

RESEARCH ARTICLE



Cost and performance comparison of tier-captive SBS/RS with a novel AVS/RS/ML

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ABSTRACT

This paper introduces a novel autonomous vehicle-based storage and retrieval system that utilizes movable lifts (AVS/RS/ML), proposed as an alternative to the tier-captive shuttle-based storage and retrieval system (SBS/RS). The newly proposed system aims to provide an affordable solution with highly utilised AGVs, that can also perform operations out of warehouse. The performance of this novel system is compared with the equivalent tier-captive SBS/RS warehouse design, where each shuttle is dedicated in a specific tier in that design. The comparison is based on the initial system investments costs, throughput rates, and average utilisation of lifts/MLs in the system. Collision prevention rules are also applied to AVS/RS/ML, and its performance is tested through simulation. The results show that the tier-captive SBS/RS system becomes cost-efficient under high throughput rate requirements, while the AVS/RS/ML technology is preferred for relatively moderate and low process rate requirements. The unit-cost per month performance metric of AVS/RS/ML is less sensitive to an increase in number of tiers in the system, compared to the tier-captive SBS/RS case, indicating that AVS/RS/ML may be promising for high-tier warehouse system designs.

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1. Introduction

Automated high-bay warehousing technology is the most efficient way of storing and retrieving goods within the intralogistics chains of modern factories, offering high storage density and other capabilities such as: direct access to each item, high process speeds, reliability, availability and optimal use of space. Various designs of such warehouses are known, which are used depending on the required size and weight of the load and the required throughput capacity. To provide the perfect racking system for individual requirements, the right design and technology should be selected. For processing small and light totes, an SBS/RS is widely used in practice (Carlo and Vis 2012; Marchet et al. 2012; Ning et al. 2016; Ekren 2017; Ekren et al. 2018). In that system design, there are tier-captive automated vehicles (shuttle carriers) and elevators positioned at the aisle ends. Those commonly used systems, besides their advantages, also have disadvantages, such as the elevators, which usually represent a bottleneck limiting the possible throughput and consequently leading to very low utilisation of the shuttle

carriers (Carlo and Vis 2012; Marchet et al. 2012, 2013). To improve the above drawbacks, double-capacity lift systems are often used, which increase the performance of the warehouse but leave the elevators as bottlenecks. Another way to increase the throughput of the warehouse might be to develop a new innovative technology avoiding those handicaps, where we propose a novel AVS/RS/ML in this work. We describe this proposed system in Sections 3 and 4. It is expected that the newly proposed system design will be technically superior to the existing mini-load warehousing technologies such as tier-captive SBS/RS in terms of cost and performance.

In this paper, we conduct a simulation-based performance comparison analysis of conventional SBS/RS and the novel AVS/RS/ML to verify the hypothesis of superiority of the novel system. The simulation models are performed by using a discrete-event modelling approach to evaluate the throughput performance of the considered technologies. Note that collision avoidance rules are also integrated in the models to prevent colliding of multiple MLs and AGVs in the system, which was mostly not

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evaluated in previous researches (Lerher et al. 2015a, 2015b; Ekren 2020). Data from a common industrial mini-load warehouse are used for the simulation models. An estimated investment cost comparison is also performed for the two systems designs shown in Section 4.

The paper is organised as follows. In Section 2, a literature review is given, discussing the main known aspects of the two systems. In Section 3, the novel AVS/RS/ML system is presented. In Section 4, the simulation models of the conventional SBS/RS and the novel AVS/RS/ML systems, the system design scenarios and the performance analyses are presented. Chapter 5 presents and discusses the results and the performance comparison. Chapter 6 summarises the main results and presents the conclusions.

2. Literature review

Generally, storage systems with multiple shuttle carriers and lifts known as Shuttle-based Storage and Retrieval Systems (SBS/RS) and Autonomous Vehicles Storage and Retrieval Systems (AVS/RS) have been the subject of many researchers over the last decade.

A dynamic storage system consisting of a conveyor, two non-passing lifts that share a mast, multiple transfer shuttles, and a storage rack were studied by Carlo and Vis (2012). Their study was concerned with the scheduling problem of two lifts in which lift handles storage or retrieval requests. An integrated look-ahead heuristic strategy simultaneously assigning a set of pre-defined requests to the lifts, and the order in which they will be handled by taking into account delays caused by interference between the lifts, has been proposed by the authors.

Ekren and Heragu (2011) compare two automated warehousing system performance by using simulation modelling. Those systems are crane-based AS/RS and AVS/RS.

Marchet et al. (2012) present an analytical model based on an open queueing network approach to estimate different performance metrics (i.e. transaction average cycle time and average waiting time) of AVS/RS for product tote movement. The proposed analytical model demonstrates good estimates for the performance measures of AVS/RS. In a later research study, Marchet et al. (2013) investigate the main design trade-offs for AVS/RS by using simulation and propose a comprehensive design framework. The authors apply their design framework in a case study, and the key design differences between the two types of AVS/RS configurations (i.e. tier-captive versus tier-to-tier) are identified.

By considering the operational characteristics of the elevator's lifting table and the shuttle carrier, such as

acceleration and deceleration and the maximum velocity, Lerher et al. (2015b) introduce an analytical travel time model to calculate the travel (cycle) time for SBS/RS. Their analysis shows that regarding all examined types of SBS/RS, the results of the proposed analytical travel time model for SBS/RS are consistent with the results of SBS/RS simulation models.

Differently, Zou et al. (2016) propose a parallel processing strategy for AVS/RS where an arrival transaction can request the lift and the vehicle simultaneously. The authors used a fork-join queueing network in which an arriving transaction is split into a horizontal motion task served by the vehicle and a vertical motion task served by the lift. The results show that the fork-join queueing network accurately estimates AVS/RS performance under the parallel processing policy.

Lerher et al. (2015a, 2015b) study travel time models and simulation modelling to track how the system designs affect the SBS/RS performance.

Wang, Mou, and Wu (2015) study a single deep SBS/RS warehouse by proposing a task-scheduling optimisation model under three correlated multi-objectives. They adopt NSGA-II for the solution of the multi-objective task-scheduling model. They observe that the Pareto optimal solution work well by the proposed algorithm.

Introducing a simulation modelling approach, Ning et al. (2016) develop an efficient simulation model that can be auto-remodelled for different storage rack configurations. The authors present a case study for a multi-elevator tier-captive SBS/RS containing 81 different rack alternatives, from which a throughput performance can be accurately evaluated.

Differently, Ekren (2017) provides a graph-based solution for performance evaluation of a SBS/RS under various design concepts. By the proposed graph-based solution, it is aimed the decision-maker evaluates a pre-defined system's performance promptly and decides on the correct design concept based on his/her requirements from thousands of alternative design scenarios of SBS/RS.

By considering a discrete-time open queueing network approach, Epp, Wiedemann, and Furmans (2017) propose a method for performance evaluation of AVS/RS with tier-captive, single-aisle vehicles. The proposed model can be utilised for designing an AVS/RS according to given system requirements, such as storage capacity, throughput, height and length of the system, as well as other operational requirements.

In contrast to research studies of SBS/RS with tier-captive shuttle carriers, Lerher (2018) propose analytical travel time models for aisle-changing shuttle carriers, which are capable of travelling in the horizontal and in the cross-aisle directions inside the SBS/RS. The expressions for the single and dual-command travel times

have been determined by assuming uniformly distributed storage locations and probability theory. The proposed models enable the calculation of the expected travel times for single and dual-command cycles of the aisle-changing shuttle carriers, from which the performance can be evaluated.

Ekren, Sari, and Lerher (2015) study ABC storage policy for SBS/RS and compare its performance under different warehousing designs by simulation modelling.

Ekren et al. (2018) propose a tool that can calculate critical performance measures of different SBS/RS designs, which are based on analytical models that can estimate the mean and variance of travel time of lifts and shuttles, as well as the mean amount of energy consumption and energy regeneration per transaction for a pre-defined SBS/RS design. In a later research study, Ekren and Akpunar (2021) develop analytical models for estimating important performance outputs from SBS/RS by using open queuing network-based software tool.

Ekren (2020) studies simulation-based experimental design to analyse the effect of warehouse design factors on several performance metrics from a tier-captive SBS/RS. In a later research study, Ekren (2021) proposes a hierarchical solution approach for multi-objective optimisation of an AVS/RS warehouse design.

Küçükyaşar, Ekren, and Lerher (2021) compare the performance measures of two SBS/RS configurations: SBS/RS with tier-captive shuttles and SBS/RS with tier-to-tier shuttles. In their research study, several storage rack design experiments based on the number of aisles, tiers and bays were conducted. The proposed results suggest that a newly proposed tier-to-tier SBS/RS design can provide a better configuration in terms of total investment cost and throughput rate.

Recently, Jerman et al. (2021) have already proposed a novel AVS/RS design with movable lifts (AVS/RS/ML) as an alternative technology to existing AVS/RS in order to balance the resource utilisations, as well as to provide an inexpensive solution with highly utilised autonomous vehicles (i.e. AGVs). In their study, two alternative AVS/RS/ML operating designs under different racking configurations have been investigated in terms of throughput rate. This study was lack in considering smart travel policies of AGVs and MLs in which we study such policies in the current work.

One of recent works is by Lerher, Ficko, and Palčič (2021) studying analytical modelling approach for SBS/RS to estimate throughput performance metrics from pre-defined system designs. Another one is by Turhanlar, Ekren, and Lerher (2022) proposing deadlock collision and prevention algorithms that could be used in flexible travel of shuttles between aisles in SBS/RS. A recent novel modelling approach, a reinforcement learn-

ing (RL) algorithm, is applied for transaction scheduling in SBS/RS (Ekren and Arslan 2022). They show that RL approach improves the system performance significantly compared some other static approaches.

Compared to the existing literature of AVS/RS and SBS/RS (see Table 1), the proposed research considers AVS/RS/ML with movable lifts (MLs) and AGVs by also taking into account collision prevention rules in travel of autonomous devices. To the best of our knowledge, this is the first study providing and formulating movable ML and AGVs system by also involving collision prevention rules and, comparing the results with tier-captive SBS/RS under different operational aspects.

3. Presentation of the novel AVS/RS/ML

The proposed novel autonomous vehicle-based storage and retrieval system with movable lifts (Figure 1) is to be used in high-bay mini-load warehouses for storage and retrieval operations, e.g. for transporting totes containing items from storage compartments to order-picking stations or directly to production assembly lines.

The main innovation of this system is the introduction of movable lifts (MLs) that can lift the autonomous guided vehicles (AGVs) when they are stationary and move themselves through the warehouse aisle when they are empty (without an AGV). In addition, the ML is suspended from the top rails and uses the bottom rail only for stabilisation and braking. For these reasons, the MLs can be designed to be simple and cost-effective.

Another advantage of this system is the ability to use one or more MLs in each aisle along with a larger number of AGVs to balance the utilisation of these two devices in the system and achieve the desired throughput with lower costs. If more than one ML is considered in an aisle, appropriate collision avoidance rules must be used.

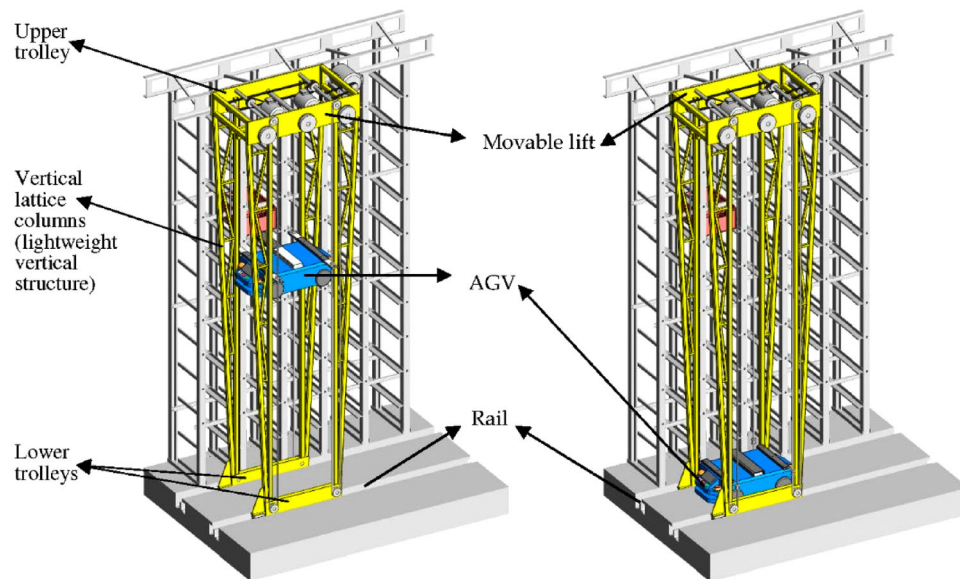
Within the AVS/RS/ML system, the AGVs will be used to handle storage and retrieval operations, as well as to transport and distribute loads throughout the production facility, and are therefore intended to travel both inside and outside the warehouse aisles.

AGVs can move horizontally within an aisle and be lifted vertically to reach the upper levels of warehouse racks using aisle-captive MLs. To perform the lifting operation, AGVs attach themselves to the lifting chains of MLs using retractable grippers (Figure 2). For storing and retrieving a load to and from a storage location, AGVs are equipped with an appropriate telescopic device (Figure 2). In some cases, stoppers are needed to anchor the lifted AGVs to the racking at the target location.

The MLs and the entire AVS/RS/ML system with their operational concepts can also be found in Jerman et al. (2021).

Table 1. The differences between models studied in AVS/RS and SBS/RS.

Literature	System type	Modelling	Objectives
Carlo and Vis (2012)	Dynamic storage system	Analytical	Throughput performance
Ekren and Heragu (2011)	AVS/RS	Simulation	Performance evaluation
Ekren, Sari, and Lerher (2015)	SBS/RS	Simulation	Performance evaluation
Ekren (2017)	SBS/RS	Simulation	Graph-based solution System's performance
Ekren et al. (2018)	SBS/RS	Analytical	Performance evaluation
Ekren and Akpunar (2021)	SBS/RS	Analytical – QNM	Performance evaluation
Epp, Wiedemann, and Furmans (2017)	AVS/RS	QNM	Performance evaluation
Ekren (2020)	SBS/RS	Simulation	Performance evaluation
Ekren (2021)	AVS/RS	Analytical and simulation	Average cycle time and average energy consumption per transaction
Küçükyavaş, Ekren, and Lerher (2021)	SBS/RS	Simulation	Performance evaluation
Jerman et al. (2021)	AVS/RS/ML	Simulation	Performance evaluation
Lerher et al. (2014)	SBS/RS	Analytical and simulation	Cycle time analysis
Lerher (2018)	SBS/RS	Analytical	Throughput performance
Marchet et al. (2012)	AVS/RS	Analytical	Performance evaluation
Marchet et al. (2013)	AVS/RS	Simulation	Design trade-offs analysis
Ning et al. (2016)	Multi-elevator SBS/RS	Simulation	Performance evaluation
Zou et al. (2016)	AVS/RS	FJQNM	Performance analysis
Wang, Mou, and Wu (2015)	SBS/RS	NSGA-II heuristic approach	Multi-objective optimisation
Lerher, Ficko, and Palčič (2021)	SBS/RS	Analytical	Performance analysis
Lerher et al. (2015a)	SBS/RS	Simulation	Design trade-offs analysis
Lerher et al. (2015b)	SBS/RS	Analytical	Performance analysis
Turhanlar, Ekren, and Lerher (2022)	AVS/RS, SBS/RS	Agent-based simulation	Deadlock prevention models
Ekren and Arslan (2022)	SBS/RS	Machine learning	Performance analysis

**Figure 1.** The novel autonomous vehicle-based storage and retrieval system design with movable lifts (AVS/RS/ML) (adopted from Jerman et al. 2021).

4. Analyses of the novel AVS/RS/ML compared to tier-captive SBS/RS

In this section, we explain the simulation models of the proposed AVS/RS/ML system and tier-captive SBS/RS along with their model assumptions and constraints. The simulation models are developed by the ARENA 16.0 commercial simulation software, which also provides an

animation feature in it that helps to verify and validate the models. Following sub-sections, the details of the models are shown.

4.1. Simulation model of the novel AVS/RS/ML

In the proposed AVS/RS/ML, there are two separate devices: AGVs and movable lifts (MLs). The simulation

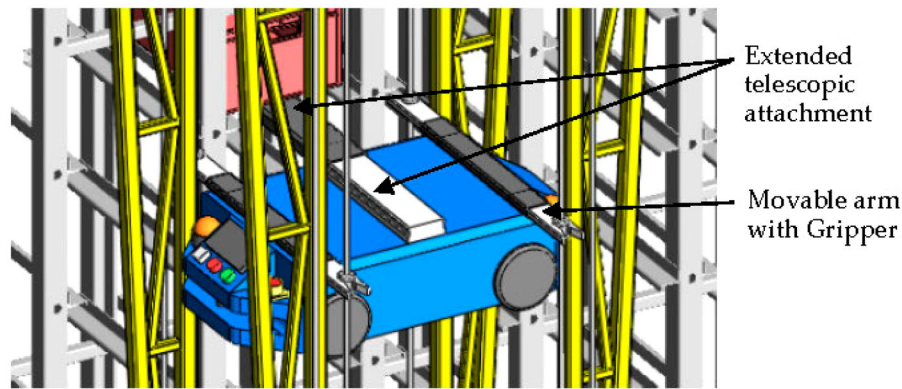


Figure 2. AGV lifted by ML to the target level (adopted from Jerman et al. 2021).

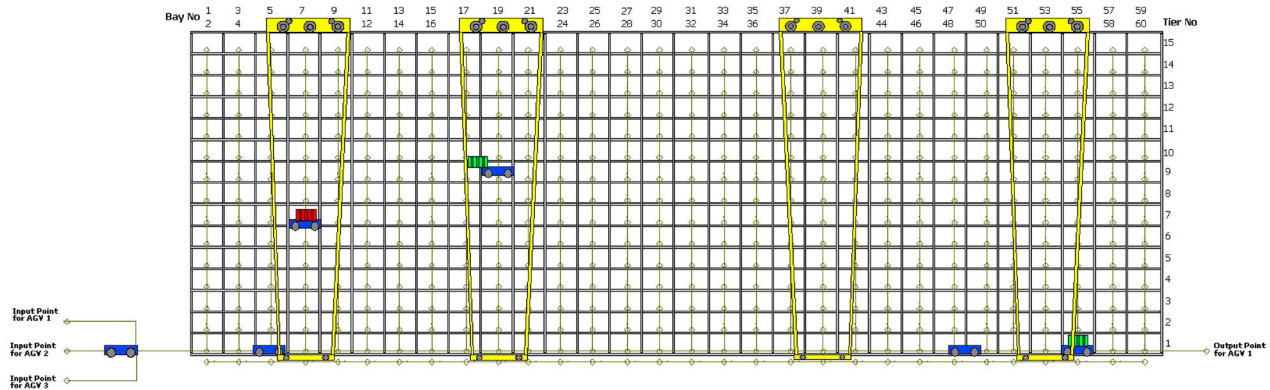


Figure 3. A snapshot from simulation animation in ARENA 16.00.

model is developed for a single aisle by assuming that each aisle is homogenous in terms of number AGVs, MLs, storage rack designs, and mean arrival rates and distributions.

Note that in each aisle, a pre-defined number of AGVs and MLs is dedicated. The numbers of AGVs and MLs are flexible so that those numbers can be changed based on the system requirements. MLs can travel in two ways down an aisle. However, to decrease the traffic congestion, AGVs are designed so that they can travel in one way within an aisle. Namely, AGVs enter the aisle from one edge point and leave the aisle from the other edge point. The input point is assumed to be located at the left entrance of each aisle, and the output point is located at the right outside of each aisle. Figure 3 shows a snapshot from the simulation animation along with some observed statistics. Storage loads arrive at the input point and retrieval loads are dropped off at the output point of the selected aisle. For example, in Figure 3, the AGV which is being lifted up in the very left-hand side ML is to complete a storage process. The AGV in the second ML from the left-hand side is retrieving a load from the storage rack. The empty AGV on very left-hand side ground is travelling to the regarding storage column to retrieve a load. The AGV in the very right-hand side has already

retrieved the load and, it travels to the output point to leave the aisle.

Note that the two MLs cannot pass each other within an aisle because of the physical structure limits of the system. The minimum distance between two MLs based on their ground levels could be a minimum two-bay distance to prevent collisions of the upper sides of the MLs. We develop a deadlock and collision prevention rules for both MLs and AGVs, and test it in the simulation models. They are explained in the following paragraphs.

The idle AGVs are assumed to wait at the input point. The flow of the AGV is from the input point to the output point. When an AGV arrives at the output point, this AGV is assumed to be ready to be assigned for a new job. In such a robotic technology, AGVs can also travel throughout the whole factory floor. We develop the number of AGVs and MLs scenarios such that AGVs never become a bottleneck in the system. The system's working principles along with the collision prevention rules are shown in Figures 4 and 5 flow charts for MLs and AGVs, respectively.

In Figure 4, the simulation model starts with the selection of idle MLs. Figure 3 shows the AGV process procedure. Note that, if the transaction address is at the first tier, then ML is not utilised and an available AGV starts

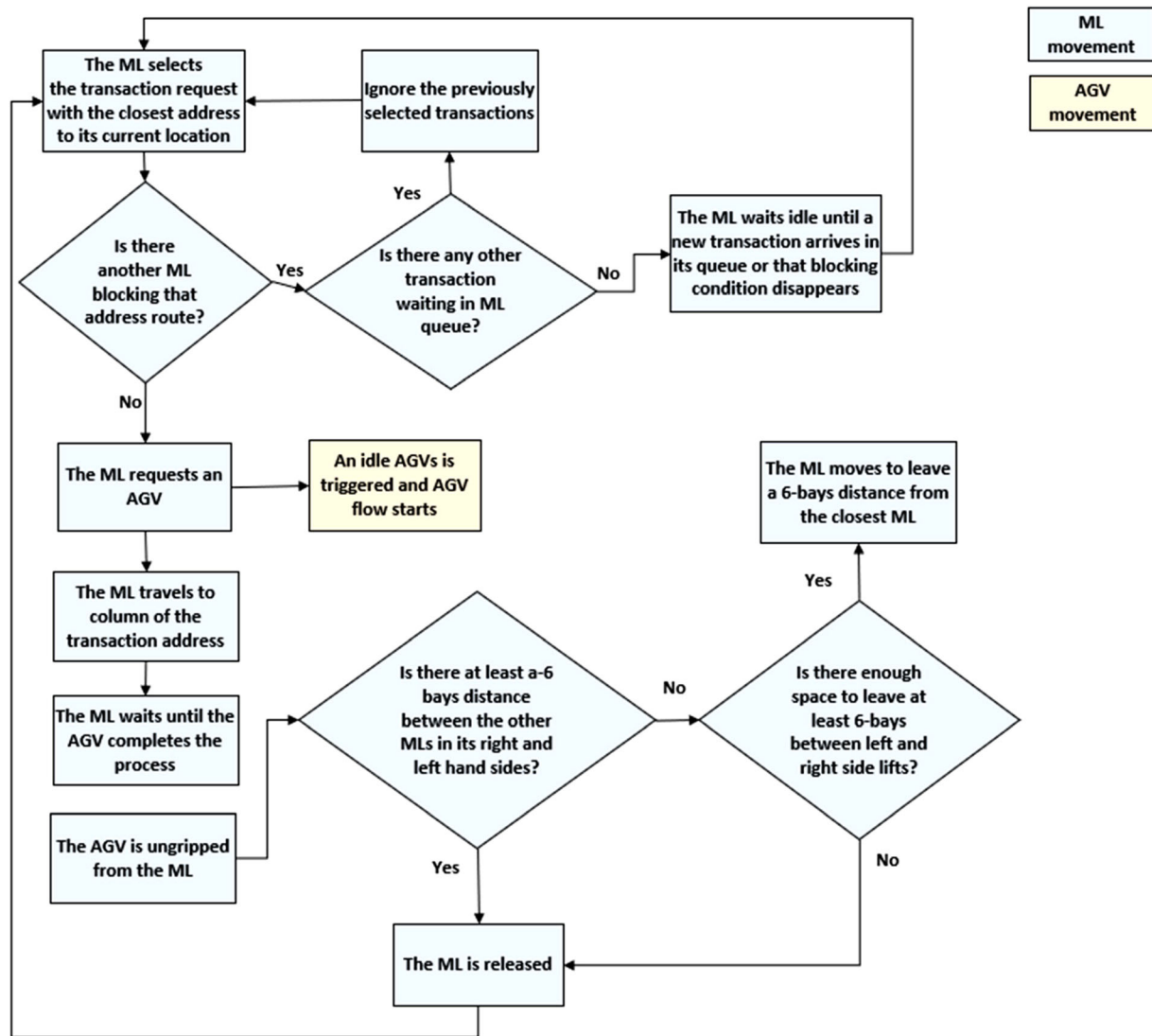


Figure 4. Simulation flow chart of ML travel.

the process immediately. There are two queues in the system, ML and AGV queues. The idle ML selects a transaction from its queue based on the closest distance rule. If currently there is another ML blocking its way through that closest transaction's column address, then the idle ML searches for another closest transaction whose column address does not include any blocking ML, for its safe travel. After the ML selects a suitable transaction to process, it also requests an AGV immediately, while travelling to the transaction column address. An available AGV selects a job from its queue, based on the closest column address to itself. Specifically, the available AGV checks its queue and selects the transaction with the closest column address to its location. After the AGV and the ML both arrive at the destination column, the AGV grips itself onto the ML to be moved by the ML to the designated tier of the storage rack. If the process is a storage operation, then the AGV is moved by the ML to the des-

ignated bay in the ML to set down the load; otherwise, the AGV is moved by the ML to the designated bay in order to pick up the load.

After the completion of the process, the AGV is moved by the ML to the first tier of the storage rack to leave the aisle through the output point. Note that while an idle AGV already completing a storage process leaves the aisle, it also checks whether or not there is any retrieval transaction request at the first tier of the storage rack through its output way. If there is, then the AGV retrieves that load before leaving the aisle. The same logic is also applied when an AGV already completes a storage process in the designated column of the storage rack. Under that condition, it can also process a retrieval request in the same column while it is lifted down by the ML. As a dwell point policy of MLs, if there is enough space, we consider that the ML aims to stay at a point by leaving the AGV a six-bay distance from its left- and right-hand side

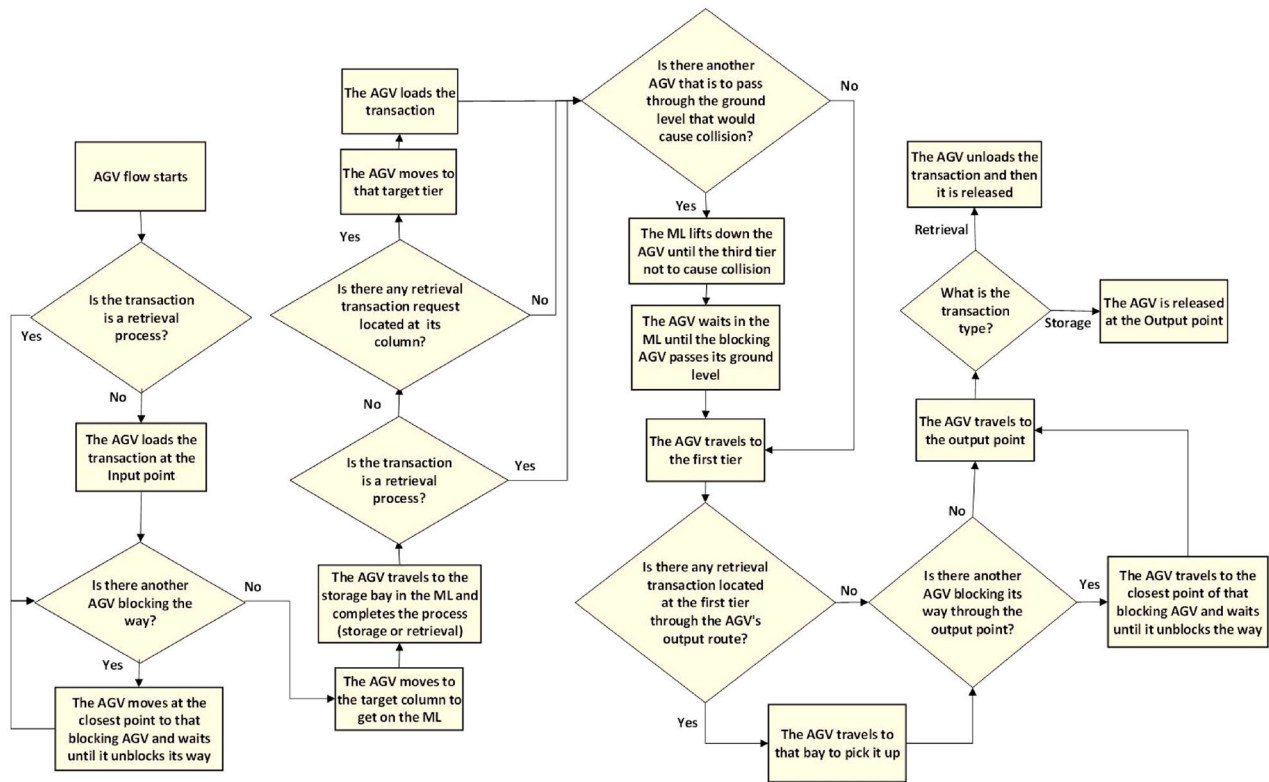


Figure 5. Simulation flow chart of AGV travel.

of the MLs. Otherwise, it stays at its last column address. This would help to have more distributed MLs throughout the aisle, as well as to decrease the collision possibility cases of MLs.

Note that in the model, there are two collision prevention rules:

- *The ML collision prevention rule:* This algorithm checks any possible ML collisions, and they are prevented by leaving at least a two-bay distance between the two closest MLs. Also, if there is a blocking ML in the way of an ML that is to make a transaction selection decision, then that ML may change the considered transaction to process. These collision cases are continuously checked during the ML travels.
- *The AGV collision prevention rule:* Two AGVs may collide while an AGV is lifted down by the ML, while another AGV tends to pass through that ML's ground level simultaneously. Another possible case might be, while an AGV is gripping or releasing on the ML on the first tier, another AGV may approach through there. For instance, in the first case, the collision is prevented by assigning a travel priority for the AGV travelling on the ground level. In the second case, priority is given to the AGV, which is already being gripped/released on the ML. For instance, those cases are shown in Figure 6 in detail.

In Case 1, while an AGV is being lifted down by the ML after completion of the process, the ML notices another AGV approaching to pass on the ground level, which might cause a collision. To prevent that possible collision case, the AGV attached to the ML is lifted down at the third tier of the storage rack and it waits there until the AGV on the ground level transits from the area. Namely, priority is assigned to the AGV travelling on the ground floor.

In Case 2, while an AGV is attaching onto an ML, another AGV travelling on ground floor approaches to pass that ML, which would cause a collision. In that case, priority is given to the AGV on the ML. More specifically, the AGV approaching on the ground floor would wait at a two-column distance to the ML. It waits there until the AGV is properly attached on the ML and starts to move in the vertical direction. Note that in the releasing case, the similar collision prevention rule is applied. Namely, the AGV travelling on the ground floor would wait at the two-column distance location to the ML, until the AGV is released from the ML and starts its horizontal travel to leave the ML.

The other simulation assumptions of the AVS/RS/ML are as follows (Jerman et al. 2021):

- Storage and retrieval transactions arrivals follow the Poisson process with an equal mean;

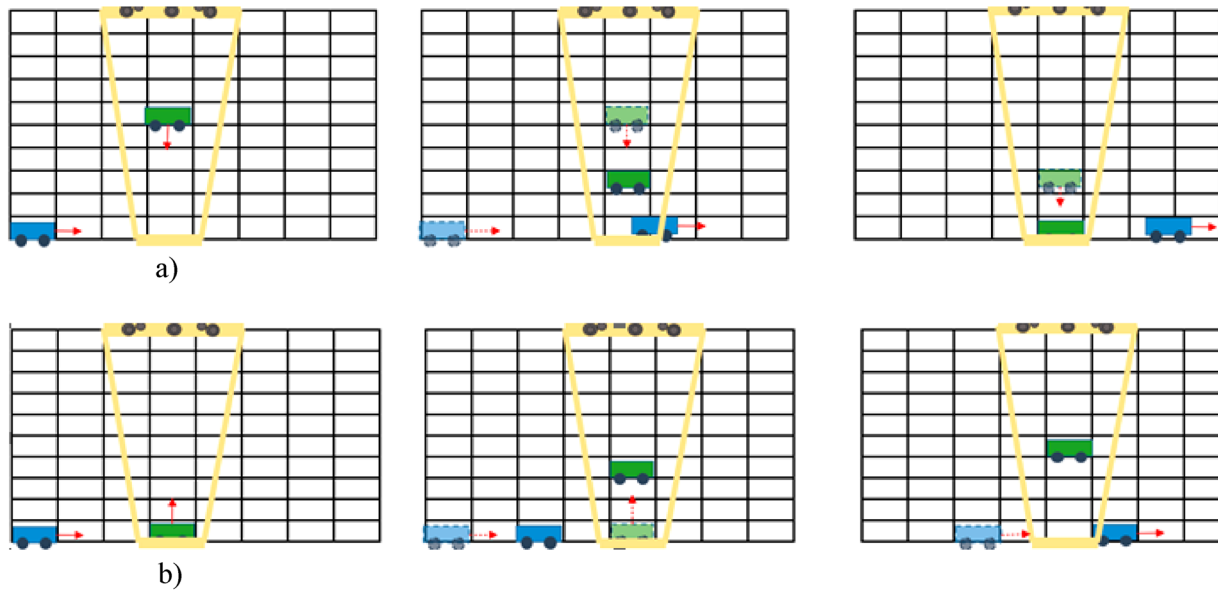


Figure 6. Two possible collision cases. (a) Case 1: Two AGVs tend to collide while one is being lifted down by the ML, (b) Case 2: Two AGVs tend to collide while one is being gripped on the ML.

- A random columns address is assigned for arriving transactions;
- If the storage or retrieval sequence of the processed transaction is at the first tier of the storage rack, then ML is not utilised;
- The maximum horizontal velocities of AGVs and MLs are $v_{xAGV} = 3 \text{ m/s}$ and $v_{xML} = 1.5 \text{ m/s}$, respectively. The maximum vertical velocity of the hoisting mechanism of ML with AGVs is $v_{yML} = 2 \text{ m/s}$;
- Accelerations and decelerations of AGVs and MLs are considered to be $a_{xAGV} = 2 \text{ m/s}^2$ and $a_{xML} = 1 \text{ m/s}^2$, respectively;
- The distance between two adjacent columns is equal to $w_{col} = 0.5 \text{ m}$. The distance between two adjacent tiers is assumed to be $h_{tier} = 0.35 \text{ m}$;
- Pick up and set down times for totes are equal to $t_p = 3 \text{ s}$ and $t_s = 3 \text{ s}$;
- Attaching and releasing times of AGVs on/from the ML are equal $t_G = t_{UG} = 1 \text{ s}$.

The simulation models are verified and validated by animating, debugging and applying degenerative tests on the models.

4.2. Simulation model of the tier-captive SBS/RS

Here, tier-captive SBS/RS design is studied for the comparison purpose. Specifically, the process throughput rate and the total investment cost performance metrics of the novel AVS/RS/ML and the tier-captive SBS/RS are compared under different warehouse designs. Tier-captive SBS/RS is utilised widely in warehouses for pro-

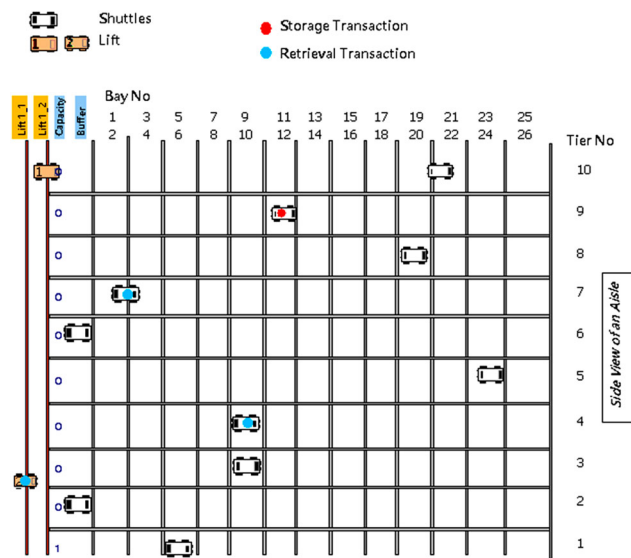


Figure 7. Tier-captive SBS/RS.

cessing mini-loads such as totes. Its transaction process rate is very high compared to its alternative warehouse technology mini-load AS/RS due to having a dedicated autonomous vehicle (i.e. shuttle) processing in each tier. In another word, since in each tier there is a dedicated shuttle serving for a specified tier within an aisle, this system is mostly utilised for systems requiring a high transaction process rate. A lifting mechanism is installed across of each aisle performing transfer of loads (i.e. totes) between tiers. When having a single lifting mechanism in each aisle while having multiple shuttles in that aisle, the average utilisation of shuttles is usually very low

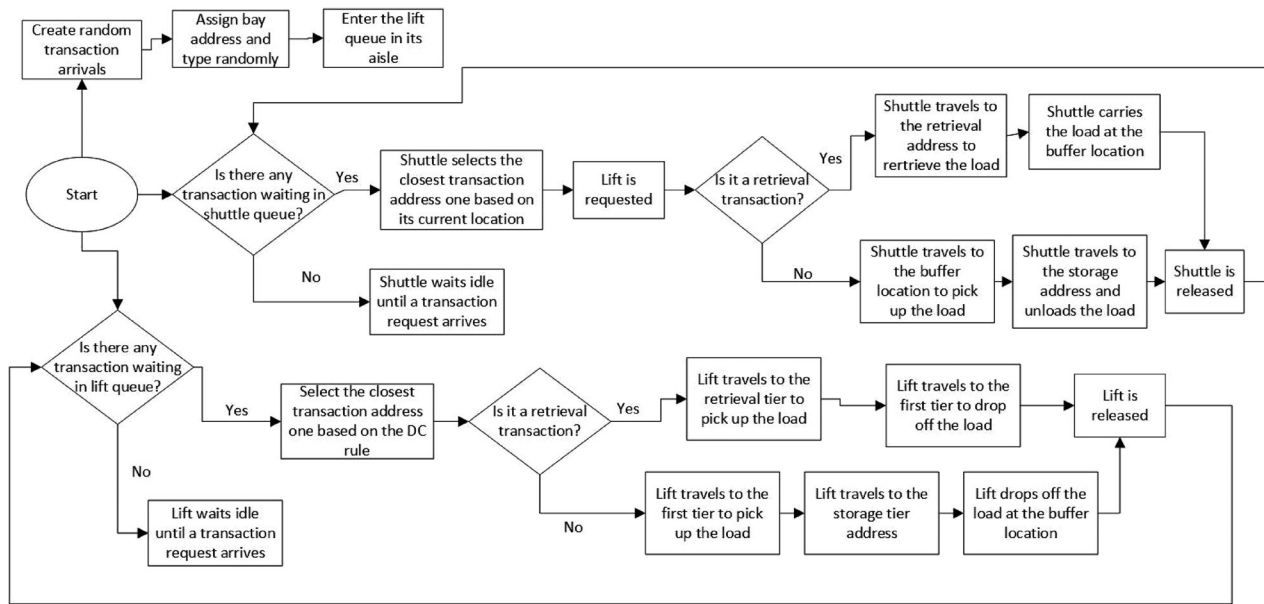


Figure 8. Flow chart of the simulation model of the tier-captive SBS/RS.

compared to the average utilisation of lifts. This unbalanced resource utilisation condition might be considered as a redundant investment cost in the system especially for shuttles. For this reason, instead of one, usually two independent lifts are used, which improve the utilisation unbalance rate to some extent. It is, on the other hand, expected that the novel AVS/RS/ML system would, by providing a flexible system design in terms of the number of resources (e.g. AGVs and even MLs), balance the utilisation more efficiently.

Figure 7 shows a tier-captive SBS/RS snapshot from the simulation animation. In each tier, there is a shuttle performing either the storage or retrieval process. A lifting system is installed along tiers to carry loads between them. The system consists of two independently operating lifts, each with the capacity of handling a single tote. There are 10 tiers in an aisle and 13 storage columns, and so, 26 bays in a tier. Thus, there are 10 shuttles in an aisle. The simulation model is built for a single aisle whose flow chart is given in Figure 8. According to that, a transaction request, its type, and storage address are created randomly. The lift and shuttle process transactions according to pre-defined selection rules. For instance, a lift selects a transaction based on dual-command (DC) and the shortest distance rule (SPT). Namely, if the lift already completes a retrieval process, since it will be on the ground level, it tends to select a storage transaction whose tier address is the closest one to its current location. ‘DC’ stands for processing in the order of storage-retrieval-storage-, etc. The shuttle assigns priority for a waiting transaction in its queue, based on the shortest distance

travel rule. Storage requests arrive at the input/out (I/O) location, which is located at the first (i.e. ground) level of the aisle. Retrieval loads are dropped off at the same location. More details on operating policy can be observed in Figure 6.

The assumptions utilised the simulation model of tier-captive SBS/RS designs flow (Lerher et al. 2015a, 2015b, 2021; Ekren 2020; Kucukyaşar, Ekren, and Lerher 2021):

- If the storage or retrieval transaction address is at the first tier, then the lifting mechanism is not utilised;
- There are two buffer locations located at either side of each tier. Totes are dropped-off at those buffer locations until they are picked up by shuttles or lifts;
- Each buffer area’s capacity is six totes;
- Each lifting table has a single-tote capacity;
- The lift drops off the storage tote on a buffer side based on which lifting table is utilised. The shuttle drops-off the tote at a buffer location randomly;
- Transaction arrivals follow the Poisson process with an equal mean of storage and retrieval;
- A random storage assignment policy is considered;
- The dwell points of lifts and shuttles are considered to be the last bay position or the buffer position based on their process types;
- The maximum velocities of shuttles and lifts are 4 and 3 m/s, respectively;
- Accelerations and decelerations of shuttles and lifts are considered as 3 and 2.5 m/s², respectively;
- Pick-up and drop-off times for totes are equal to $t_p = 3$ s and $t_s = 3$ s;

Table 2. Notations and definitions of the performance metrics.

Notation	Definition	Unit
$TC_{SBS/RS}$	Total investment cost of the tier-captive SBS/RS warehouse	EUR
$TC_{AVS/RS/ML}$	Total investment cost of the AVS/RS/ML warehouse	EUR
Δ	Average throughput rate	Number of transactions/hour
$\eta_{AGV/Shuttle}$	Average utilisations of an AGV or shuttle	%
$\eta_{ML/Lift}$	Average utilisation of an ML or lift	%

- The distance between two adjacent bays is equal and 0.5 m. The distance between two adjacent tiers is assumed to be 0.35 m.

To compare the two systems' performances, we conduct an experimental design work whose details are explained in the following section.

4.3. Design scenarios and performance analysis of AVS/RS/ML

In this study, the performance of the proposed AVS/RS/ML system is compared with the tier-captive SBS/RS based on their throughput performance metrics and initial investment costs under the same warehouse designs in terms of warehouse volume (number of tiers, bays, aisles, etc.). In the existing literature, tier-captive SBS/RS is declared to be a preferred technology due to its high throughput capacity rate. However, these systems might have high initial investment cost due to its increased number of shuttle carriers designated in each tier of the storage rack. The handicap of tier-captive SBS/RS is that due to the high number of shuttles in the system, the average utilisation of shuttles is usually very low compared to the average utilisation of lifts. Therefore, in the analyses, we also observe the average utilisation of vehicles and lifts performance metrics in the system to understand how we balance them.

Table 2 shows the notations utilised and their definitions for the performance metrics.

The performance metrics in Table 2 are observed in all described system experiments of AVS/RS/ML and tier-captive SBS/RS. We conduct different warehouse designs to compare the performance of the two systems. Table 3 shows the parameters utilised in the systems designs. The experiments are conducted based on the physical system configurations: the number of tiers (T), the number of columns (C), warehouse volume (Q), the number of AGVs (n_{AGVs}), the number of MLs (n_{MLs}), etc. as shown in Table 3.

The experiments are conducted based on velocity profiles (e.g. the maximum velocity and the acceleration/deceleration values) of shuttles/AGVs and lifts/MLs,

Table 3. Notations and definitions of the utilised design parameters.

Notation	Definition	Unit
T	Number of tiers in a single aisle	
C	Number of columns at single side of a single aisle	
A	Number of aisles in the warehouse	
Q	Warehouse volume	
N_{AGVs}	Number of AGVs in an aisle	
N_{MLs}	Number of MLs in an aisle	
$N_{Shuttles}$	Number of shuttles in an aisle	
L, H	Length and height of the storage rack	m
v_x, v_y	The maximum velocity of the of shuttles/AGVs on vertical (y) and horizontal (x) directions	m/s
a_x, a_y	The acceleration/deceleration of shuttles/AGVs on vertical (y) and horizontal (x) directions	m/s ²

which are given in Table 4. And, all the experimental scenarios along with the parameter levels are given in Table 5. Note that, we complete a total of 36 scenarios under a single warehouse volume, $Q = 12,000$ storage units. Here, Q is calculated by (1).

$$Q = 2 \cdot T \cdot A \cdot C \quad (1)$$

Note that in Table 5, the number of lifts is equal to one, and the number of shuttles is equal to T , the number of tiers, in the tier-captive SBS/RS. The number of AGVs and MLs change based on the intended experiment. More specifically, they are changed according to the total investment cost values and throughput rates, where the two systems can compete with each other.

Remember that one of the performance metrics considered in the comparison purpose of those two systems is the total investment cost (TC). To calculate the TC values, we set the unit cost parameters as in Table 6. Those values are approximate and obtained from the interviews with experienced material handling specialist from practice.

Total costs of the systems are calculated by (2) and (3) for SBS/RS and AVS/RS/ML warehouses, respectively. Note that (λ) is a pre-defined value in the simulation models. The (λ) values are adjusted in the simulation models so that the system runs approximately under 95% average utilisation values of the bottleneck servers (i.e. lifting and ML mechanisms). Note that, each metre of height of the storage racks would bring cost for lifts and MLs in tier-captive SBS/RS and AVS/RS/ML, respectively.

$$TC_{SBS/RS} = A \cdot (T \cdot C_{Shuttle} + C_{Lift} + H \cdot C_{Lift/H}) \quad (2)$$

$$TC_{AVS/RS/ML} = A \cdot (N_{AGVs} \cdot C_{AGV} + N_{MLs} \cdot C_{ML} + H \cdot C_{ML/H}) \quad (3)$$

We complete a steady-state analysis with five independent random replications for each scenario of SBS/RS

Table 4. Velocity profiles for AVS/RS/ML and the tier-captive SBS/RS.

Design	Velocity profile	Shuttle/AGV		Lift		ML	
		v_x (m/s)	a_x (m/s ²)	v_x (m/s)	a_x (m/s ²)	v_y (m/s)	a_y (m/s ²)
AVS/RS/ML	Low	2	1	1	0.5	1.5	1
	High	3	2	1.5	1	2	2
Tier-Captive SBS/RS	Low	2.5	1.5	2	1.5	–	–
	High	4	3	3	2.5	–	–

Table 5. Experimental design scenarios.

Scenario No.	System type	T	A	C	Velocity profile	$N_{AGVs}/N_{Shuttles}$	N_{MLs}/N_{Lifts}
1	AVS/RS/ML	10	20	30	Low	6	4
2	AVS/RS/ML	10	20	30	High	6	4
3	AVS/RS/ML	10	15	40	Low	7	5
4	AVS/RS/ML	10	15	40	High	7	5
5	AVS/RS/ML	10	12	50	Low	7	5
6	AVS/RS/ML	10	12	50	High	8	5
7	AVS/RS/ML	20	10	30	Low	9	6
8	AVS/RS/ML	20	10	30	High	9	6
9	AVS/RS/ML	20	7	40	Low	8	6
10	AVS/RS/ML	20	7	40	High	8	6
11	AVS/RS/ML	20	6	50	Low	9	7
12	AVS/RS/ML	20	6	50	High	9	7
13	AVS/RS/ML	30	7	30	Low	8	5
14	AVS/RS/ML	30	7	30	High	8	5
15	AVS/RS/ML	30	5	40	Low	10	7
16	AVS/RS/ML	30	5	40	High	10	7
17	AVS/RS/ML	30	4	50	Low	12	7
18	AVS/RS/ML	30	4	50	High	12	7
19	SBS/RS	10	20	30	Low	10	1
20	SBS/RS	10	20	30	High	10	1
21	SBS/RS	10	15	40	Low	10	1
22	SBS/RS	10	15	40	High	10	1
23	SBS/RS	10	12	50	Low	10	1
24	SBS/RS	10	12	50	High	10	1
25	SBS/RS	20	10	30	Low	20	1
26	SBS/RS	20	10	30	High	20	1
27	SBS/RS	20	7	40	Low	20	1
28	SBS/RS	20	7	40	High	20	1
29	SBS/RS	20	6	50	Low	20	1
30	SBS/RS	20	6	50	High	20	1
31	SBS/RS	30	7	30	Low	30	1
32	SBS/RS	30	7	30	High	30	1
33	SBS/RS	30	5	40	Low	30	1
34	SBS/RS	30	5	40	High	30	1
35	SBS/RS	30	4	50	Low	30	1
36	SBS/RS	30	4	50	High	30	1

and AVS/RS/ML. The replication length is 45 days with a 15-day warm-up period. The simulation results are summarised in the below section.

5. Results and discussion

In this section, we provide the results of the simulations runs and discuss on those results. We provide the simulation results for average of five replications along with the confidence intervals (CIs) at 95% level in Table 7.

Table 7 results are summarised by graphs in Figures 9–12 for interpretation of the results. Figure 9 shows λ in comparison of the total cost of each experiment. In Figure 9, the results are also shown by tier-based categorising. Remember that each experiment is conducted

Table 6. Unit cost parameters.

Notation	Description	Amount
C_{AGV}	Cost of an AGV	25,000 EUR
$C_{Shuttle}$	Cost of a shuttle	25,000 EUR
C_{ML}	Cost of an ML	30,000 EUR
C_{Lift}	Cost of a lift	30,000 EUR
$C_{ML/H}$	Cost of ML per metre of H	2000 EUR
$C_{Lift/H}$	Cost of lift per metre of H	3000 EUR

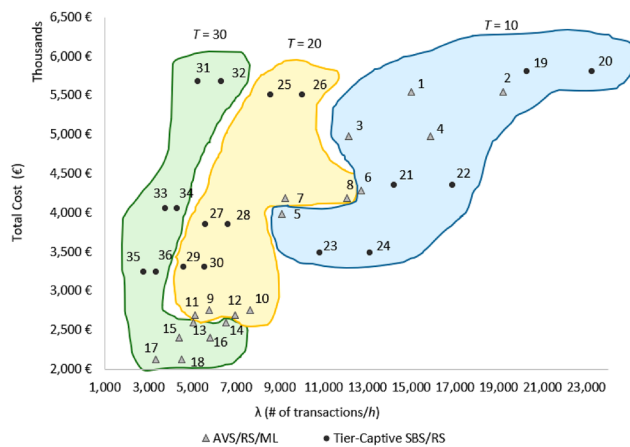
for the same warehouse volume, 12,000 storage locations.

From Figure 9, it is observed that the AVS/RS/ML usually provides lower total investment costs than the tier-captive SBS/RS. However, while up to around 9000 λ value, the AVS/RS/ML outperforms tier-captive SBS/RS in terms of total cost, when the λ values are higher

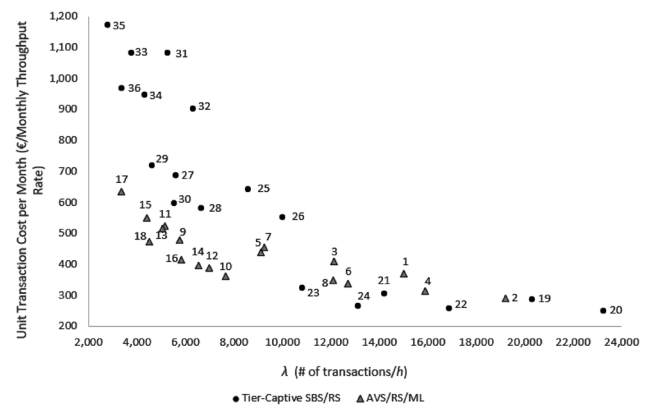
Table 7. Results of experiments with 95% confidence interval.

Scenario No.	$TC_{AVS/RS/ML}$	λ	η_{AGV}	η_{ML}	Scenario No.	$TC_{SBS/RS}$	Δ	$\eta_{Shuttle}$	η_{Lift}
1	5,540,000 €	15,010 ± 952	90% ± 0.08%	96% ± 0.13%	19	5,810,000 €	20,280 ± 1,110	39% ± 0.06%	96% ± 0.09%
2	5,540,000 €	19,210 ± 1521	89% ± 0.11%	96% ± 0.16%	20	5,810,000 €	23,230 ± 572	37% ± 0.02%	96% ± 0.03%
3	4,980,000 €	12,139 ± 1232	95% ± 0.1%	96% ± 0.21%	21	4,357,500 €	14,207 ± 863	20% ± 0.03%	96% ± 0.08%
4	4,980,000 €	15,889 ± 1477	93% ± 0.1%	96% ± 0.17%	22	4,357,500 €	16,886 ± 641	19% ± 0.02%	96% ± 0.05%
5	3,984,000 €	9100 ± 1077	95% ± 0.08%	96% ± 0.19%	23	3,486,000 €	10,797 ± 523	43% ± 0.02%	96% ± 0.06%
6	4,284,000 €	12,711 ± 1474	88% ± 0.11%	96% ± 0.17%	24	3,486,000 €	13,094 ± 764	41% ± 0.05%	96% ± 0.05%
7	4,190,000 €	9236 ± 1488	86% ± 5.3%	94% ± 8.14%	25	5,510,000 €	8,573 ± 549	17% ± 0.02%	96% ± 0.05%
8	4,190,000 €	12,086 ± 1383	85% ± 0.07%	94% ± 0.08%	26	5,510,000 €	9998 ± 1123	16% ± 0.03%	96% ± 0.07%
9	2,758,000 €	5768 ± 1212	94% ± 0.1%	96% ± 0.19%	27	3,857,000 €	5604 ± 886	18% ± 0.02%	96% ± 0.07%
10	2,758,000 €	7639 ± 1373	93% ± 0.09%	96% ± 0.17%	28	3,857,000 €	6630 ± 863	17% ± 0.02%	96% ± 0.04%
11	2,694,000 €	5145 ± 1256	96% ± 0.1%	95% ± 0.24%	29	3,306,000 €	4598 ± 998	19% ± 0.03%	96% ± 0.1%
12	2,694,000 €	6971 ± 1123	95% ± 0.06%	96% ± 0.12%	30	3,306,000 €	5535 ± 650	18% ± 0.02%	96% ± 0.04%
13	2,597,000 €	5044 ± 958	81% ± 0.07%	96% ± 0.08%	31	5,680,500 €	5251 ± 898	10% ± 0.02%	96% ± 0.08%
14	2,597,000 €	6549 ± 1569	80% ± 0.11%	96% ± 0.11%	32	5,680,500 €	6299 ± 515	10% ± 0.01%	96% ± 0.04%
15	2,405,000 €	4386 ± 3163	91% ± 0.05%	96% ± 0.06%	33	4,057,500 €	3750 ± 905	11% ± 0.02%	96% ± 0.09%
16	2,405,000 €	5809 ± 1129	89% ± 0.07%	96% ± 0.1%	34	4,057,500 €	4286 ± 559	10% ± 0.01%	96% ± 0.05%
17	2,124,000 €	3350 ± 1252	80% ± 0.1%	95% ± 0.14%	35	3,246,000 €	2769 ± 1022	11% ± 0.02%	96% ± 0.09%
18	2,124,000 €	4502 ± 1327	79% ± 0.1%	96% ± 0.12%	36	3,246,000 €	3350 ± 982	11% ± 0.02%	96% ± 0.07%

Note: EUR is expressed with a sign €.

**Figure 9.** Throughput performance in comparison with total investment cost.

than 9000, the tier-captive SBS/RS tends to become better from the cost efficiency perspective. This can be commented that, tier-captive SBS/SR becomes cost efficient under high throughput rate system requirements, rather than relatively low throughput rate system requirements. Hence, for relatively moderate and low throughput rate requirements, AVS/RS/ML technology can be preferred in warehouses. In another word, not to spend a redundant investment cost for a warehouse technology, companies should determine their process rate expectations explicitly, before investing on such technologies. Based on AVS/RS/ML or tier-captive SBS/RS, it is concluded that process rate plays significant role on total investment cost. From Figure 9, it can also be observed that, when the number of tiers decreases in the warehouse design, transaction process rate tends to increase in both systems. However, the investment cost increases in AVS/RS/ML more, compared to tier-captive SBS/RS.

**Figure 10.** Hourly throughput rate versus unit investment cost per transaction.

Since, when the total investment cost increases, throughput rate also tends to increase, it might also be better to observe, the unit investment cost per transaction, where we provide them in Figure 10.

Figure 10 shows hourly throughput rate versus unit transaction cost, based on the monthly process rate. As in Figure 9, from Figure 10 it can also be observed that when transaction rate capacity increases in the system, the unit investment cost per transaction becomes lower in tier-captive SBS/RS than AVS/RS/ML. This means that the money spent for investment to process a single transaction in AVS/RS/ML is lower under relatively low throughput rate designs than the tier-captive SBS/RS designs. Hence, once again, if the company's requirement is not a high process rate capacity, then it may be better to invest in AVS/RS/ML technology.

Figure 11 shows conducted design (based on the number of tiers) versus unit investment cost per transaction graph. According to that figure, it is observed that the

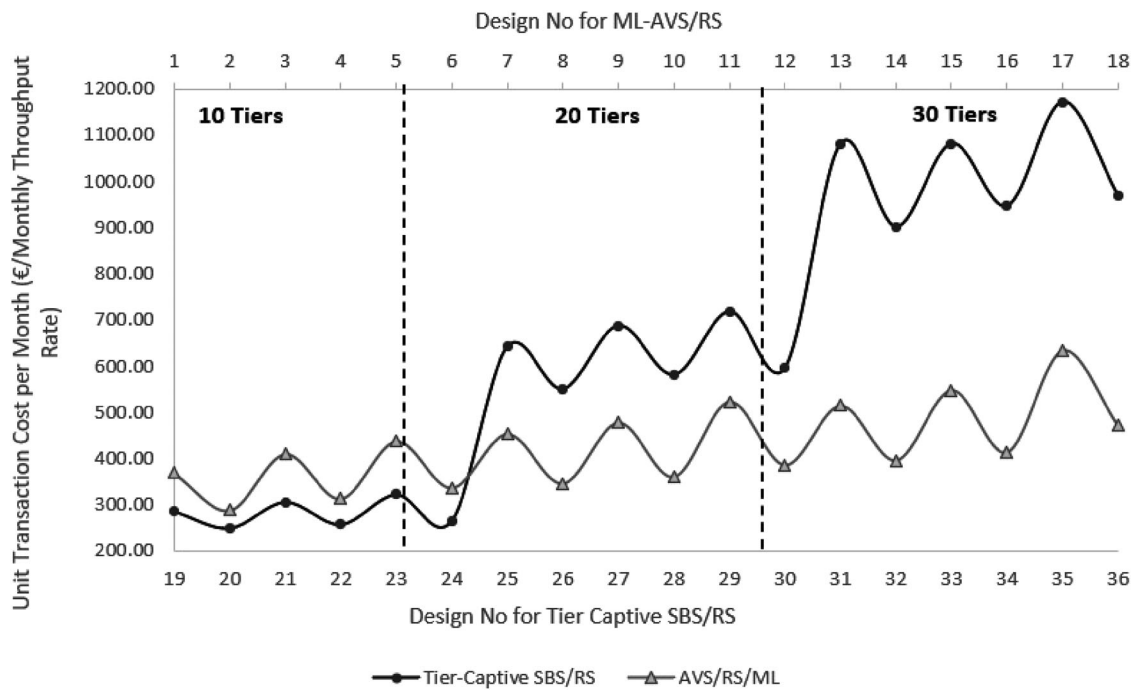


Figure 11. Design (based on number of tiers) versus unit investment cost per transaction.

unit cost per transaction increases by the number of tiers increase. This is probably because that when number of tiers increases in the system, the total investment cost increases drastically especially in the tier-captive SBS/RS because of the increased number of shuttles. Besides, also as observed in Figure 9, increase in number of tiers decreases the transaction process rate. Hence, this causes the unit cost per transaction to decrease under the increased numbers of tiers scenarios especially in tier-captive SBS/RS designs. It should be noted that the reason that the gap between two systems' costs increases drastically in the high number of tiers case is due to that drastic investment cost increase in tier-captive SBS/RS.

Figure 12 shows, the number of tiers versus average utilisation of lift/ML, AGV, and the shuttle graph. As mentioned previously, the simulation models are run under roughly 95% average utilisation values of the bottleneck servers (i.e. lifts/MLs). From Figure 12, it is observed that average utilisation of shuttles is very low compared to the average utilisation of lifts. However, in AVS/RS/ML, those utilisation values are well balanced in AGVs and MLs.

To sum up, the average utilisations of shuttles and lifts are more balanced in AVS/RS/ML than tier-captive SBS/RS. Before investing for such a warehouse automation technology, a practitioner should define his/her process rate requirements and select the most proper system design accordingly. He/she could also consider unit investment cost per transaction performance metric in

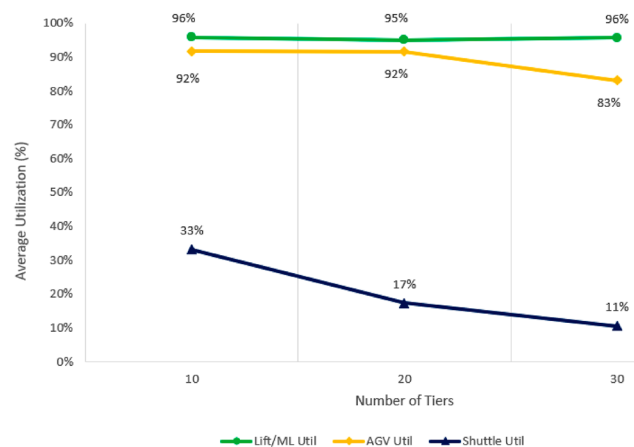


Figure 12. Number of tiers versus average utilisation.

his/her evaluation, providing significant insight on the total cost and throughput rate relationship.

6. Conclusions

This paper studies a novel automated warehousing technology AVS/RS/ML, developed as an alternative system design to tier-captive SBS/RS. In the proposed design, it is aimed to provide an inexpensive AVS/RS solution with highly utilised AGVs, also capable of warehouse operations out-of-warehouse plant. We compare the performance of this novel system with its equivalent tier-captive SBS/RS warehouse design in terms of

their initial investments costs, throughput rates, and average utilisation of lifts/MLs in the system. We develop collision prevention algorithms and implement on the AVS/RS/ML system by simulating the models to test their effectiveness. We conduct 18 design experiments for each technology solution and compare their performances by averages of five independent replications. The results show that, tier-captive SBS/SR becomes cost efficient under high throughput rate system requirements rather than relatively low throughput rate system requirements. Hence, for relatively moderate and low process rate requirements, AVS/RS/ML technology can be preferred by warehouse managers. Besides, it is observed that unit-cost per month performance metric in AVS/RS/ML is not very sensitive to increase of number of tiers in the system, compared to the tier-captive SBS/RS case. Hence, AVS/RS/ML might become more cost-efficient when a high-tier warehouse system design is considered.

As far as future works, more smart transaction selection and collision prevention algorithms can be developed to increase performance of AVS/RS/ML. Also, the performance of the system performances can be compared for different measures such as queueing performance metrics, flow times, variances, etc. As well, more warehouse capacity experiments as well as a detailed cost analysis by involving waiting space requirements of AGVs and loads can also be conducted.

A future study could compare the performance of this new technology with other warehousing technologies, such as Fixed-aisle Unit-load Automated Storage and Retrieval Systems (AS/RSs). Also, modelling the flexible travel of AGVs in the other side of the warehouse, taking into account their actual speed based on empty or full travel conditions, can also be considered as a future study.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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