Impact of Class-Based Storage, Sequencing of Retrieval Requests and Warehouse Reorganisation on Throughput of Shuttle-Based Storage and Retrieval Systems

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Shuttle-based storage and retrieval systems (SBS/RS) are an important part of automated warehouses. SBS/RS are often used if throughput demand is high. SBS/RS can have significant advantages compared to crane-based automated storage and retrieval systems (AS/RS) with regard to throughput, energy efficiency and flexibility, depending on the application. Therefore, in the last ten years, the market for SBS/RS has grown considerably. Research of SBS/RS has not been as thorough as in the case of AS/RS. In particular, the development and investigation of the storage management policies class-based storage, sequencing of retrieval requests and warehouse reorganization and the resulting throughput increases and reductions in energy consumption during their application have considerable potential. This paper demonstrates the potential for throughput improvement in the application of these storage management policies. A simulation model is used to determine the throughput. The results show that significant optimization of the throughput is achieved by the application of the presented storage management policies.

Keywords: *Shuttle carrier, shuttle-based storage and retrieval systems, class-based storage, sequencing, warehouse reorganization, simulation*

1. INTRODUCTION

SBS/RS consists of one or more shuttle carriers, at least one elevator, a rack structure and a control system [1]. Systems with aisle- and tier-captive shuttle carriers are often used for high troughput demands. Tier-to-tier shuttle carriers cannot change the aisle, but the tiers. In such cases, the shuttle carrier uses the elevator to change to another tier. This can lead to throughput-reducing waiting times.

Aisle- and tier-captive SBS/RS use a shuttle carrier for each tier, which cannot leave the tier. The shuttle carrier and the elevator use buffer locations at each tier to store or retrieve totes, see figure 1. As a result, the horizontal and vertical transport are largely decoupled from one another. Accordingly, aisle- and tier-captive SBS/RS can often achieve a higher throughput than tier-to-tier SBS/RS.

In many cases, SBS/RS can achieve a higher throughput compared to AS/RS. They also require less energy and are characterized by a higher flexibility. In this paper we consider aisle- and tier-captive SBS/RS as well as the potential to increase throughput by using the storage management policies class-based storage, sequencing of retrieval requests and warehouse reorganization.

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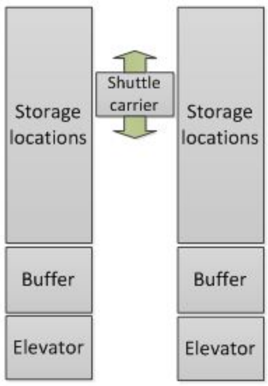

Figure 1. Aisle- and tier-captive SBS/RS, top view

This article is structured as follows: Chapter 1 provides an introduction. Chapter 2 contains an expla–nation of the existing literature (2.1), the description of the simulation model and the model assumptions (2.2) as well as the storage management policies class-based storage (2.3), sequencing of retrieval requests (2.4) and warehouse reorganization (2.5). At the end of the chapter the results of the simulation study are shown and interpreted (2.6). Chapter 3 contains the conclusions.

2. STORAGE MANAGEMENT POLICIES

2.1 Literature

Studies concerning aisle- and tier-captive systems often use random storage assignment [2-14].

In [15] the impact of the class-based storage policy was studied for systems in wich the shuttle carrier can reach every storage location, in [16] for tier-to-tier systems and in [17] for aisle- and tier-captive systems.

In [17], tier-based zones were examined. All the storage locations of one tier were assigned to one zone. It is thus possible to optimize the travel time for the elevator, but not the travel time of the shuttle carriers, because they travel through each storage location in a tier with the same probability. The elevator can therefore produce a maximum throughput per tier which corresponds to the throughput of the shuttle carrier. Because the throughput of the shuttle carrier is not increased, this is the limitation of the total throughput per tier. In [17], the elevator travels to 20% of the tiers with a probability of 80% because the A-class-articles were created with 80% probability and assigned to 20% of the tiers. If a SBS/RS had more tiers, the elevator then travels with the probability of 80% to more tiers. If the elevator travels to only a few tiers with high frequency, the shuttle carriers in these tiers usually become the bottleneck of the SBS/RS. The elevator has waiting times at the tiers, because the possible interarrival times from the elevator at a tier are higher as the interarrivel times of the shuttle carrier. If the elevator travels with high frequency to more tiers, the waiting times of the elevator drop, because more shuttle carriers are available. If the elevator travels to a lot of tiers with high frequency, the elevator becomes usually the bottleneck of the system.

The storage management policy sequencing of retrieval requests for SBS/RS is discussed in some works, e. g. in [18, 19]. In [18], three orders were considered ahead of time and the optimum sequence was determined. The SBS/RS in [18] has two lifting platforms which share a mast and thus the possibility of a blockage or a waiting time of an elevator is given. The sequencing of orders reduces waiting times and prevents blockages. In [19], a modified fish-swarm algorithm is used for optimization.

According to current knowledge, there are no publications for SBS/RS with the storage management policy warehouse reorganization. However, there are several publications available for AS/RS, whose ideas and algorithms can be adapted for SBS/RS [20, 21, 22].

In [23, 24] SBS/RS were studied with regard to energy requirement. No storage strategies were used to reduce energy requirements. Several studies on storage management policies for reducing energy requirements, e. g. [25, 26] have been conducted for AS/RS.

2.2 Simulation model and model assumptions

The simulation model determines the maximum average throughput for the selected parameter combination. The study relates to an aisle with two shelves with storage locations: left and right from the aisle (see Figure 1). In each scenario, it is assumed that requests are available for processing at any time. Table 1 shows the parameter values for the scenarios considered. The parameter values correspond to a calculation example from [1]. The negative number in Table 1 means that the Input/Output-point (I/O point) is one meter above the first tier. Acceleration and velocity of elevators and shuttle carriers are varied for certain scenarios, according to Table 2 and Table 3.

Figure 1 shows the storage configuration used, a SBS/RS with two elevators per aisle. The SBS/RS is single-deep. The capacity for totes per travel is one for the elevators and the shuttle carriers. Here, a tote corresponds to one article (one tote = one article). Each storage location can store one tote. The capacity of the buffer is either one or five, that means a buffer in one tier has either one or five locations to store or retrieve totes. The storage ratio of the SBS/RS are 50%, which means that 50% of all storage locations in SBS/RS are occupied by totes. The dwell-point of a shuttle carrier after processing a request is at the position of the buffer location.

Table 1. Parameter values

Rack	Parameter value
Number of tiers	12
Distance between tiers [m]	0.4
Distance between first tier and I/O-point [m]	-1
Number of bays	100
Distance between bays [m]	0.5
Elevator	
Velocity [m/s]	2
Acceleration [m/s^2]	2.5
Pick-up and set-down time [s]	2
Positioning and switching times [s]	0.5
Shuttle carrier	
Velocity [m/s]	2
Acceleration [m/s^2]	2
Pick-up and set-down time [s]	4
Positioning and switching times [s]	0.5
Storage ratio [%]	50

Table 2. Variation Velocity and Acceleration elevator

Elevator variation	
Velocity [m/s]	7
Acceleration [m/s^2]	7

Table 3. Variation Velocity and Acceleration shuttle carrier

Shuttle carrier variation	
Velocity [m/s]	7
Acceleration [m/s^2]	7

2.3 Class-based storage

In order to determine the optimum zoning related to the throughput, the zones must be arranged so that the average elevator travel time is as short as possible, and the average throughput per tier of the elevator corresponds approximately to the average throughput of the shuttle carrier. For the optimization, the theoretically possible average throughput per elevator and shuttle carrier is needed. This value represents the throughput that would be achieved if no waiting times occur. If the throughput without waiting times of the elevator per tier corresponds to that of the shuttle carrier in the tier, no or very low waiting times are to be expected. The greater the deviation between the throughput of the elevator per tier and the shuttle carrier, the higher the waiting times. If, for example, the average throughput of the shuttle carrier is significantly higher than the average throughput of the elevator, the shuttle carrier has high waiting times. The actual average throughput of the shuttle carrier then corresponds to the average throughput of the elevator in this tier.

In addition, the number of storage locations to be reserved per zone must be taken into account. This depends mainly on the average time the articles spend in the SBS/RS. Zoning results in articles with a high stock turnover frequency being placed near the I/O point. The determination of a suitable zoning can be heuristic or by means of an algorithm. Finding an optimal zoning is an optimization problem that maximizes the throughput of the elevator per tier and the throughput of the shuttle carrier, provided that the throughput of the elevator per level can not be greater than the throughput of the shuttle carrier in this tier (vice versa). Either the shuttle carrier limits the throughput of the elevator in a tier, or the elevator limits the throughput of the shuttle carrier in this tier. The goal of the optimization is the maximum achievable throughput of the elevator. This requires the minimization of the throughput limitation. The waiting times of elevator and shuttle carriers in the tiers with high freqency are to be minimized.

The following scenarios show the potential for throughput optimization through the storage management policy class-based storage. Different zonations are used for different scenarios. To compare the results, the reference storage management policy random storage assignment is used. Each storage location get storage or retrieval requests with the same probability. In the storage management policy random storage assignment, the simulation results are compared with the results of an analytical model according to [1].

The zone number is set to three zones. Zone A contains 240 storage locations (B: 360, C: 600) and receives storage or retrieval requests with a probability of 60% (B: 30%, C: 10%). The frequency of storage or retrieval requests of a zone is determined by the stock turnover rate of the articles assigned to this zone.

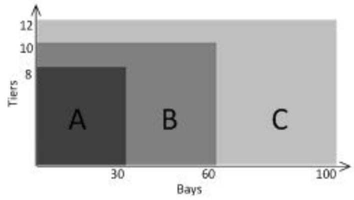

Figure 2. Variant 1

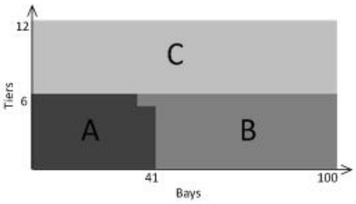

Figure 3. Variant 2E

Figure 2 shows variant 1 of the zoning for the scenarios single-command cycle (Elevators perfom single-command cycles) and dual-command cycle (Elevators perform dual-command cycles), all scenarios use variant 1. The zones in Figures 2-8 are marked by grayscale. Zone A has the darkest and zone C the brightest gray level. Figure 3 shows variant 2E for the single-command cycle scenario. Figure 4 shows variant 2D for the dual- command-cycle scenario. Variants 2E and 2D use parameter values from Table 1.

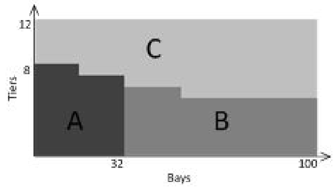

Figure 4. Variant 2D

Figure 5 shows variant 2EL for the singe-command cycle scenario. Figure 6 shows variant 2DL for the dual-command scenario. Variants 2EL and 2DL use para–meter values according to Table 1, except the acceleration and velocity of the elevator. These values are used according to Table 2.

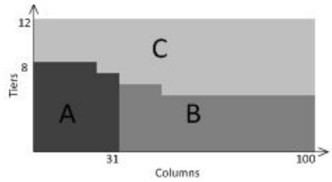

Figure 5. Variant 2EL - acceleration and velocity elevator = 7 m/s^2

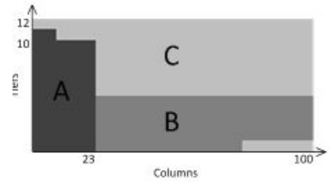

Figure 6. Variant 2DL - acceleration and velocity elevator = 7 m/s^2

Figure 7 shows variant 2ESH for the singe-command cycle scenario. Figure 8 shows variant 2DSH for the dual-command scenario. Variants 2ESH and 2DSH use parameter values from Table 1, except the acceleration and velocity of the shuttle-carrier. These values are used according Table 3.

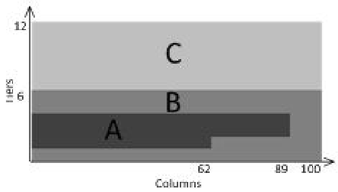

Figure 7. Variant 2ESH – acceleration and velocity shuttle carrier = 7 m/s^2

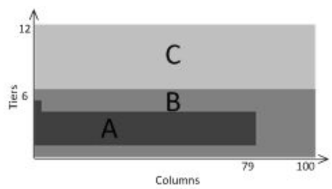

Figure 8. Variant 2DSH – acceleration and velocity Shuttle-Carrier = 7 m/s^2

The variants 2E, 2D, 2EL, 2DL, 2ESH and 2DSH are optimized zonations and differ from each other because they are adapted to the respective travel times of the elevators, 2E, 2EL and 2ESH for single-command cycles and 2D, 2DL and 2DSH for dual-command cycles.

In the single-command cycle scenario, both eleva– tors perform only single-command cycles, which equates to a storage or a retrieval request in one cycle. In the dual-command cycle scenario, both elevators perform dual-command cycles, representing a storage and a retrieval request in one cycle. In the single-command cycle scenario, one elevator uses the buffer locations to store totes. The other elevator uses the buffer locations to retrieve totes. In the dual-command cycle, both elevators use the buffer locations alternating per tier to store or retrieve totes. Figure 9 shows the use of the buffer locations for the first four tiers of the SBS/RS. In both scenarios, shuttle carriers perform dual-command cycles.

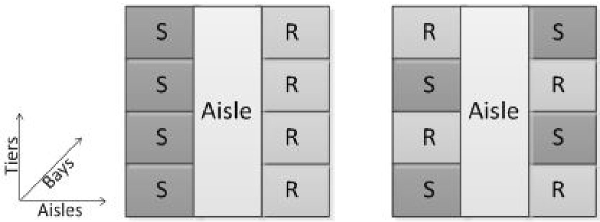

Figure 9. Use of the buffer locations for single-command (left) and dual-command cycles (right), front view, S: Storage buffer, R: Retrieval buffer

2.4 Sequencing of retrieval requests

The storage management policy sequencing of retrieval requests sorts retrieval requests with the aim of minimum travel time. The sorting can use simple rules for route and travel time optimization, or use algorithms that find the global optimum (usually over the complete enumeration) or a local optimum. The higher the quantity of requests to be sorted, the higher is the computational effort for the complete enumeration. To minimize the computational effort, therefore, faster optimization algorithms are often used, eg. evolutionary algorithms or the gradient method. A distinction is made between block sequencing (sorting a certain number of requests) and dynamic sequencing (sorting of all available requests) [27].

For the example shown in this publication, a sorting rule is used to minimize the travel time after a storage. Only the elevators are optimized. The elevators perform dual-command cycles and select after a storage a retrieval request according to the criterion shortest travel time. If a retrieval request is waiting on the buffer location at one tier above or under the current tier, this request is processed. Otherwise a check is performed in order to determine whether the higher or lower tiers have retrieval requests. The request made on a tier with the shortest travel time is selected. Figure 10 shows an example. The number indicates the tier in which the request is located, the following letter indicates the type of request, storage or retrieval. For example, 8R means a retrieval request in tier 8.

Figure 10. Sequencing of retrieval requests

2.5 Warehouse reorganization

Warehouse reorganization can be used individually for different scenarios. The common features of each warehouse reorganization are described below. The processes that are always required for a warehouse reorganization are identified.

Processes of each warehouse reorganization are:

- Determination of the totes to be rearranged.
- Determination of the optimal storage locations for the totes to be rearranged (optimal in the sense of the fastest possible processing time, or the compliance with a defined processing time).
- Rearrangements with minimum or a defined travel time.

Algorithms are required for each of these processes. These can be based on simple or complex rules with high computational effort. In order to determine the totes to be reprocessed, it should be known which requests are to be expected when and during which time they should be processed. If it is not known exactly which requests are expected, as they are expected to be very short-term, a forecast of the expected requests is required. This can be generated on the basis of data from past request receipts. The complete enumeration or a heuristic approach, e. g. evolutionary algorithms, can be used to determine the optimal storage locations of the articles for the totes to be rearranged and to do the rearrangement with minimal travel time. Heuristic approaches are often used in publications of warehouse reorganization for AS/RS [20-22].

It should be noted that the warehouse reorganization increases the energy costs and the maintenance costs of the SBS/RS, because the elevator and shuttle carriers travel more often. The advantages of warehouse reorganization are shorter order processing times, lower labor costs and higher delivery reliability. In the scenario described here, it is shown how the warehouse reorganization reduces order processing times as well as the throughput in periods with a high number of requests can be increased. The totes are moved to more favorable storage locations.

The scenario refers to a warehouse reorganization performed and compares the time of order processing and throughput with the case that no warehouse reorganization has been performed. The implementation of the rearrangements is done by an algorithm. In the scenario, the rearrangements take place in a rest phase of the SBS/RS, e. g. at night. No storage or retrieval requests are processed during this time. The time required to relocate the totes from the original storage locations to the intended storage locations is measured.

The algorithm for the rearrangements can also be used for zoning changes in the warehouse, e. g. if changes in the article frequency occur. If certain articles are assigned to another zone, they can be transferred to the new zone by the algorithm.

A processing of 480 retrieval requests, which have been rearranged and are located in storage locations near the I/O point (tier 1 - 6, bays 1 - 42), is executed. The totes were previously placed (unfavorably) in the rear area of the SBS/RS, distributed on the tiers 7 - 12 and the bays 61 - 100. Each request refers to an article assigned to a specific storage location. Figure 11 shows the arrangement of the articles after the warehouse reorganization in the SBS/RS.

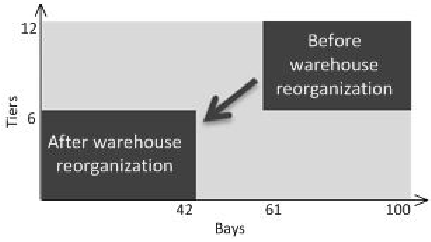

Figure 11. SBS/RS after warehouse reorganization

The algorithm for the rearrangements uses a zone classification for articles and storage locations. The articles stored in the unfavorable storage locations get the zone number one, and all other articles get the zone number two. The storage locations 1 - 42 in tier 1 – 6 get the zone number one, all other storage locations get the zone number 2. The elevators use alterning storage and retrieval buffer locations, as shown in Figure 9.

The algorithm for the elevators and shuttle carriers asks the following questions and peforms the following actions.

Elevator:

Is there an article on a retrieval buffer location at the next available tier above or below? If yes, travel to retrieval buffer location and pick-up article.

Is there a free storage buffer location for an article in the next available tier above or below? If yes, travel to storage buffer location and set-down article.

Shuttle-carrier:

Are there articles stored in this tier that need to leave this tier? If yes, travel to storage location and pick-up article, travel to retrieval buffer location and set-down article.

Are there articles stored in the storage buffer location that need to be stored in this tier? If yes, travel to storage buffer location and pick-up article. Search for a free and allowed storage location that is closest to the buffer location, travel to storage location and set-down article.

Are there articles in this tier that need to be rearranged within the tier? If yes, search for a free and allowed storage location that is closest to the buffer location for the article. Travel to storage location and pick-up article, travel to new storage location and set-down article.

The algorithm can be described by the following Code.

Elevator:

1. Set c to 1.
2. Set t to number of actual tier.
3. If an article is stored in retrieval buffer location of tier t + c: Set t_c to t + c, go to 4. Else: If an article is stored in retrieval buffer location of tier t – c: Set t_c to t - c, go to 4. Else: Increment c by 2, go to 3.
4. Set j to zone number of article in retrieval buffer location of tier t_c.
5. Travel to tier t_c.
6. Pick-up article from retrieval buffer location.
7. Set c to 1.
8. Set t to t_c.
9. If no article is stored in storage buffer location of tier t + c and number of stored articles in tier t + c from zone j < storage locations for zone j tier t + c: Set t_c to t + c, go to 10. Else: If no article is stored in storage buffer location of tier t - c and number of stored articles in tier t - c from zone j < storage locations for zone j tier t - c: Set t_c to t - c, go to 10. Else: Increment c by 2, go to 8.
10. Travel to tier t_c.
11. Set-down article to storage buffer location , go to 1.

Shuttle-carrier:

1. Set i to 1.
2. If an article is stored in storage location i: Set j to zone number of stored article in storage location i. Else: Increment i by 1, go to 2.
3. If number of stored articles in this tier from zone j > storage locations for zone j in this tier: Go to 4. Else: If j = last zone number: Go to 8. Else: Increment i by 1, go to 2.
4. Travel to storage location i.
5. Pick-up tote.
6. Travel to retrieval buffer location.
7. Set-down article. Go to 2.
8. If an article is stored in storage buffer location: Go to 9. Else: Go to 17.
9. Set i to 1.
10. Set j to zone number of stored article in storage buffer location.
11. Set s to zone number of storage location i.
12. If no article is stored in storage location i and s = j: Go to 13. Else: Increment i by 1, go to 11.
13. Travel to storage buffer location.
14. Pick-up article.
15. Travel to storage location i.
16. Set-down article. Go to 1.
17. Set i to 1.
18. If an article ist stored in storage location i: Set j to zone number of stored article in storage location i. Else: Increment i by 1, go to 18.
19. Set s to zone number of storage location i.
20. If s ≠ j: Set i_rearrange to i. Else: Increment i by 1, go to 18.
21. Set i to 1.
22. Set s to zone number of storage location i.
23. If no article is stored in storage location i and s = j, go to 24. Else, increment i by 1, go to 22.
24. Travel to storage location i_rearrange.
25. Pick-up article.
26. Travel to storage location i.
27. Set-down article, go to 1.

Warehouse reorganization in the case of aisle- and tier-captive systems includes rearrangements where either only one shuttle carrier (if an article is moved to a storage location in the same tier) or two shuttle carriers and one elevator are required (if an article is moved to a storage location in another tier).

In this scenario, during a period of a high number of requests, the elevators and shuttle carriers perform single-command cycles. Retrival request are often time-critical because they have delivery deadlines. Therefore, the delivery schedule can be increased during periods of high request volumes by prioritizing the retrieval requests. The retrieval requests are randomly distributed after execution of the warehouse reorganization, whereby the elevator travels to the tiers 1 - 6 and the shuttle carriers travels to the bays 1 - 42. For comparison, the results are determined without warehouse reorganization, the elevators travel to the tiers 7 - 12 and the shuttle carriers to the bays 61 - 100.

2.6 Results

Table 4 shows the simulation results of the storage management policies random storage assignment and class-based storage. The cursively written values were calculated for comparison according to [1]. The throughput results in the following tables and figures refer to the throughput of one elevator. In the scenarios shown here, two elevators are used per aisle. Thus, twice the throughput can be achieved per aisle. Table shows the combinations between the storage management policies random storage assignment, class-based storage and sequencing of retrieval requests.

Table 4: Simulation results, random storage assignment and class-based storage

	Throughput single-command cycle elevator (SC_L) [Totes/h]		Throughput dual-command cycle elevator (DC_L) [Totes/h]	
Buffer Capacity	1	5	1	5
Random storage assignment (C)	451.74 *453.64*	453.45 *453.64*	517.51 *518.72*	514.79 *518.72*
Class-based storage variant 1 (Z1)	483.95	484.83	537.68	540.26
Class-based storage variant 2 (Z2)	501.87	506.30	547.98	552.73

Table 5. Simulation results, combinations between random storage assignment, class-based storage and sequencing of retrieval requests

	Throughput dual-command cycle [totes/h]	
Buffer Capacity	1	5
Random storage assignment + Sequencing of retrieval requests (CR)	542.82	542.79
Class-based storage variant 1 + Sequencing of retrieval requests (Z1R)	554.41	554.01
Class-based storage variant 2 + Sequencing of retrieval requests (Z2R)	559.50	568.95

Table 6 shows the simulation results of the storage management policies random storage assignment and class-based storage for the variation of the acceleration and velocity of the elevators (7 m/s^2). The cursively written values were calculated for comparison according to [1]. Table 7 shows the combinations between the storage management policies random storage assignment, class-based storage and sequencing of retrieval requests for the variation of the acceleration and velocity of the elevators.

Table 6. Simulation results, random storage assignment and class-based storage, acceleration and velocity elevator = 7 m/s^2

	Throughput single-command cycle elevator (SC_L) [Totes/h]		Throughput dual-command cycle elevator (DC_L) [Totes/h]	
Buffer Capacity	1	5	1	5
Random storage assignment (C)	535.46 *535.83*	535.77 *535.83*	596.13 *597.92*	594.07 *597.92*
Class-based storage variant 1 (Z1)	556.37	556.67	611.84	608.55
Class-based storage variant 2 (Z2)	565.09	570.27	606.60	609.74

Table 7. Simulation results, combinations between random storage assignment, class-based storage and sequencing of retrieval requests, acceleration and velocity elevator = 7 m/s^2

	Throughput dual-command cycle [totes/h]	
Buffer Capacity	1	5
Random storage assignment + Sequencing of retrieval requests (CR)	614.71	609.06
Class-based storage variant 1 + Sequencing of retrieval requests (Z1R)	622.21	619.97
Class-based storage variant 2 + Sequencing of retrieval requests (Z2R)	619.28	623.66

Table 8 shows the simulation results of the storage management policies random storage assignment and class-based storage for the variation of the acceleration and velocity of the shuttle carriers (7 m/s^2). The cursively written values were calculated for comparison according to [1]. Table 9 shows the combinations between the storage management policies random storage assignment, class-based storage and sequencing of retrieval requests for the variation of the acceleration and velocity of the shuttle carriers (7 m/s^2).

Table 8. Simulation results, combinations between random storage assignment, class-based storage and sequencing of retrieval requests, acceleration and velocity shuttle carrier = 7 m/s^2

	Throughput single-command cycle elevator (SC_L) [Totes/h]		Throughput dual-command cycle elevator (DC_L) [Totes/h]	
Buffer Capacity	1	5	1	5
Random storage assignment (C)	453.69 *453.61*	453.38 *453.61*	516.92 *518.71*	515.26 *518.71*
Class-based storage variant 1 (Z1)	479.73	484.09	540.50	540.19
Class-based storage variant 2 (Z2)	503.18	522.95	563.75	570.81

Table 9. Simulation results, combinations between random storage assignment, class-based storage and sequencing of retrieval requests, acceleration and velocity shuttle carrier = 7 m/s²

	Throughput dual-command cycle [totes/h]	
Buffer Capacity	1	5
Random storage assignment + Sequencing of retrieval requests (CR)	534.99	532.34
Class-based storage variant 1 + Sequencing of retrieval requests (Z1R)	553.64	552.92
Class-based storage variant 2 + Sequencing of retrieval requests (Z2R)	569.93	577.99

Figure 12 visualizes the simulation results from Table 4 and Table 5 in the form of a bar graph. The abbreviations used are taken from Table 4 and Table 5. If a number is present after an abbreviation, this number indicates the buffer capacity. For example, SC_L_1 means the throughput with single-command cycle for the elevator with a buffer capacity of one.

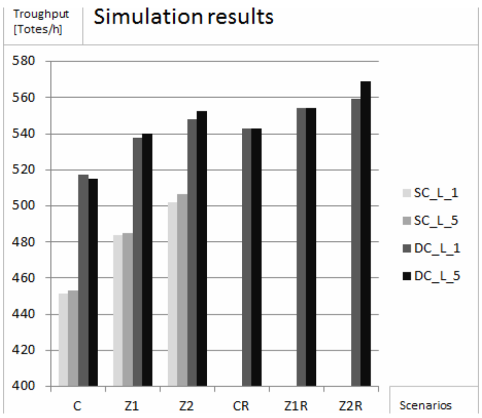

Figure 12. Simulation results, class-based storage and sequencing of retrieval requests

Figure 13 visualizes the simulation results from Table 6 and Table 10 in the form of a bar graph, with the same abbreviations used in Figure 12.

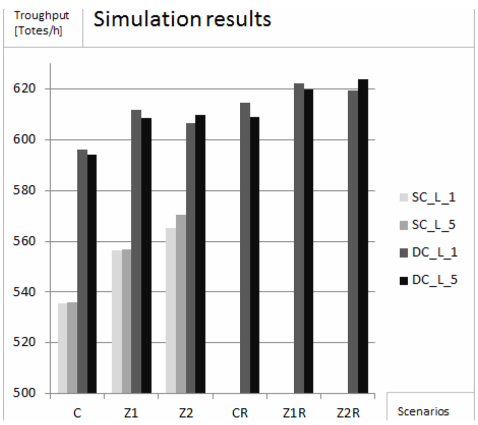

Figure 13. Simulation results, class-based storage and sequencing of retrieval requests, Acceleration and Velocity elevator = 7 m/s²

Figure 14 visualizes the simulation results from Table 8 and Table 9 in the form of a bar graph, with the same abbreviations used in Figure 12.

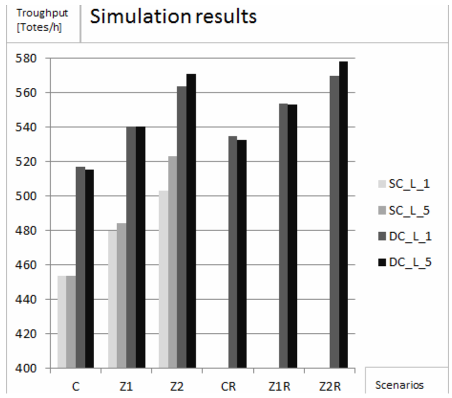

Figure 14. Simulation results, class-based storage and sequencing of retrieval requests, Acceleration and Velocity Shuttle-Carrier = 7 m/s²

Table 11 shows the simulation results of the storage management policy warehouse reorganization. The cursively written values were calculated for comparison according to [1]. The throughput results in Table 11 refer to the throughput of an elevator. Per aisle, the double throughput can be achieved because two elevators are used for one aisle.

Table 12 shows the time needed for the rearran–gements of the articles by the algorithm for warehouse reorganization.

Table 11: Simulation results, warehouse reorganization

	No warehouse reorganization (NWR)		Warehouse reorganization (WR)	
Buffer Capacity	1	5	1	5
Throughput [LE/h]	212.13 *212.808*	213.75 *212.808*	500.70 *509.80*	509.87 *509.80*
Processing time [min]	67.88	67.37	28.76	28.24

Table 12: Time needed for the rearrangement of articles

	Rearrangements	
Buffer Capacity	1	5
Processing time [min]	94.6	70.71

Figure 15 visualizes the simulation results for the processing time for 480 retrieval requests in the form of a bar graph. The abbreviations used are taken from Table 11. The number after the abbreviations indicates the number of buffer locations used, e. g. NWR_1 means without warehouse reorganization with a buffer capacity of one.

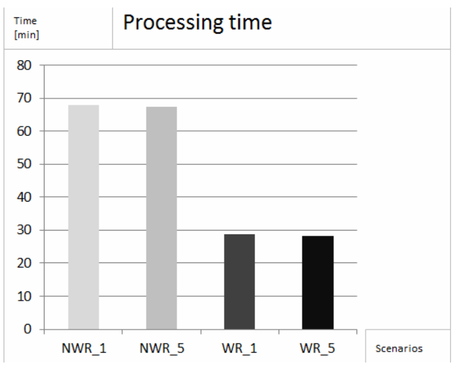

Figure 15. Simulation results, processing time for 480 retrieval requests

The results show the potential of the storage management policies to increase throughput.

As can be seen in Table 4, Table 6 and Table 8, the simulation results concur to the analytical model from [1] (analytical results are cursively written).

If the elevator performs dual-command cycles, the throughput increases in all scenarios significantly between 6.92% and 14.56%, compared to single-command cycles. The increase in throughput with dual-command cycles compared to single-command cycle is highest in all scenarios with random storage assignment, because the travel distances and travel times of the elevator per tote can be reduced most. Zoning optimize in most cases also the travel times of the elevator, so the change from single-command cycle to dual-command cycle has less influence on throughput.

The impact of the buffer capacity on throughput remains very small; the highest difference is in scenario single-command cycle with class-based storage variant 2ESH. When using a buffer capacity of five, the throughput is 3.39% higher than when using a buffer capacity of one. This is caused by the zoning of variant 2ESH. The lower the frequently used tiers and the lower the buffer capacity, the more likely it is that the elevator or the shuttle carrier have more waiting times, because either all buffers for storage are filled or all buffers for retrieval are empty.

The impact of different zonings is clearly visible. For example, the zoning of variant 2ESH leads to an increase in throughput of 15.34% (2DSH: 10.78%), compared with random storage assignment, buffer capacity five. Variants 2E, 2D, 2ESH and 2DSH has a higher throughput than variant 1; for example, the throughput in variant 2E is 4.43% higher than for variant 1.

The potential to increase throughput with class-based storage is lower as the elevator travels with higher acceleration and velocity, see Figure 12 and Figure 13. Increasing acceleration and velocity of the shuttle carriers leads to a higher increase of throughput, see Figure 12 and Figure 14.

The lower throughput in most cases in variant 1 can be explained: In variant 1, the elevator travels to the tiers 1 - 10 with a higher probability than for the variants 2E, 2D, 2ESH and 2DSH. The elevator travels over longer distances and requires more travel time accordingly. In variant 2E, e. g., the two zones A and B are assigned to the tiers 1 - 6. Therefore, the elevator travels to these tiers with a probability of 90%. The travel time of the elevator is correspondingly lower and the throughput higher. The prerequisite is that the shuttle carriers do not become the bottleneck of the system. With six tiers and a probability of 90% of all requests in this tiers, the shuttle carriers are not the bottleneck of the SBS/RS in this scenario. But, for example, with three tiers the shuttle carriers would become the bottleneck of the SBS/RS. Then the travel time of the elevator would increase, because the elevator would have long waiting times. But if the shuttle carriers are able to travel faster, the elevator travel distances can be further reduced, see variant 2ESH and 2DSH. Four tiers are frequently used by the elevator.

The zonings of variants 2EL and 2DL are very similar to variant 1, because variant 1 is near the optimum of achievable throughput for this scenario. This is caused by the higher acceleration and velocity of the elevators. More tiers can be served by the elevator without or few waiting times.

Also the travel time of the shuttle carriers is optimized by zoning. In variant 2E, e. g., the shuttle carriers travel to the bays 1 - 41 in the tiers 1 - 5 with a probability of 60%. The travel time of the shuttle carrier is therefore reduced and a higher throughput can be achieved. The prerequisite is that the shuttle carriers have no or very little waiting times due to elevator.

The optimal zoning is found when the elevator can produce the maximum throughput. This can be done only if elevator and shuttle carrier cycle times are as similar as possible in the high frequented tiers, as already mentioned in Chapter 2.2. This coordination is achieved by zoning.

Optimal zoning may differ significantly depending on the parameter values, as shown by variants 2E, 2D, 2EL, 2DL, 2ESH and 2DSH. The optimal zoning at increased acceleration and velocity of the elevator tends to increase the number of frequently used tiers, as shown by variants 2EL and 2DL. The optimal zoning at increased acceleration and velocity of the shuttle carrier tends to decrease the number of frequently used tiers, as shown by variants 2ESH and 2DSH.

Even the application of a relatively simple sequencing of retrieval requests leads to a throughput increase between 1.10% – 5.44%. It should be noted that the sequencing of retrieval requests cannot reach its full potential at times of orders. If requests have to be prioritized due to tight time constraints, the throughput is reduced. This would be the case, for example, if the allowed waiting time of a tote on a buffer location is set to a maximum of 3 minutes. Then the elevator would only travel in part optimally. The tighter the time, the more the throughput approaches the result without a sequencing of retrieval requests.

Furthermore, the sequencing of retrieval requests with elevators with many tiers leads to a higher throughput increase than with elevators with less tiers, because the travel times decrease significantly more than with elevators with few tiers. The highest relative increase in throughput can be achieved with the combination of random storage assignment and sequencing of retrieval requests, compared to random storage assignment. The relative increase throughput that can be achieved through the combination of class-based storage and sequencing of retrieval requests (compared to class-based-storage) is lower, because the elevator travels with high frequency to only a few tiers. This results in a less significant reduction of travel time.

Warehouse reorganization doubles the throughput in the scenario shown, thus halving the processing time for the retrieval requests (for 480 retrieval requests from over one hour to half an hour). The order processing time is thus reduced and all downstream processes profit accordingly. Labor costs are reduced and delivery reliability is increased. To shorten the process time, are rearrangements of the articles performed. The rearran–

gements increase the energy and maintenance costs of the SBS/RS.

The combination of the storage management policies class-based storage and sequencing of retrieval requests generates a throughput increase of up to 10.52% with variant 2D, 4,98% with variant 2DL and 12,17% with variant 2DSH, compared to random storage assignment with the according acceleration and velocity of elevators and shuttle carriers.

The highest throughput difference of 27.48% exists between the scenario of single-command cycle with random storage assignment and a buffer capacity of one and the scenario of dual-command cycle with zoning variant 2DSH and sequencing of retrieval requests and a buffer capacity of five.

The increase in throughput through the storage management policies class-based storage and sequ–encing of retrieval requests is achieved by reducing the distance traveled for elevators and shuttle carriers. This results in a lower energy consumption of the SBS/RS as a desired secondary effect.

3. CONCLUSIONS

This is concerned with the impact of storage mana–gement policies on troughput. The studies about the storage management policies class-based storage, sequ–encing of retrieval requests, and warehouse reorga–nization have shown that there is considerable potential to increase the throughput of SBS/RS.

The storage management policy class-based storage increases the throughput by zoning, which minimizes the travel times of elevators and shuttle carriers and matches these times in the high frequented tiers so that the elevators and the shuttle carriers have as little waiting time as possible. In the examined scenarios, throughput increases were achieved by up to 15.34% for single-command cycles and 10.78% for dual-command cycles.

The storage management policy sequencing of retrieval requests sorts the requests for the elevator according to the criterion of the shortest travel time. This results in throughput increases of up to 5.44% in the scenarios considered.

The combinations of class-based storage and sequencing of retrieval requests leads to an increase of throughput by up to 12,17% .

A change from single-command cycles with random storage assignment to dual-command cycles with class-based storage in combination with sequencing of retrieval requests results in troughput increases up to 27.48%.

The storage management policy warehouse reorganization stores the totes in the examined scenario required for expected retrieval requests to more favorable storage locations and thus reduces the order processing time in periods of high request volumes and increases the throughput of the SBS/RS. The throughput could be doubled in the scenario shown and the processing time was halved.

The class-based storage and the sequencing of retrieval requests also leads to a lower energy consumption of the SBS/RS.

Further interesting research topics for future work may include algorithms for storage management policies:

- Automatic determination of the optimal zoning for SBS/RS and their continual adaptations when changing the storage frequency of the articles.
- Sequencing of retrieval requests which also includes shuttle carriers.
- Warehouse reorganization, i. e. the determination of the totes to be reprocessed, the finding of suitable storage locations as well as the execution of the rearrangements with minimal travel time.

Minimizing the rearrangements and the rearrangement path in multiple depth SBS/RS as well as finding favorable dwelling-points for the elevators and shuttle carriers have the potential to increase throughput.

Furthermore, the research of storage management policies is of interest for the reduction of energy demand, e. g. a mass-based storage, an energetic storage or the adjustment of the velocity of elevators and shuttle carriers to the current number of requests.

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REFERENCES

[1] VDI-2692, Automated vehicle storage and retrieval systems for small unit loads, Berlin: Beuth-Verlag, 2015.

[2] Marchet, G. et. al Analytical model to estimate performances of autonomous vehicle storage and retrieval systems for product totes, International Journal of Production Research, Vol. 50, No. 24, pp. 7134-7148, 2012.

[3] Marchet, G., Melacini, M., Perotti, S. and Tappia, E., Development of a framework for the design of autonomous vehicle storage and retrieval systems, International Journal of Production and Research, Vol. 51, No. 14, pp. 4365-4387, 2013.

[4] Zhang, S., Zhao, N., Zhao, Y., Universal Simu–lation Model of Autonomous Vehicle Storage & Retrieval System, Proceedings of the 21st Inter–national Conference on Industrial Engineering and Engineering Management 2014, pp. 325-330, 2015.

[5] Lerher, T., Travel time model for double-deep shuttle-based storage and retrieval system, International Journal of Production Research, Vol. 54, No. 9, pp. 2519-2540, 2016.

[6] Lerher, T., Ekren, B., Sari, Z. and Rosi, B., Method for evaluating the troughput performance of shuttle-based storage and retrieval systems, Technical gazette, Vol. 23, No. 3, pp. 715 – 723, 2016.

[7] Lerher, T., Ekren, B., Sari, Z. and Rosi, B., Simulation Analysis of Shuttle Based Storage and Retrieval Machines, International journal of simulation modelling 14 (1), pp. 48-59, 2015.

[8] Lerher, T., Ekren, B., Dukic, G. and Rosi, B., Travel time model for shuttle-based storage and retrieval systems, International Journalof Advanced

Manufacturing Technology, Vol. 78, No. 9, pp.1705-1725, 2015

[9] Epp, M., Wiedemann, S., urmanns, K.: A discrete-time queueing network approach to performance evaluation of autonomous vehicle storage and retrieval systems, International Journal of Produc–tion Research, Vol. 55, No. 4, pp. 960-978, 2017.

[10] Hu, Y., Huang, S., Chen, C., Hsu, W., Toh, A., Loh, C., Song, T., Travel time analysis of a new automated storage and retrieval system, Computers and Operations Research, Vol. 32, No. 6, pp. 1515-1544, 2005

[11] Eder, M., Kartnig, G., Throughput optimization of shuttle systems using an analytical calculation model, Logistics Journal, Proceedings, 2016.

[12] Trummer., W., Jodin, D., What throughput have shuttle systems?, Hebezeuge & Fördermittel, Vol. 54, No. 5, Berlin, pp. 240-242, 2014.

[13] Eder, M., Kartnig, G., Geometry optimization of shuttle systems using an analytical calculation model, 25. Deutscher Materialfluss-Kongress, VDI-Verlag GmbH, 2016.

[14] Ning, Z., et al.: An efficient simulation model for rack design in multi-elevator shuttle-based storage and retrieval system, Simulation Modelling Practice and Theory, Vol. 67, pp. 100 – 116, 2016.

[15] Kuo, P., Krishnamurthy, A., Malmborg, C., Perfor–mance modelling of autonomous vehicle storage and retrieval systems using class-based storage policies, in: International Journal of Computer Applications in Technology, Vol. 31, No. 3/4, pp. 238-248, 2008.

[16] Kaczmarek, S., Goldenstein, J., ten Hompel, M., Performance analysis of autonomous vehicle sto–rage and retrieval systems depending on storage management policies, Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management, 2014.

[17] Ekren, B., Sari Z., T. Lerher, Warehouse design unter class-based storage policy of shuttle-based storage and retrival system, IFAC-PapersOnLine, Vol. 48, No. 3, pp. 1152-1154, 2015.

[18] Carlo, H., Vis, I., Sequencing dynamic storage systems with multiple lifts and shuttles, International Journal of Production Economics, Vol. 140, pp. 844-853, 2012.

[19] Fang, Y., Tang, M., The AVS/RS Scheduling Optimization Based on Improved AFSA, Interna–tional Journal of Control and Automation, Vol. 7, pp. 53-64, 2014.

[20] Carlo, H., Giraldo, G., Toward perpetually organi-zed unit-load warehouses, Computers & Industrial Engineerin, Vol. 63, No. 4, pp 1003- 1012, 2012.

[21] Chen, L., Langevin, A. and Riopel, D., A tabu search algorithm for the relocation problem in a warehousing system., International Journal of Production and Economics, Vol. 129, No. 1, pp. 147-156, 2011.

[22] Pazour, J. and Carlo, H., Warehouse reshuffling: Insights and optimization, Transportation Research, Vol. 73, pp. 207-226, 2015.

[23] Lerher, T., Troughput and energy related performance calculations for shuttle based storage and retrieval systems, New York, 2016.

[24] Akpunar, A., Ekren, B., Lerher, T., Energy efficient design of autonomous vehicle based storage and retrieval system, Journal of Applied Engineering Science, Vol. 15, No. 1, pp. 25-34, 2017.

[25] Sommer, T., Energy-efficient storage space allocation in automated warehouses, Logistics Journal, Vol. 2013, 2013.

[26] Siegel, A., Schulz, R., Schmidt, T. and Zadek, H., Modeling of the energy requirements of automated storage and retrieval systems and various storage strategies to reduce energy requirements, Logistics Journal, Vol. 2013, 2013.

[27] Han, M. et al. On sequencing retrievals in an automated storage /retrieval system, Vol. 19, No. 1, IE Transactions, pp. 56-66, 1987.

УТИЦАЈ СКЛАДИШТЕЊА ЗАСНОВАНОГ НА КЛАСИ РОБЕ, РЕДОСЛЕД ЗАХТЕВА ЗА ПРОНАЛАЖЕЊЕ УСКЛАДИШТЕНЕ РОБЕ И РЕОРГАНИЗАЦИЈА СКЛАДИШТА ПРЕМА ПРОТОКУ ОПСЛУЖИВАЊА ШАТЛОМ И СИСТЕМА ЗА ПРОНАЛАЖЕЊЕ УСКЛАДИШТЕНЕ РОБЕ

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Системи аутоматских складишта опслуживаних складишним возилима – шатловима – и проналажења ускладиштене робе (SBS/RS) су важан део аутоматског складишта. Системи SBS/RS се често користе уколико постоји потреба за великим протоком. Имају значајне предности у односу на системе аутоматских складишта опслуживане дизалицама и проналажења ускладиштене робе (AS/RS) у погледу протока, енергетске ефикасности и флексибилности, у зависности од примене. Последњих десет година на тржишту постоји све већа потреба за SBS/RS складиштима. Истраживања система SBS/RS нису толико интензивна као у случају AS/RS складишта. Развој и истраживање управљања складиштем заснованог на складиштењу робе према класи, израда редоследа захтева за проналажење ускладиштене робе и реорганизација складишта, као и резултујуће повећање и смањење потрошње енергије представљају значајан потенцијал. Показано је да постоји потенцијал за побољшање пропусне моћи складишта код примене оваквог управљања складиштем. У раду се користи модел за симулацију одређивања протока. Резултати показују да је остварена значајна оптимизација пропусне моћи применом приказаног управљања складиштем.