faculty of Mechanical and Industrial Engineering

Michael Eder
Senior Scientist
Technische Universität Wien
Faculty of Mechanical and Industrial Engineering

Georg Kartnig
Professor
Technische Universität Wien
Faculty of Mechanical and Industrial Engineering

This study investigates and compares the performance of shuttle-based storage and retrieval (SBS/RS) and robotic compact storage and retrieval systems (RCS/RS). SBS/RS, featuring lifts and shuttles, excel in high-speed storage and retrieval, achieving significant throughput efficiencies, particularly in high-demand scenarios. In contrast, RCS/RS enable high storage densities. The performance evaluation is based on existing analytical models, which integrate cycle time models and queueing theory. Results indicate that SBS/RS outperforms RCS/RS, particularly in smaller systems. However, with a low number of vehicles, RCS/RS demonstrates superior performance. These insights assist in selecting the appropriate system based on specific operational requirements.

Keywords: *SBS/RS, RCS/RS, Warehousing, Automated Storage Systems, Material Handling, Cycle time models, Queueing theory*

1. INTRODUCTION

Changing consumer behaviour, demographic shifts, and disrupted supply chains due to multiple crises worldwide are just three drivers of the incredible transformation in logistics and warehousing. These challenges are being addressed by modern technologies such as artificial intelligence, quantum computing, and blockchain. Additionally, climate change and targeted decarbonisation are compelling companies to rethink their strategies [1].

Storage systems are a crucial part of a functional supply chain. The number of automated storage systems has been growing rapidly, especially in recent years. Shuttle-based storage and retrieval systems (SBS/RS) and robotic compact storage and retrieval systems (RCS/RS) are two common types of automated small-parts storage systems. Both systems have different application fields and optimal operating conditions. Some material handling providers also attempt to combine the advantages of these two systems [2].

However, the performance of these two types has not been compared yet, most likely due to the lack of analytical approaches, particularly for RCS/RS.

Based on the research gap outlined above, this investigation intends to compare SBS/RS and RCS/RS both qualitatively in terms of their advantages and applications and quantitatively with a focus on performance. Hence, this study aims to address research questions about how storage capacity and the number of vehicles affect system performance by directly comparing these variables. The analytical models have both been validated by a discrete event simulation. The approaches are derived from Eder (2020) and Trost (2024).

Correspondence to: Philipp Trost, University Assistant
Technische Universität Wien - Faculty of Mechanical and Industrial Engineering,
Getreidemarkt 9, BA Hochhaus, 3. Stock A-1060 W, Austria
E-mail: philipp.trost@tuwien.ac.at

This paper is structured as follows: After a theoretical review in Section 2, Section 3 will examine the two types of systems in detail. Section 4 will outline the foundational concepts of the applied approaches and subsequently compare the performance of the two systems. The paper concludes with a comprehensive summary and a discussion of future research directions in this field.

2. THEORETICAL BACKGROUND

The literature on automated storage systems and their performance is extensive and well-established. However, research specifically focused on Shuttle-based Storage and Retrieval Systems (SBS/RS) and Robotic Compact Storage and Retrieval Systems (RCS/RS) is relatively limited. Despite SBS/RS being studied for around 15 years, analytical approaches remain sparse.

Initial approaches were developed by Heragu et al. [3], Roy et al. [4], and Marchet et al. [5], who considered tier-captive systems with single command cycles. Later, Kartnig and Oser [6], Eder [7], Lerher et al. [8], and Wang et al. [9] explored systems with dual command cycles. Numerous simulation studies have since examined various system configurations and strategies.

For double-/multiple-deep SBS/RS, Lerher [10,11] and Eder [12,13] pioneered analytical approaches, with Lerher focusing on travel time and Eder on aisle throughput.

In the case of RCS/RS, while several simulation studies exist (e.g. [14]), only two notable analytical approaches predict throughput: Zou et al. [15], using a semi-open queueing network, and Trost and Eder [16,17,18]. Zou et al.'s approach is limited by its use of simplifications and complex analytical solutions, whereas Trost and Eder's method is versatile and applicable for single or multiple robots serving various picking stations.

In summary, while there are several analytical approaches for SBS/RS and some for RCS/RS, there has been no comprehensive qualitative comparison of their advantages and application fields nor a quantitative comparison of their performance using existing methods.

3. SYSTEM DESCRIPTION

This section aims to present and compare SBS/RS and RCS/RS, highlighting the advantages of each system type. Additionally, it will outline the assumptions necessary for investigating their performance.

3.1 Shuttle-based systems

Shuttle-based storage and retrieval systems (SBS/RS) are advanced automated warehouse technologies engineered to optimise efficiency and throughput in material handling. The shuttles in these systems markedly reduce the time required for storage and retrieval operations (Figure 1).

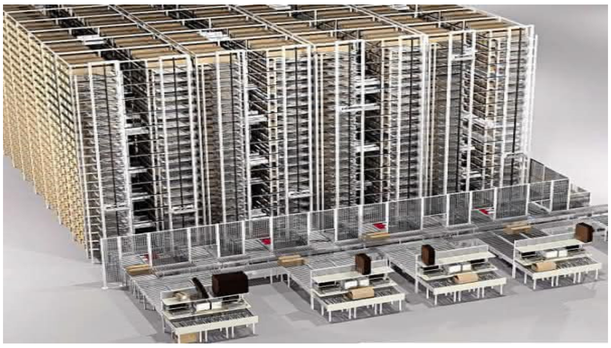

Figure 1. Example of an SBS/RS (Source: Knapp)

The SBS/RS discussed in this paper are fully automated storage solutions employing a lift and multiple shuttles to enhance storage and retrieval performance. Each aisle features a lift positioned at the front for vertical transportation of containers between the I/O point and the designated storage tier. Typically, I/O points are located on the first tier, directly in front of the lifts. Buffers are positioned between the lifts and shuttles on each tier to ensure smooth operations. Each shuttle is dedicated to a specific tier, resulting in one shuttle per tier in a rack, and handles one container at a time along the aisle. The racks are single-deep and double-sided, with each storage location accommodating a single tote. These assumptions align with those used for SBS/RS models from a European material handling provider.

In summary, the key advantage of SBS/RS systems is their high throughput capacity, which makes them ideal for applications that require efficient storage solutions with high demand rates for a limited range of product types.

3.2 Robotic compact storage systems

RCS/RS systems are fully automated warehouses operated by robots from above, designed for storing small goods in standardised plastic containers stacked vertically using a Last-In-First-Out (LIFO) strategy. This top-down approach to storage and retrieval results in exceptionally high volume-density rates by eliminating the need for aisles (see Figure 2).

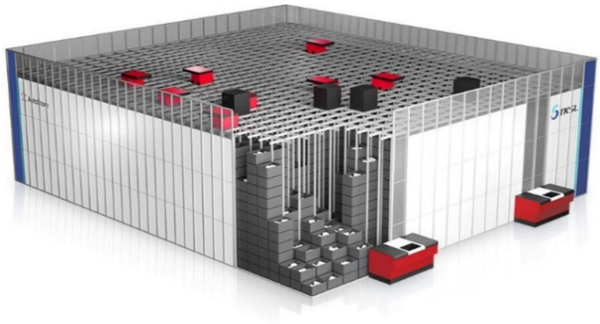

Figure 2. Example of an RCS/RS (Source: AutoStore)

These systems consist of four main components: the grid, containers, robots, and the picking station with an I/O shaft. The storage grid functions as an orthogonal railway network for the robots and a framework for the stacked containers. Goods are placed in plastic containers, which are then stacked within the grid. The robots perform the storage and retrieval tasks within this network.

The picking station is the fourth key component, serving as the warehouse’s input and output point (I/O point). It is connected to the grid level and the storage system via the I/O shaft.

The advantages of implementing an RCS/RS include its high storage density, which ensures efficient use of space, high availability due to significant redundancy, and straightforward expandability and modular scalability [19].

3.3 Assumptions

The investigation of the systems relies on the assumptions outlined by Eder [12] and Trost and Eder [17]. Specifically, the SBS/RS comprises two lifts - one dedicated to the input and one to the output transfer of containers - and a number of shuttles equal to the number of tiers in each aisle. Conversely, the RCS/RS system uses the robot's lifting mechanism for the vertical transport of containers to and from the picking station via the I/O shaft. The number of robots is chosen to ensure optimal utilisation of the picking station.

To further investigate and compare the performance of these systems, the following assumptions, applicable to both SBS/RS and RCS/RS, are adopted:

- The vehicles operate in a dual command cycle under the First-Come-First-Served (FCFS) rule.
- There are always containers waiting at the I/O point of the systems.
- The containers are stored and ordered evenly distributed over all stack heights, storage depths, and storage locations along the grid.
- If the stack height/storage depth is larger than one, relocations are possible.
- The filling degree is limited to allow relocations.
- A relocation container is relocated to the next free storage location.
- Both systems abstain from return relocations.

These assumptions provide a consistent foundation for a fair comparison of SBS/RS and RCS/RS performance.

4. SYSTEM COMPARISON

The analytical approaches for SBS/RS [14] and RCS/RS [17] integrate cycle time models with queueing systems. The cycle time models are used to calculate the interarrival times of the vehicles and lifts, while queueing theory connects these cycle time models and addresses the interactions between the components of the systems. For SBS/RS, the primary focus is on the waiting times of the lift and shuttle, whereas for RCS/RS, the emphasis is on the waiting times for a free I/O shaft. Eder's approach [14] for SBS/RS employs a single queue with limited capacity, assuming Markov characteristics for the interarrival times (lift) and generally distributed service times of the shuttles at the lift, resulting in an M|G|1|K system with a capacity of K=2.

Trost and Eder's analytical approximations for RCS/RS [17] assume Markovian characteristics for both the arrival and service processes (M|M|1|K) with $K=n_R+1$. They suggest that while an M|G|1|K model might offer slightly improved approximation quality, the analytical calculation of the variation coefficient is impractical due to the numerous influencing parameters.

Table 1 provides an overview of the general data for the study:

Table 1. General input data

Parameter	Value
Container (LxWxH)	650x450x330 mm
Filling degree	f = 90%
Number of aisles/stations	m=1

Table 2 outlines the input parameters needed for evaluating the performance of the SBS/RS. Notably, the number of shuttles is equivalent to the number of tiers.

Table 2. Specific input data for the SBS/RS

Parameter	Value
Number of tiers	∊ {8,…,50}
Storage depth	sd ∊ {1,…,5}
Lift velocity	v_{lift} = 5.0 m/s
Lift acceleration	a_{lift} = 7.0 m/s^2
Shuttle velocity	$v_{shuttle}$ = 2.0 m/s
Shuttle acceleration	$a_{shuttle}$ = 2.0 m/s^s
Time for transfer to/from the lift	t_{tL} = 1.4 s

Table 3 provides the input data for an RCS/RS system. The number of robots is selected to ensure optimal utilisation of the picking station.

Table 3. Specific input data for the RCS/RS

Parameter	Value
Stack height	sh ∊ {14,16,24}
Robot velocity	v_{robot} = 3.1 m/s
Robot acceleration	a_{robot} = 2 m/s^2
Robot lifting velocity	v_z = 1.6 m/s
Robot lifting acceleration	a_z = 0.8 m/s^s
Robot locking and unlocking time	t_L = 1.0 s
Robot wheel-exchange time	t_{WX} = 1.0 s

Designing a new storage system, the storage capacity, the number of utilised vehicles, and the resulting performance are, together with the costs, the four relevant parameters. Hence, the following study focuses on the expected throughput in dependence on the storage capacity (Section 4.1) and the number of vehicles (Section 4.2).

4.1 Storage capacity

Figure 3 illustrates the throughput of SBS/RS and RCS/RS as a function of the storage capacity. As shown, the throughput of small SBS/RS is significantly high.

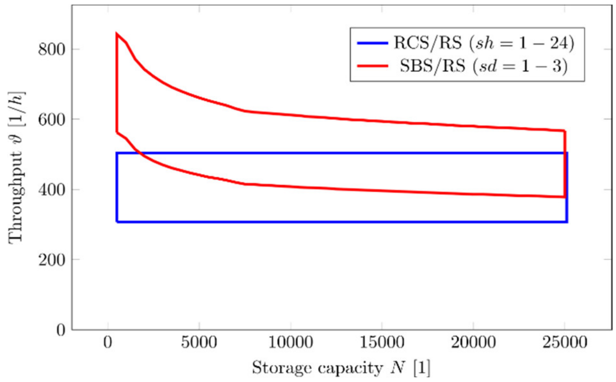

Figure 3. Throughput over the number of storage locations

In contrast, the performance of RCS/RS remains constant across varying storage capacities, as the picking station is the limiting factor besides the number of vehicles.

4.2 Number of vehicles

Figure 4 presents the throughput of SBS/RS and RCS/RS based on the number of vehicles given for a fixed storage capacity of 5,400:

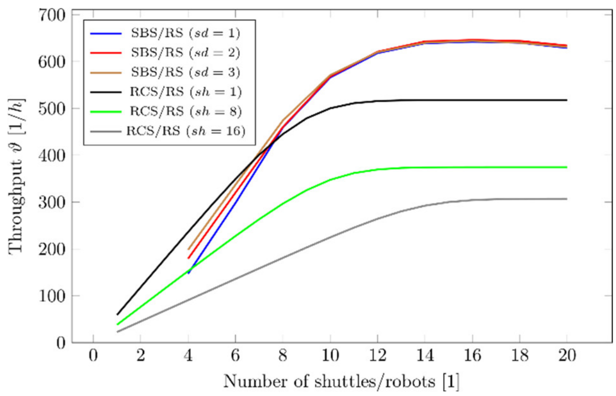

Figure 4. Throughput over the number of vehicles

With up to 7 operating vehicles at a stack height of 1, an RCS/RS delivers higher performance than an SBS/RS.

5. CONCLUSION

This paper provided a comparative analysis of SBS/RS and RCS/RS. SBS/RS, characterised by their high throughput capabilities, are ideal for high-demand scenarios with a limited range of product types. Conversely, RCS/RS excel in high storage density environments by eliminating aisles. They are well-suited for applications requiring high storage density and scalability.

The comparison revealed that SBS/RS outperform RCS/RS in smaller systems, while RCS/RS demonstrates superior performance with fewer vehicles. The advantages of each system provide valuable insights for selecting the appropriate system based on operational needs.

Future research should take into account cost considerations and explore additional RCS/RS configurations to offer more practical recommendations.

REFERENCES

[1] DHL Logistics Trend Radar [Online] https://www.dhl.com/at-en/home/insights-and-innovation/insights/logistics-trend-radar.html" [accessed on 2024-07-29]

[2] Kartnig, G., Grösel, B., & Zrnić, N. (2012). Past, state-of-the-art and future of intralogistics in relation to megatrends. FME Transactions, 40(4), 193-200.

[3] Heragu, S. S., Cai, X., Krishnamurthy, A., & Malmborg, C. J. (2011). Analytical models for analysis of automated warehouse material handling systems. International Journal of Production Research, 49(22), 6833–6861.

[4] Roy, D., & Krishnamurthy, A. (2011). Improving throughput capacity in multi-tier warehouses with autonomous vehicles. In Iie annual conference. proceedings (p. 1).

[5] Marchet, G., Melacini, M., Perotti, S., & Tappia, E. (2013). Development of a framework for the design of autonomous vehicle storage and retrieval systems. International Journal of Production Research, 51(14), 4365–4387.

[6] Karnig, G., & Oser, J. (2014). Throughput Analysis of S/R shuttle systems. In International Material Handling Research Colloquium, 2014.

[7] Eder, M. (2019). An analytical approach for a performance calculation of shuttle-based storage and retrieval systems. Production & Manufacturing Research, 7(1), 255-270.

[8] Lerher, T., Ekren, B. Y., Dukic, G., & Rosi, B. (2015). Travel time model for shuttle-based storage and retrieval systems. The International Journal of Advanced Manufacturing Technology, 78 (9–12), 1705–1725.

[9] Wang, Y., Mou, S., & Wu, Y. (2016). Storage assignment optimization in a multi-tier shuttle warehousing system. Chinese Journal of Mechanical Engineering, 29(2), 421–429.

[10] Lerher, T. (2016). Travel time model for double-deep shuttle-based storage and retrieval systems. International Journal of Production Research, 54(9), 2519–2540

[11] Lerher, T. (2018). Warehousing 4.0 by using shuttlebased storage and retrieval systems. FME Transactions, 46(3), 381-385.

[12] Eder, M. (2020). An approach for a performance calculation of shuttle-based storage and retrieval systems with multiple-deep storage. The International Journal of Advanced Manufacturing Technology, 107(1), 859-873.

[13] Eder, M., & Kartnig, G. (2018). Calculation method to determine the throughput and the energy consumption of s/r shuttle systems. FME Transactions, 46(3), 424-428.

[14] Trost, P., Kartnig, G., & Eder, M. (2023). Simulation study of RCS/R-systems with several robots serving one picking station. FME Transactions, 51(2), 201-210.

[15] Zou, B., Koster, R. D., & Xu, X. (2018). Operating policies in robotic compact storage and retrieval systems. Transportation Science, 52(4), 788-811.

[16] Trost, P., & Eder, M. (2024). An analytical performance approach for RCS/RS with one robot serving multiple stack heights under a one-path relocation strategy. Scientific Reports, 14(1), 3593.

[17] Trost, P., & Eder, M. (2024). A performance calculation approach for a robotic compact storage and retrieval system (RCS/RS) serving one picking station. Production & Manufacturing Research, 12(1), 2336056.

[18] Trost, P., & Eder, M. (2024). An analytical approach for the performance calculation of an RCS/RS with several picking stations. The International Journal of Advanced Manufacturing Technology, 1-18.

[19] Kartnig, G., Trost, P., & Eder, M. (2023, June). Rcs/rs under throughput investigation. In 16th proceedings of the International Material Handling Research Colloquium 2023, Dresden, Germany, 2023.

NOMENCLATURE

a	Acceleration rate
f	Filling degree of the storage system
H_C	container height
L_C	container length
m	Number of picking stations
N	Storage capacity
n_R	Number of robots
n_{tiers}	Number of tiers
sd	Storage depth
sh	Stack height
t_L	Robot locking and unlocking time
t_{tL}	Time for transfer to/from the lift
t_{WX}	Robot wheel-exchange time
W_C	Container width
v	Velocity rate