Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 58-19 (2024) 1216–1221

A design framework for shuttle-based automated storage systems

Ilaria Battarra*, Riccardo Accorsi, Giacomo Lupi, Riccardo Manzini

**Alma Mater Studiorum - University of Bologna, Bologna, Italy*
(e-mail: ilaria.battarra2@unibo.it, riccardo.accorsi2@unibo.it, giacomo.lupi2@unibo.it, riccardo.manzini@unibo.it).*

Abstract: Shuttle-based automated storage systems are blooming in modern companies as well as research interest in these systems due to their high storage density, flexibility, and short cycle time. This study aims to introduce a novel design framework exploring different layout configurations affecting system performance under three main dimensions: racks, material handling vehicles, and buffer areas. This taxonomy supports the definition of a standard notation and increases the awareness of future industrial and academic research regarding variant design configurations. A review of the literature reveals the state-of-art and existing gaps.

Copyright © 2024 The Authors. This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

Keywords: automated warehouse, shuttle-based storage system, taxonomy, automated vehicle storage and retrieval system, AVS/RS, SBS/RS, framework, design, classification.

1. INTRODUCTION

Warehouses play a crucial role in modern supply chains as dynamic hubs for managing the flow of goods and balancing suppliers' needs and consumers' demands. With the recent advancements in automation and Internet of Things (IoT), large flexibility, short response time, and high storage density are pivotal to improving overall supply chain efficiency.

Warehousing operations include various activities such as receiving, quality inspection, handling, storage, physical stock counting, packaging, and outbound delivery. These activities can be manual or automatic. Traditional warehouses usually involve manual labor and conventional material handling equipment (e.g., forklifts, basic shelving). Drive-in, block-storage, and cross-docking are among the most common. While these traditional storage solutions have been the backbone of warehousing and logistics for many years, they come with certain disadvantages compared to automated solutions. Automation enhances efficiency by eliminating redundant operations and reducing the execution time of necessary activities in warehouse operations [Kamali, 2019]. Increasing precision and accuracy reduces the risk of errors and safety risks for workers. Space utilization is maximized by adopting technologies like vertical lifts or stacker cranes.

The automated storage solutions mainly differ in the level of automation and the typology of material handling vehicles. One of the most common is the automated storage and retrieval system (AS/RS). This storage system adopts a stacker crane that moves vertically and horizontally simultaneously, transporting one or two palletized unit loads (ULs). It can access multiple levels of racks or shelving structures, maximizing vertical space within the warehouse. Nevertheless, no more than one stacker crane can move into an aisle, neglecting parallel movements along the system levels. Moreover, the space is not well exploited because the maximum rack depth depends on the length of the crane's forks, which is usually a few meters.

The shuttle-based storage system is blooming in modern companies to overcome these limits. It mainly differs for the storage/retrieval (S/R) machine and rack configuration. The movements of the S/R machine are split and assigned to independent vehicles that move simultaneously. This system usually handles palletized unit loads or plastic containers (i.e., totes). In the first case, it is widely known as the automated vehicle storage and retrieval system (AVS/RS). In the second case, it is known as the shuttle-based storage and retrieval system (SBS/RS). These storage solutions can rely on deep channels (named lanes) reaching dozens of meters, providing high storage density, flexibility, and short cycle time. The cycle time is the elapsed time between when a storage (retrieval) request occurs and reaches the storage location (exits of the warehousing system). It defines the system throughput, which is the number of requests completed per unit of time. Keeping this time short is necessary to address the challenges of just-in-time production, e-commerce, and globalization trends. Many studies illustrated analytical and simulative models to measure, monitor, and optimize system performance, such as S/R cycle time and system throughput. They are linked to initial assumptions regarding the vehicle's kinematics, storage policy, dispatching rules, storage (S) or retrieval (R) arrival and service rates, and physical design. This study focuses on the physical design of shuttle-based storage systems to introduce and classify the design features affecting system performance under three dimensions: racks, material handling vehicles, and buffer areas. The resulting framework provides a standard notation to increase the awareness of industrial and academic research regarding all the possible shuttle-based design configurations. The proposed taxonomy represents an original contribution to literature studies on shuttle-based storage systems by addressing the lack of a design-based classification and pointing out the current literature gaps.

The remainder of this study is described as follows: Section 2 illustrates the most relevant design features of the shuttle-

2405-8963 Copyright © 2024 The Authors. This is an open access article under the CC BY-NC-ND license.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2024.09.086

based storage system. A standard notation is presented through a novel framework. Section 3 emphasizes how literature studies have addressed the design features identified in this study and points out major literature gaps. Finally, Section 4 presents some conclusions and outlines for further research.

2. SYSTEM DESIGN FEATURES

A shuttle-based automated storage system consists of n-independent levels connected by an elevator system (see lift-in and lift-out in Fig.1), which provides vertical movement (y-direction). There are two buffers (see *buffer-in* and *buffer-out*, Fig.1) to collect the incoming and outgoing ULs out of the storage system. Each system level is equipped with buffer areas called bays (see *bay-in* and *bay-out*, Fig.1) and conveyor systems (see *conv*, Fig.1). Given a generic level, the horizontal movement is performed by a vehicle, called *shuttle*, which moves along the main cross-aisle (x-direction). It withdraws or deposits the ULs within the lanes (z-direction) thanks to the fork system. In the case of deep-lane storage systems, an additional independent vehicle, called *satellite*, is introduced for performing horizontal movements within the lanes (z-direction). The satellite is required because the shuttle's forks cannot reach great depths. Figure 1 exemplifies a shuttle-based deep-lane AVS/RS with four system levels connected by two dedicated lifts, one for S and one for R requests.

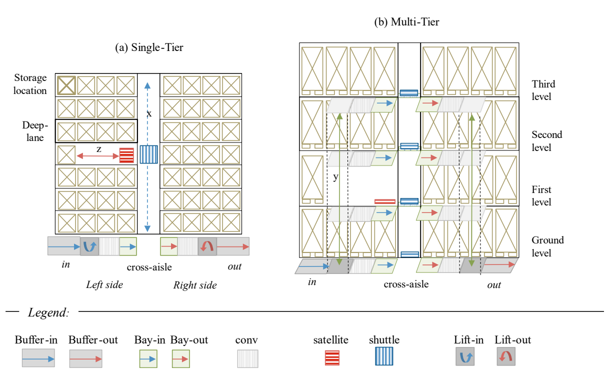

Fig.1. Example of a lift- and shuttle-based deep-lane AVS/RS

This AVS/RS configuration does not meet all possible layout configurations of shuttle-based storage systems. For instance, a hybrid configuration between the AVS/RS and the traditional crane-based (i.e., AS/RS) involves the multilevel shuttle. In this case, the shuttle is incorporated into an elevator system that simultaneously enables movements vertically and horizontally. The system levels are divided into sets, and each set is served by a multilevel shuttle. This paper aims to illustrates the most relevant design features of the shuttle-based storage systems. These features concern three dimensions: (1) racks, (2) material handling vehicles, and (2) buffer areas. A detailed description of each element follows:

(1) Racks. A shuttle-based storage system consists of a double-sided cross-aisle with lanes on the left and the right (as illustrated in Fig.1a). The rack configuration differs for the unit load handled, number of levels, number of aisles, lane depth (i.e., number of ULs within a lane), and Depth Strategy.

- The storage system can handle palletized ULs (*Pallet*) or plastic totes (*Tote*).
- The number of system levels usually depends on the physical constraints of the building and the type of UL stored. AVS/RSs for palletized ULs have fewer levels because each requires a few meters in height (y-direction). On the contrary, SBS/RSs for totes have many levels because each requires just a few tens of centimeters in y. A system with one single level is called a *single-tier* (*ST*). Otherwise, it is a *multiple-tier* system (*MT*). This distinction clarifies the modeling approaches proposed by literature studies.
- The storage system is made of one or more storage blocks. A storage block consists of n-independent levels and a main cross-aisle at each level, as illustrated in Fig.1. A storage system with one storage block is called a *single-aisle* (SA). Otherwise, it is a *multiple-aisles* (*MA*) system. Fig.2 shows the plan view of a *MA* storage system made of two storage blocks.
- The lane depth defines the number of ULs that can be stored in the lane. It is a *single-deep* (*SD*) or *double-deep* (*DD*) lane if it can host one or two ULs. Otherwise, it is a *multiple-deep* (*MD*) lane and can reach dozens of meters. The *MD* lanes in Fig. 2 can store up to 4 ULs. The lane depth is the same on both sides of the cross-aisle; thus, the storage system is symmetrical (*S*) to the cross-aisle. Otherwise, it is asymmetric (*AS*).
- The Depth Strategy defines if the number of storable ULs changes over time. It can be fixed over time (*Fix)* or variable (*Var*). This latter configuration is helpful for multiple-aisle storage systems where lanes share the back, as illustrated in Fig.2 by red lines. There is no physical constraint between the lanes, the satellite can reach all the storage locations, entering on both sides (i.e., from cross-aisles 1 and 2 in Fig.2). The lane depth can be redefined every time both lanes are empty. This strategy can be helpful when specific storage policies are adopted. An example is the mono stock-keeping unit (SKU) policy, where only ULs of the same SKU can be stored together. Modeling the lane depth according to the SKU's batch provides a more compact storage system and increases space efficiency.

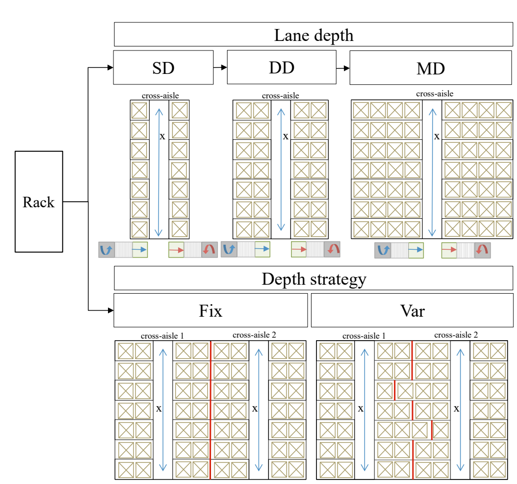

Fig.2. Lane depth and depth strategy

(2) Material handling vehicles. Different types of vehicles are involved for processing S/R requests. The main distinction regards the type of movement provided.

- Vertical movement (y-direction) is provided by an elevator system that consists of a lift (*Lift*) or a conveyor system (*Conv*). In some storage systems, there is no elevator system because ULs are directly brought by forklifts (*Fork*) at the system levels. In the case of a lift-based system, the elevator can serve a storage block (*aisle-captive – AC*) or moves among storage blocks (*aisle-to-aisle – AA*). In the *AA* case, the lift is called *a movable lift (ML).*

- Horizontal movements (x- and z- directions) are provided by one or two vehicles, according to the lane depth. For *single-* and *double-deep* racks, there is only one vehicle that moves back and forth along the main cross-aisle (x-direction). It is the shuttle (*Sh*) or the multilevel shuttle (*MLSh*). Both options mentioned above are valid for the multiple-deep rack, with the addition of an independent vehicle called satellite *(Sat),* which moves within the lanes (z-direction). The two resulting configurations, *ShSat* and *MLShSat,* are exemplified in Fig.3. Moreover, vehicles can be assigned to a single level (*tier-captive configuration - TC*) or travel among levels (*tier-to-tier configuration - TT*) thanks to the elevator system (i.e., the lift).

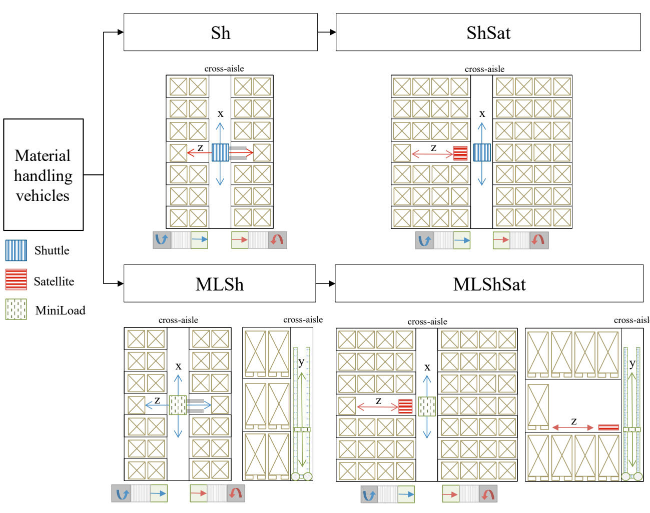

Fig.3. Material handling vehicles: horizontal movements.

These vehicles mainly differ in terms of loading capacity. The most relevant combinations are illustrated in Fig.4. and described as follows:

- Sh and MLSh. The shuttle and the multilevel shuttle can simultaneously handle one (Sh1UL, MLSh1UL) or two ULs. According to the cross-aisle width, the double-loading capacity can be developed among the z- or x-direction, as illustrated in *Sh2UL(z), MLSh2UL(z),* and *Sh2UL(x), MLSh2UL(x)* in Fig. 4.

- Sat. The satellite can handle one (*Sat1UL*) or two ULs simultaneously. The double-loading capacity can be developed only in the z-direction, as illustrated *Sat2UL(z)* in Fig. 4. In addition, it can perform parallel tasks (*R - Released*) or wait for the Sh/MLSh (*NR - NotReleased*). In this latter case, the shuttle always carries the satellite on board and remains in front of the storage lane when the satellite is released into a lane. Otherwise, a *R* satellite is independent, and the shuttle can move along the cross-aisle to load/unload ULs without waiting for the satellite. In this case, more than one satellite can be assigned to the same Sh/MLSh (*number 1, number >1*).

- Lift. The lift can transport one (*L1UL*) or two ULs simultaneously. According to the bay-in and -out capacity, the double-capacity can be developed in the z- or x-direction, as illustrated in Fig.4 L2UL*(z)* and *L2UL(x)*. Moreover, a lift can serve only S requests *(LIn),* R requests (*LOut*), or both (*LIO*). In the former case, it is dedicated. Otherwise, as in the *LIO* option, it is shared. Finally, the number of lifts serving a storage system can be one (*number 1*) or more (*number >1*).

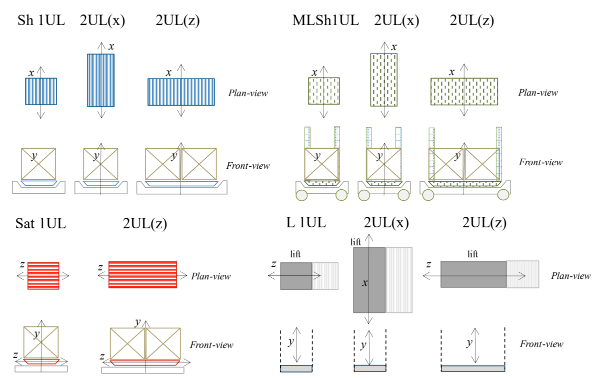

Fig.4. Vehicles loading capacity.

(3) Buffer areas. The shuttle-based storage system is equipped with buffers at the ground level called *buffer-in* and *buffer-out*. The former contains the incoming ULs for the lift/conveyor, while the latter collects the outgoing ULs from the lift/conveyor. These buffers are always present, except for the storage systems served by forklifts because ULs are withdrawn or deposited directly at the system levels. Moreover, as regards the tier-captive storage systems, there are additional buffers at the system levels called *bay-in* and *bay-out*. They are the interface between the lift/conveyor and the shuttle. Since they are located next to the lift/conveyor system, the lift location and its capacity are usually linked to the bay ones (see Fig.5). The features that define the possible bays/buffers configurations are described below.

- Location. Both buffers and bays can be located on one front of warehouse B(*N*), on the other B(*S*), or on one side B*(W/E)*, as exemplified in Fig.5.

- Level. The buffers are usually placed at the ground level (*level 1*), but they can be elsewhere (*level >1*).

- Capacity. The bays at the system levels have a low capacity due to limited space. They usually host one (*1UL*) or two ULs. In the case of double-capacity, the capacity is chosen in line with the lift one, as shown in

Fig.5. For instance, the *B2UL(x)* is coupled with an *L2UL(x)*. Also, *buffer-in* and *buffer-out* follow the lift configuration. Still, their capacity is usually higher because they manage all the incoming and outgoing ULs, but little relevant for measuring system performance because it is not a system bottleneck.

- Type. Both buffers and bays can be dedicated to incoming ULs (*BIn*), outgoing ULs (*BOut*), or both (*BIO*). The type is selected according to the lift (i.e., if the lift can serve both S and R requests, the bay must be a *BIO*).

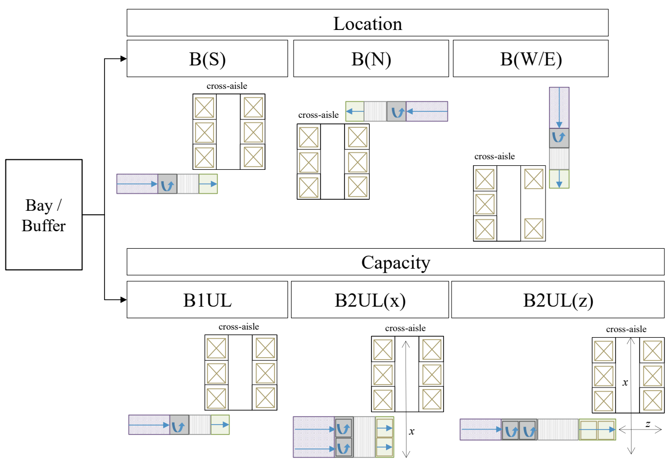

Fig. 5. Buffer/bay location and capacity.

The tree diagram framework illustrated in Figure 6 summarizes the previously introduced design features affecting the storage system layout. The resulting configurations are based on the proposed standard notation.

transfer car [Tappia et al. (2017)]. In addition, there is no distinction between the buffer areas at the ground level (i.e., *buffer-in* and *buffer-out* in Fig.1) and the ones at the tiers (i.e., *bay-in* and *bay-out* in Fig.1). Researchers usually adopt the term buffer area [Marchet et al. (2013), Marolt et al. (2022)]. Recently, D'Antonio and Chiabert (2019) and Battarra et al. (2022) adopted the term bay to discern the ones at the system levels from the ones at the ground level. Other studies used the term bay for the storage locations within the lanes [Ekren and Akpunar (2021), Ekren et al. (2013)]. These are some of the examples illustrating how a lack of standard notation can lead to misunderstandings.

3. A LITERATURE SURVEY

Literature studies investigated the performance of shuttle-based storage systems under variant design configurations. This section reveals the state-of-art of the design features identified in this study.

Regarding the rack dimension (1), the modeling approaches adopted by the literature focus on single-level (SL) systems, assuming a uniform distribution of the S and R requests among all levels [Epp et al. (2017), Marchet et al. (2012)]. Other contributions considered all the levels and their interaction [Roy et al. (2015)]. In the case of tier-to-tier (TT) vehicles, the former approach cannot be pursued because vehicles move among levels. Concerning the lane depth, early studies discussed single- (SD) and double-deep (DD) systems [Marchet et al. (2013), Lerher et al. (2015)]. The double-deep storage rack saves 50% of aisle space compared to the single one [Lerher (2016)]. This saving increases for multi-deep (MD) systems providing a higher storage capacity and better space area utilization [Manzini et al. (2016), Marolt et al. (2022)] but also higher costs and more complexity due to the

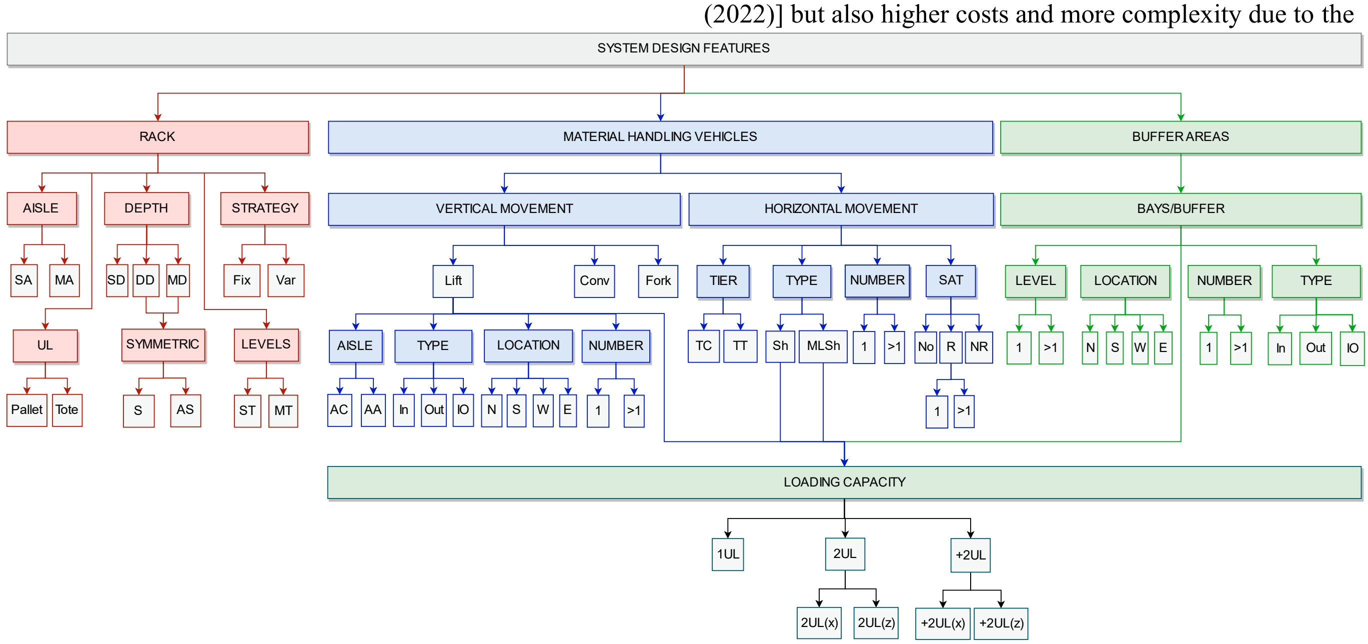

Fig.6. Design-based framework of shuttle-based systems

Literature studies show a lack of standard notation. Although many studies adopted the name shuttle for the vehicle that travels the main cross-aisle, it was called in other ways, such as shuttle carrier [Lerher et al. (2015), Liu et al. (2018)] or

presence of the satellite. The complexity of the system investigated also increases for multiple-aisle (MA) systems [Ekren et al. (2013), Roy et al. (2012)], especially when movable lifts are adopted [Jerman et al. (2021), Ekren et al.

(2023)]. Most of the studies deal with single-aisle (SA) systems [Tappia et al. (2017)]. No attention has been paid to comparing different lane depth strategies, assuming permanently fixed (Fix) depths. Finally, only Battarra et al. (2022a) investigated asymmetrical storage systems. Other studies mainly refer to symmetric ones.

Concerning material handling vehicles (2), literature studies mainly focused on shuttle-based systems equipped with lifts [Epp et al. (2017)]. Few investigated conveyor-based storage systems [Roy et al. (2015)]. Recent studies moved to non-traditional storage systems served by multilevel shuttles [Lerher et al. (2021)] or equipped with multiple-aisle lifts [Jerman et al. (2021)]. In addition, great attention has been dedicated to the comparison of the shuttle- and crane-based systems (i.e., AS/RS) [Ekren and Heragu (2012)]. Literature studies lack a description of the loading capacities and locations. They mostly assumed single-capacity vehicles. The few exceptions are Ekren and Akpunar (2021), who considered double-capacity lifts, and Battarra et al. (2022a) and Lupi et al. (2023), who involved both single- and double-capacity lifts, shuttles, and satellites. Nevertheless, none of these studies examined the location implications. Finally, as regards the released option, most of the studies considered the satellite as dependent on the shuttle, and few of them adopted the released option and enabled parallel movements [Battarra et al. (2022a), D'Antonio et al. (2018), (2019)].

Finally, buffer areas (3) are usually neglected by literature or modeled as infinite queues [Wang et al. (2016), Zhang et al. (2009)]. Several studies mainly focused on the lift, which has been proven to be the bottleneck in lift-based storage systems [Marchet et al. (2013)]. To overcome this limit, modern automated storage systems increased the number and capacities of the elevator system [Ekren et al. (2023)], adopting dedicated (one for S and one for R requests) and double-capacity lifts. Consequently, the bottleneck shifted from the elevator system to the bays, as well as the researcher's interest. Queuing models with limited capacity for shuttles and satellites have been developed to provide more accurate performance estimation [Eder (2020, 2022)]. Other studies linked the shuttle availability to the bay status [Zuo et al. (2016)]. When the bay is full, the vehicle is unavailable, and no S/R requests can be received. Vehicle blocking occurs every time a bay is full, with a decrease in system performance, such as throughput. Nevertheless, the existing models lack monitoring of the number of requests waiting in the bays because they usually join S and R requests in a unique queue.

As described above, some relevant design features are neglected or slightly mentioned in existing literature studies. Nevertheless, the most significant literature gap concerns the lack of a standard way of describing the design features of the shuttle-based storage systems. Misunderstandings and difficulties in comparing models and results are the results of this. The proposed design framework introduces a new and standard taxonomy. Classifications regarding design features of automated storage systems are widespread in the literature, such as the one presented by Roodbergen and Vis (2009) for AS/RSs or by Azadeh et al. (2017) for robotized and automated warehouse systems. Nevertheless, little attention has been paid to the design features of shuttle-based storage systems. This paper aims to fill this gap.

4. CONCLUSIONS AND FURTHER RESEARCH

This study illustrates the most relevant design features for a shuttle-based storage system under three dimensions: racks, material handling vehicles, and buffer areas. The resulting novel framework illustrates the possible combinations thanks to a standard notation. A review of literature conducted on thirty studies on shuttle-based storage systems analyses the features mentioned above and reveals the state-of-art. The most relevant literature gaps refer to:

1. Variable lane depth strategy
2. Asymmetrical storage systems
3. Shuttles and satellites' double-capacity
4. Bays capacity and location
5. Buffers level and number

These design features differ in terms of complexity and impact on system performance. The (1) and (2) elements affecting system rack configuration have a twofold effect on system storage density and space efficiency. Adopting different lane depths, as well as varying the depth over time, can provide more compact warehousing and reduce empty locations, as illustrated by Lupi et al. (2024). The (3) and (4) elements regard the capacity of vehicles and bays. They can affect system performance in terms of S/R cycle time and system throughput. Moreover, monitoring the filling degree of the bays can turn attention to this element (i.e., bay capacity) as a driver in the design configuration of a storage system instead of a direct consequence of the rack layout. Finally, the (5) element implies having multiple input and output buffers. This implication can benefit the S/R cycle time by reducing lifts' service time and bottlenecks. This configuration matches with the recent multilevel shuttle-based storage system, which has been poorly investigated.

REFERENCES

Azadeh K, De Koster R and Roy D (2017). Robotized and Automated Warehouse Systems: Review and Recent Developments. Social Science Research Network. Pages 61.

Battarra I, Accorsi R, Manzini R, and Rubini S (2022a). Hybrid model for the design of a deep-lane multisatellite AVS/RS. Int J Adv Manuf Technol, 121, 1191–1217

Battarra I, Accorsi R, Manzini R, and Rubini S (2022b). Storage efficiency in a deep-lane AVS/RS, IFAC-PapersOnLine. Volume 55, Issue 10, Pages 1337-1342.

D'Antonio G, De Maddis M, Bedolla JS, Chiabert P and Lombardi F (2018). Analytical models for the evaluation of deep-lane autonomous vehicle storage and retrieval system performance. Int J Adv Manuf Technol (2018) 94:1811–1824.

D'Antonio G and Chiabert P (2019). Analytical models for cycle time and throughput evaluation of multi-shuttle deep-lane AVS/RS. Int J Adv Manuf Technol, 104:1919–1936.

Eder M (2020). An approach for performance evaluation of SBS/RS with shuttle vehicles serving multiple tiers of multiple-deep storage rack. Int J Adv Manuf Technol, 110:3241–3256

Eder M (2022). An analytical approach for a performance calculation of shuttle-based storage and retrieval systems with multiple-deep and class-based storage. Production & Manufacturing Research, 10(1):321–336.

Ekren BY and Heragu SS (2012). Performance comparison of two material handling systems: AVS/RS and CBAS/RS, IJPR, 50:15, 4061-4074.

Ekren BY, Heragu SS, Krishnamurthy A, and Malmborg CJ (2013). An Approximate Solution for Semi-Open Queueing Network Model of an Autonomous Vehicle Storage and Retrieval System. IEEE Transactions on Automation Science and Engineering, 10, 205-215.

Ekren BY and Akpunar A (2021). An open queuing network-based tool for performance estimations in a shuttle-based storage and retrieval system. Applied Mathematical Modelling, Volume 89, Part 2, Pages 1678-1695.

Ekren BY, Lerher T, Küçükyaşard M and Jerman B (2023). Cost and performance comparison of tier-captive sbs/rs with a novel avs/rs/ml. IJPR.

Epp M, Wiedemann M and Furmans K (2017). A discrete-time queueing network approach to performance evaluation of autonomous vehicle storage and retrieval systems. IJPR, 55:4, 960-978.

Jerman B, Ekren BY, Küçükyaşar M and Lerher T (2021). Simulation-Based Performance Analysis for a Novel AVS/RS Technology with Movable Lifts. Applied Sciences. 11, 2283.

Kamali, A (2019). Smart warehouse vs traditional warehouse - Review. Automation and Autonomous System, 11, 9-16.

Lerher T, Ekren BY, Dukic G and Rosi B (2015). Travel time model for shuttle-based storage and retrieval systems. Int J Adv Manuf Technol, 78(9‑12):1705‑1725.

Lerher T (2016). Travel time model for double-deep shuttle-based storage and retrieval systems. IJPR, 54(9):2519‑2540.

Lerher T, Ficko M and Palčič I (2021). Throughput performance analysis of Automated Vehicle Storage and Retrieval Systems with multiple-tier shuttle vehicles. Applied Mathematical Modelling. Volume 91, Pages 1004-1022.

Liu T, Gong Y and De Koster R (2018). Travel time models for split-platform automated storage and retrieval systems. International Journal Production Engineering, 197-214.

Lupi G, Accorsi R, Battarra I and Manzini R (2023). Configuration of an AVS/RS Using a Data-Driven Queueing Network Model. Springer, p. 381-390.

Lupi G, Accorsi R, Battarra I and Manzini, R (2024). Space efficiency and throughput performance in AVS/RS under variant lane depths. Int J Adv Manuf Technol, Volume 131, pages 1449–1466.

Manzini R, Accorsi R, Baruffaldi G, Cennerazzo T and Gamberi M (2016). Travel time models for deep-lane unit-load autonomous vehicle storage and retrieval system (AVS/RS). IJPR, 54:4286–4304.

Marchet G, Melacini M, Perotti S and Tappia E (2012). Analytical model to estimate performances of autonomous vehicle storage and retrieval systems for product totes. IJPR, 50:7134‑7148.

Marchet G, Melacini M, Perotti S and Tappia E (2013). Development of a framework for the design of autonomous vehicle storage and retrieval systems. IJPR, 51(14):4365‑4387.

Marolt J, Kosanić N and Lerher T (2022). Relocation and storage assignment strategy evaluation in a multiple-deep tier captive automated vehicle storage and retrieval system with undetermined retrieval sequence. Int J Adv Manuf Technol, 118:3403‑3420.

Roy D, Krishnamurthy A, Heragu SS and Malmborg CJ (2012). Performance analysis and design trade-offs in warehouses with autonomous vehicle technology. IISE Transactions, 44(12):1045–1060

Roy D, Krishnamurthy A, Heragu S and Malmborg C J. (2015). Stochastic models for unit-load operations in warehouse systems with autonomous vehicles. Annals of Operations Research, (2015) 231:129–155.

Roodbergen, K.J. and Vis, I.F.A. (2009). A survey of literature on automated storage and retrieval systems, European Journal of Operational Research 194(2), 343-362.

Tappia E, Roy D, De Koster R and Melacini M (2017). Modelling, analysis, and design insights for shuttle-based compact storage systems. Transportation Science 51, 269‑295

Wang Y, Mou S and Wu Y (2016). Storage assignment optimization in a multi-tier shuttle warehousing system. Chinese journal of chemical engineering, 29: 421–429.

Zhang L, Krishnamurthy A, Malmborg CJ and Heragu SS (2009). Variance-based approximations of transaction waiting times in autonomous vehicle storage and retrieval systems. European J Ind Eng, 3:146–169, 01.

Zou B, Xu X, Gong Y and De Koster R (2016). Modeling parallel movement of lifts and vehicles in tier-captive vehicle-based warehousing systems. European J Oper Resear, 51–67.