PEDRO HENRIQUE CONSTANTE MOYA

NOVEL AUTOMATED STORAGE AND RETRIEVAL SYSTEMS: SYSTEMATIC LITERATURE REVIEW AND FUTURE RESEARCH AGENDA

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To my family and friends.

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"Those who stand for nothing fall for anything."

– Alexander Hamilton

ABSTRACT

This thesis addresses material handling systems applicable to warehouse operation activities, considering the recent technological advances on this matter. In particular, it focuses on novel automated storage and retrieval systems based on vehicles or shuttles, which are able to improve warehouse performance in terms of productivity, flexibility and robustness compared to traditional systems. Five distinct types of storage and retrieval systems are studied. Firstly, they are extensively described, by presenting how they operate, their particularities, application area, advantages and disadvantages. Then, a systematic review of the existent literature on these types of systems is performed, by analyzing and classifying a total of 84 papers. Finally, this thesis brings forward a future research agenda on automated storage and retrieval systems, by identifying research trends and research opportunities on the subject, finding that short-term decisions on operational and control policies and the environmental dimension are issues to be addressed by future studies.

Keywords: warehouse automation; storage and retrieval system; systematic literature review; future research agenda.

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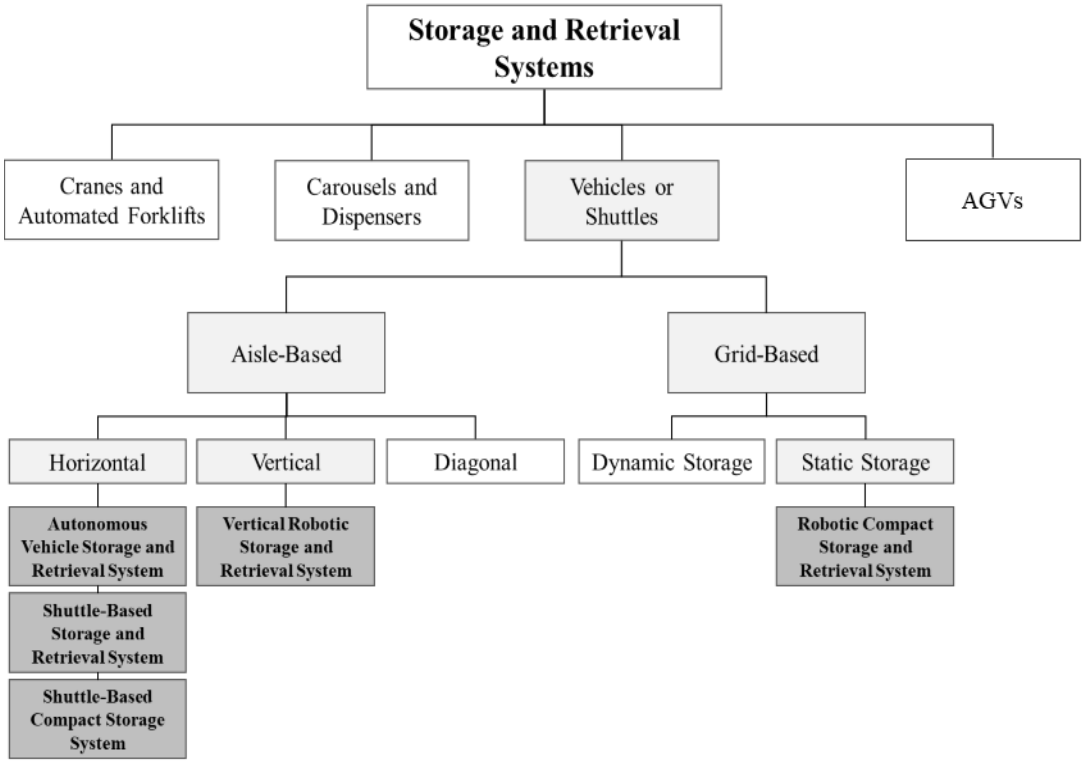
1 Introduction

When it comes to warehouse operations, large spaces are required for the warehouse facilities, and the operations can be described as labor intensive. In that sense, the warehouse building needs to be large, in order for that to have space to store the item assortment in racks, move stock, load and unload containers, inspect orders, and maneuver and dock the trucks (AZADEH; DE KOSTER; ROY, 2019).

Recent technological advances led to a quick development of new warehouse automations which, in turn, resulted in novel types of material handling systems to meet stricter performance requirements in the market as they allow warehouse activities to achieve better productivity, flexibility and robustness. This is especially true with the advent of e-commerce, which shapes the recent order profile towards more product variety, with less volume and short response time (EKREN, 2020). These new recent systems offer several research opportunities, which are investigated by this thesis, focusing particularly on storage and retrieval systems.

Based on Azadeh, De Koster and Roy (2019), which address automated storage and retrieval systems, these systems can be classified according to the storage and retrieval device adopted: ***(i)*** crane and automated forklifts; ***(ii)*** carousels and dispensers; ***(iii)*** vehicles or shuttles; and ***(iv)*** automated guided vehicles (AGVs). Two types of systems with vehicles or shuttles can be distinguished: ***(i)*** aisle-based systems, which are characterized by storage racks composed by storage aisles and can be further classified into horizontal, vertical or diagonal; and ***(ii)*** grid-based systems, which rely on a grid rather than on aisles and can have either a dynamic or static storage. Among aisle-based systems, a horizontal system adopts vehicles or shuttles that move only horizontally, relying on a lifting mechanism for the vertical movement, whereas in the vertical and the diagonal systems the devices deployed are able to move vertically and diagonally, respectively. Besides, regarding grid-based systems, a dynamic storage means that already stored goods need to move when a storage or retrieval transaction is performed, unlike in the static storage in which the goods stored do not move until its retrieval. Figure 1 illustrates a classification of storage and retrieval systems, including the presented segmentation for systems with vehicles or shuttles.

Figure 1 – Classification of storage and retrieval systems.



Source: Azadeh, De Koster and Roy (2019).

This thesis addresses five novel types of storage and retrieval systems adopting vehicles or shuttles as storage and retrieval devices, also addressed by Azadeh, De Koster and Roy (2019). These types of systems, colored with dark gray in Figure 1, are named: ***(i)*** autonomous vehicle storage and retrieval system (AVS/RS); ***(ii)*** shuttle-based storage and retrieval system (SBS/RS); ***(iii)*** shuttle-based compact storage system (SBCSS); ***(iv)*** vertical robotic storage and retrieval system (VRS/RS); and ***(v)*** robotic compact storage and retrieval system (RCS/RS).

These novel systems, developed as advances in autonomous vehicles technology, have helped manufacturers of material handling systems pursue the use of autonomous vehicles instead of fixed-path cranes in unit load storage and retrieval, like adopted by the traditional crane-based automated storage and retrieval systems (CBAS/RS), in which the storage and retrieval devices are cranes (EKREN; HERAGU, 2012). Some potential advantages of the systems under study over the crane-based alternatives, which explain the popularity of the former in the past decade, are a lower initial investment, a lower response time, a higher flexibility, and a higher robustness to failure (ROY et al., 2012) (HERAGU et al., 2011).

The AVS/RS uses rail-guided vehicles moving in rectilinear paths within and across aisles of the storage racks and lifts for the vertical movement. The SBS/RS operates similarly to the AVS/RS, but with tier-captive and aisle-captive shuttles. The SBCSS can be considered a particular type of the SBS/RS with high-density storage area due to multiple-deep storage lanes. The VRS/RS, in turn, does not use lifts as it has robots that can move independently in the horizontal and vertical directions. Moreover, the RCS/RS is a grid-based system with vertical stacking approach that relies on robotic technology. All these systems will be better described further in this thesis, in Chapter 4.

Considering the context of technological advances and quick development of new storage and retrieval systems, this thesis aims at studying the above-mentioned systems to shed light on the current state of the literature on these systems and to identify opportunities for the future research agenda. This is done by performing a systematic literature review, which includes presenting the main contributions in the literature, analyzing them according to several aspects, identifying research trends and searching for gaps that can be exploited by future research. In total, 84 papers were included in the literature review.

1.1 Motivations for this Thesis

There are three main motivations which led to the development of this study. The first motivation is to study in detail novel storage and retrieval systems, which are increasingly important for warehouse activities with the growth of e-commerce. The second motivation refers to investigating the multiple modeling approaches adopted in the literature to study these systems, including, for example, queuing network models and simulation, which were studied during the author's Industrial Engineering graduation course. Lastly, the third motivation is to learn in practice how to develop a robust and consistent systematic literature review, which might be an important knowledge for a potential opportunity in the research field.

1.2 Objectives and Contributions of this Thesis

The first objective of this graduation thesis is to extensively describe the storage and retrieval systems selected, presenting their characteristics, advantages, application fields and decisions to properly design, operate and control them. The second objective is to bring forward the current state of the literature for these five systems, through a consistent systematic literature review. For this purpose, as will be presented in Chapter 2, the following aspects were considered: environment of adoption, modeling approach, research category, research issues addressed and the consideration of the environmental perspective. Moreover, the third objective of this thesis is to present a research agenda by identifying gaps in the current literature that could be further explored by new studies on this subject.

With these objectives, the main contribution of this thesis is to provide support for future studies on storage and retrieval systems, by providing an extensive description of the systems selected, presenting the most relevant contributions in the literature and proposing clear research opportunities to extend the current literature.

1.3 Structure of this Thesis

The remainder of this thesis is organized as follows. In Chapter 2, the methodology adopted for the systematic literature review is presented, as well as a descriptive analysis of the papers selected. In Chapter 3, there is an overview on the modeling approaches mostly used to model automated storage and retrieval systems. Chapter 4 describes the five novel systems under study. Chapter 5 presents the current state of the literature and identifies research gaps that should be addressed by the future research agenda. Lastly, in Chapter 6, there is the conclusion of this thesis, presenting its summary, limitations and final considerations of the author.

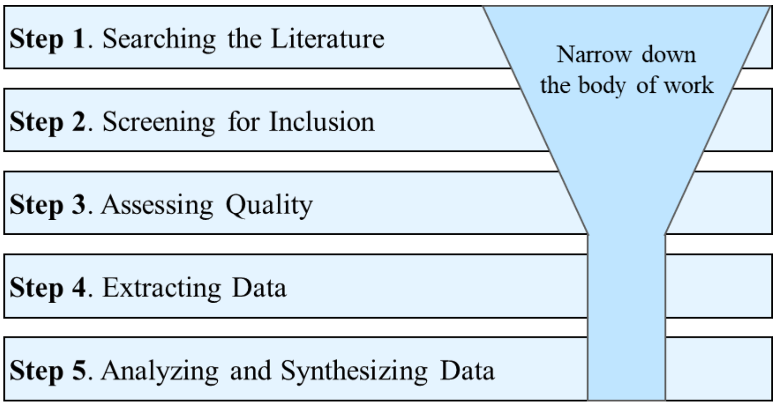
2 Literature Review Methodology and Descriptive Analysis

In this chapter, the methodology adopted for searching, selecting and analyzing the papers for the systematic literature review is presented. Furthermore, there is a descriptive analysis of all the papers included in the literature review.

2.1 Literature Review Methodology

In this chapter, the methodology adopted for conducting the systematic literature review is presented. This methodology is aligned to the one presented by Xiao and Watson (2019). The steps followed are the following: ***(i)*** searching the literature; ***(ii)*** screening for inclusion; ***(iii)*** assessing quality; ***(iv)*** extracting data; and ***(v)*** analyzing and synthesizing data. These steps are shown in Figure 2. It is worth mentioning that the body of work is narrowed in the first three steps, as the papers to be reviewed are being selected, starting with a pool of potential papers in the first step, from which some are excluded in the two following steps.

Figure 2 – Steps for conducting the systematic literature review.



Source: Xiao and Watson (2019).

Xiao and Watson (2019) group literature reviews into four different review categories based on their purposes: ***(i)*** describing; ***(ii)*** testing; ***(iii)*** extending; and ***(iv)*** critiquing. A descriptive review examines the state of the literature considering specific research questions, areas or concepts, differing from other review categories since it does not aim to expand upon the literature, but only to provide an account of the state of the literature. A testing review aims at answering a question about the literature or testing specific hypothesis. Moreover, an extending review not only develops a summary of the data, but also attempts to build upon the literature to create new contributions. Lastly, a critiquing review involves comparing a set of literature against an established set of criteria previously chosen.

Based on these four review categories, the systematic literature review proposed and developed in this thesis can be classified as descriptive. This is taken into consideration when planning and performing the five steps for conducting the review shown in Figure 2.

2.1.1 Searching the Literature

The first step for conducting a systematic literature review refers to finding materials for the review. The quality of the literature review is highly dependent on the literature collected; thus, a systematic literature review significantly depends on a systematic process for the search of literature (XIAO; WATSON, 2019). This process can be further divided into decisions on: ***(i)*** channels for searching the literature; ***(ii)*** keywords used for the search; ***(iii)*** sampling strategy; ***(iv)*** refining results with additional restrictions; and ***(v)*** stopping rule.

Channels for searching the literature: According to Xiao and Watson (2019), there are three major sources to find literature: ***(i)*** electronic databases; ***(ii)*** backward searching; and ***(iii)*** forward searching.

Electronic databases are usually the typical first stop when searching the literature since they are considered to be the predominant source of published literature collections (PETTICREW; ROBERTS, 2008). Therefore, it was decided to start the search of literature using electronic databases. The Scopus search engine was chosen as it is the largest abstract and citation database of peer-reviewed literature (SCHOTTEN et al., 2017).

The backward search refers to identifying relevant work cited by papers previously found and it is necessary to have a full list of literature. This method is performed by going backwards by reviewing the citations for the papers previously identified to determine other papers that should be considered as well (WEBSTER; WATSON, 2002). This method was also adopted in the search for literature to be reviewed in this thesis. More precisely, the papers cited by the literature selected after the quality assessment were gathered and assessed based on their titles and abstracts to decide whether they should be included in the systematic review, considering the same criteria adopted for the papers found through the Scopus search engine.

Lastly, the forward search, which refers to looking for papers that have cited key papers previously found and determining new papers that should be included in the systematic review

(WEBSTER; WATSON, 2002), was also adopted in this thesis. Search engines, including the Scopus one, provide support in this process of forward searching of papers. More precisely, the list of papers that cited the literature selected after the quality assessment was gathered using the Scopus search engine, and these potential papers were assessed in order to verify whether they should be included in the systematic review, based on their titles and abstracts.

Keywords used for the search: The definition of keywords was performed separately based on the types of storage and retrieval systems, divided on the following search clusters: ***(i)*** cluster of the AVS/RS and the SBS/RS; ***(ii)*** cluster on the SBCSS; ***(iii)*** cluster on the VRS/RS; and ***(iv)*** cluster on the RCS/RS. The papers on the AVS/RS and the SBS/RS were searched together as the AVS/RS is usually used to refer to the SBS/RS and vice versa, since these two systems are quite similar, as will be explained further in this thesis.

Given the importance of considering search strings using the operators “AND” and “OR”, many search engines, including the Scopus one, allow the use of Boolean operators in the search (XIAO; WATSON, 2019). Search strings are frequently built using “AND” to join the main terms and “OR” to include synonyms (BRERETON et al., 2007). Therefore, for each search cluster presented above, the main terms referring to the systems and their synonyms, if necessary, were identified, and the search string was built using “AND” and “OR”.

For the first search cluster, the search string constructed was: "AVS/RS" OR "autonomous vehicle storage and retrieval system" OR "autonomous vehicle-based storage and retrieval system" OR "S/R shuttle system" OR "SBS/RS" OR "shuttle-based storage and retrieval system" OR (("storage and retrieval system" OR "warehouse" OR "warehousing system") AND ("autonomous vehicles" OR "vehicle-based")). For the second cluster, the search string built was: "shuttle-based compact storage system" OR (("deep-lane" OR "multiple-deep") AND ("autonomous vehicle storage and retrieval system" OR "AVS/RS" OR "shuttle-based storage and retrieval system" OR "SBS/RS")). For the third cluster, the search string constructed was: "vertical robotic storage and retrieval system" OR "VRS/RS". Lastly, for the fourth cluster, the search string constructed was: "robotic compact storage and retrieval system" OR "RCS/RS".

Moreover, it is very important to document the retrieval date to allow other researchers to backtrack the literature search and to repeat it in the future on the same database to identify new papers that might have shown up since the initial search was performed (OKOLI;

SCHABRAM, 2010). Therefore, Table 1 shows the date of the last search for each cluster group, as well as the query string used in the Scopus search engine and the number of documents found.

Table 1 – Query strings, number of results and retrieval date for each search cluster.

Search Cluster	Query String	Document Results	Retrieval Date
AVS/RS + SBS/RS	TITLE ("AVS/RS" OR "autonomous vehicle storage and retrieval system" OR "autonomous vehicle-based storage and retrieval system" OR "S/R shuttle system" OR "SBS/RS" OR "shuttle-based storage and retrieval system" OR (("storage and retrieval system" OR "warehouse" OR "warehousing system") AND ("autonomous vehicles" OR "vehicle-based")))	117	17/10
SBCSS	TITLE ("shuttle-based compact storage system" OR (("deep-lane" OR "multiple-deep") AND ("autonomous vehicle storage and retrieval system" OR "AVS/RS" OR "shuttle-based storage and retrieval system" OR "SBS/RS")))	11	18/10
VRS/RS	TITLE ("vertical robotic storage and retrieval system" OR "VRS/RS")	2	21/10
RCS/RS	TITLE ("robotic compact storage and retrieval system" OR "RCS/RS")	3	21/10

Source: The author.

Sampling strategy: The search of the literature involves some sort of filtering, guided not only by the search strategy but also by a sampling strategy to be applied on the papers previously found (SURI; CLARKE, 2009). As sampling strategy, it was decided to limit the search to papers published in journals in order to consider only high-quality peer-reviewed papers. Therefore, gray literature, such as reports, theses and conference proceedings, were excluded from the search. It is worth mentioning that the year of publication was not considered as criteria to sample the papers.

Refining results with additional restrictions: There are no absolute rights and wrongs in this process; however, there is a clear trade-off that must be considered: on one hand, the refinement must be broad enough to include enough papers to make the systematic literature review meaningful; on the other hand, the review must be practically manageable, considering constraints of time, money and personnel (OKOLI; SCHABRAM, 2010). The publication language is a frequently adopted criteria for refining the papers selected in the previous steps since reviewers can only read materials in a language they can understand (XIAO; WATSON, 2019). The publication language was the only additional restriction adopted in the search process, considering only papers in English among those previously gathered.

Stopping rule: The stopping rule refers to defining the criteria to stop the search of literature and moving on to the screening for inclusion. The end of the search was reached when no new relevant citations were discovered and papers cited in newly discovered literature had already been reviewed, as proposed by Levy and Ellis (2006).

2.1.2 Screening for Inclusion

After gathering a list of papers as output of the previous step, researchers should further screen each paper to decide whether it should be included for data extraction and analysis. This decision is usually performed following a two-stage procedure: firstly, an assessment of the papers for inclusion based on the review of abstracts, followed by a refined quality assessment based on a full-text review. The screening for inclusion refers to the early assessment based only on the abstract (XIAO; WATSON, 2019).

The purpose of this early screening is to exclude from the systematic literature review papers with content inapplicable to the research questions or to the established criteria, without the need to resort to the full texts (XIAO; WATSON, 2019). In this step, reviewers should be inclusive, which means that in case of doubt, the papers should be included and moved on to the next steps for further assessment (OKOLI; SCHABRAM, 2010).

The inclusion and exclusion criteria can be based on research design and methodology (OKOLI; SCHABRAM, 2010). As criteria, for each search cluster already presented, only papers studying the appropriate storage and retrieval systems were included. Moreover, the research design was also considered as criteria, being literature review papers excluded since they do not help to develop the research goals of this thesis. It is worth highlighting that these criteria are quite easily verifiable based only on the review of the abstracts, without the need to resort to the full-text papers.

Lastly, it is important to document the list of papers excluded in this step. It provides record keeping, which in turn establishes reliability among researchers and allows others to reproduce the steps followed by the author and validate them (OKOLI; SCHABRAM, 2010). Therefore, Tables 11, 12, 13 and 14, in Annex 1, show all the papers that have been excluded for each search cluster in this step, as well as the papers that have been excluded due to the sampling strategy or the additional restrictions adopted.

2.1.3 Assessing Quality

After screening for inclusion, researchers should obtain the full texts of the papers previously found for the quality assessment stage. Quality assessment is a process to refine the full-text papers and is the final stage in preparing the pool of papers for the data extraction and synthesis (XIAO; WATSON, 2019).

The quality assessment depends on the type of review that is being performed (XIAO; WATSON, 2019). In this sense, Okoli and Schabram (2010) recognized that this step does not necessarily need to be used to exclude papers, but rather serve as a tool for reviewers to be aware of and acknowledge differences in study quality. Therefore, in this thesis the assessment of the full-text papers is not used to exclude papers based on their quality to be as inclusive as possible when studying the literature, including papers of all quality levels to reveal the full picture of the state of the literature. Thus, this step was performed in order to verify the relevance of the papers included in the screening step and to acknowledge differences between papers. At the end, only papers which full texts were not found were excluded from the systematic literature review in this step. Table 2 represents the search funnel for the four search clusters adopted, showing the number of papers excluded by each criteria.

Table 2 – Search funnels for each search cluster.

Search cluster	**AVS/RS + SBS/RS**	**SBCSS**	**VRS/RS**	**RCS/RS**
Papers identified through electronic database searching	**117**	**11**	**2**	**3**
- Papers excluded due to sampling strategy, i.e., not published in journals	30	0	1	0
- Papers excluded due to additional restrictions, i.e., not in English	7	0	0	0
Papers selected for the Screening for Inclusion step	**80**	**11**	**1**	**3**
- Papers excluded in the screening step due to system studied	11	0	0	0
- Papers excluded in the screening step due to research design	1	0	0	0
Papers selected for the Assessing Quality step	**68**	**11**	**1**	**3**
- Papers excluded since full text was not found	5	0	0	0
Papers identified through electronic database searching included	**63**	**11**	**1**	**3**
+ Papers identified through forward or backward searches	3	1	1	1
Total number of papers included	**66**	**12**	**2**	**4**

Source: The author.

Like in the screening for inclusion, it is important to keep record of the papers excluded in the quality assessment. Thus, all the papers excluded in this step were also documented and are shown in Tables 11, 12, 13 and 14, in Annex 1.

As shown in Table 2, a total of 117 papers were found using the query string selected for the search cluster on the AVS/RS and the SBS/RS. Following the methodology presented so far, some papers were excluded due to: ***(i)*** not being published in journals; ***(ii)*** not being published in English; ***(iii)*** the system studied; ***(iv)*** the research design; and ***(v)*** full text not found. Lastly, some papers were added to the literature review from backward and forward search. It is worth mentioning that out of the 66 papers included in the literature review from the first search cluster, 28 papers studied the AVS/RS, whereas 38 addressed the SBS/RS. This segmentation was also done in the quality assessment phase since it was necessary to resort to the full-text documents to distinguish the type of system considered by each paper. The same steps were followed for the other three search clusters: 12, two and four papers on the SBCSS, the VRSRS and the RCSRS, respectively, were included in the literature review, as depicted in Table 2. Therefore, in total **84 papers** were selected for the next steps of the systematic literature review.

2.1.4 Extracting Data

According to Xiao and Watson (2019), there are several established methods for extracting data and they significantly depend on the category of the literature review. They argue that the review category affects the synthesis method, which, in turn, guides the data extraction process. As already presented, the systematic review proposed and developed in this thesis can be classified as descriptive since it aims at examining and mapping the current state of the literature.

As mentioned, in total 84 papers were selected to be reviewed, considering the four search clusters adopted. The data extraction step started by collecting some basic information on each paper, including: ***(i)*** title; ***(ii)*** authors; ***(iii)*** source title; and ***(iv)*** year of publication. This information was gathered directly from the Scopus search engine, without needing to resort to the full-text papers.

In addition, to allow a mapping of the current state of the literature, each paper was classified according to the following aspects: ***(i)*** type of storage and retrieval system; ***(ii)*** environment of adoption; ***(iii)*** research category; ***(iv)*** research issue; ***(v)*** modeling approach; and

(vi) consideration of environmental perspective. For the aspects ***(i)***, ***(ii)*** and ***(iii)*** above, the papers were classified according to some predefined classification categories, and for the aspects ***(iv)*** and ***(v)***, there were not any predefined categories due to the wide range of research issues addressed and modeling approaches adopted. The categories used for classifying the type of system were the five storage and retrieval systems under study. The environment of adoption refers to the context in which the storage and retrieval systems are implemented, being classified into: ***(i)*** distribution and ***(ii)*** factory. For the research category, the options were chosen similarly to Azadeh, De Koster and Roy (2019), being: ***(i)*** system analysis; ***(ii)*** system design; and ***(iii)*** operations planning and control. Papers classified as *system analysis* work on modeling techniques to assess the performance of the system; papers categorized as *system design* focus on system design optimization or provide insights by studying design trade-offs; and papers labeled as *operations planning and control* develop software optimization of the system or investigate different operational and control policies. *System design* is related to long-term decisions, whereas *operations planning and control* refers to short-term decisions. It is important to note that each paper could be classified in more than one research category. The last aspect, consideration of environmental perspective, was considered a binary value to represent whether the environmental perspective is addressed.

Therefore, for each paper reviewed, the following information was gathered in an Excel spreadsheet, providing an overview of the papers included in the systematic review:

- title;
- authors;
- source title;
- year of publication;
- type of storage and retrieval system;
- environment of adoption;
- research category;
- research issue;
- modeling approach;
- consideration of environmental perspective.

2.1.5 Analyzing and Synthesizing Data

Once the data extraction process is complete, the reviewer organizes the data according to the category of the literature review chosen, usually resorting to some combination of charts, tables, and a textual description (XIAO; WATSON, 2019). As a descriptive systematic review, all the papers selected were presented and their classifications according to the aspects already mentioned were summarized in tables, shown in Chapter 5, to present the current state of the literature for each storage and retrieval system under study.

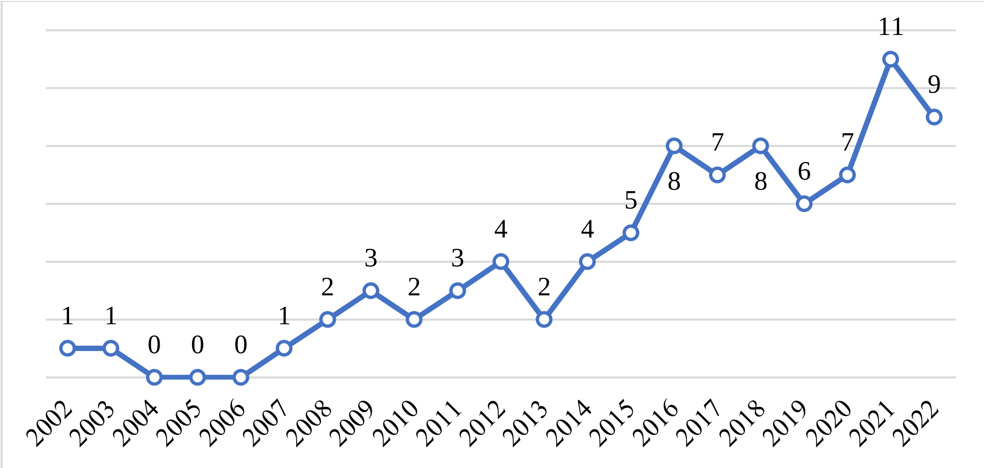
Systematic reviews also differ based on how they analyze and synthesize data of quantitative and qualitative studies (XIAO; WATSON, 2019). In this thesis an integrated design, which analyzes and synthesizes quantitative and qualitative research together, was adopted. The only criteria adopted to segregate studies when analyzing and synthesizing data was the type of storage and retrieval system. This choice was made to clearly map what has been studied for each type of system and facilitate the identification of opportunities for future research.

2.2 Descriptive Analysis

A descriptive analysis is usually used in systematic literature reviews to describe the papers selected for the review, being the frequency distribution of publications by year and publications by study category the most frequent analysis (HANEEM et al., 2017). Therefore, once the methodology used for the search, selection and analysis of the papers has already been presented, a descriptive analysis to describe the papers included in the literature review will be made.

Figure 3 shows the number of papers reviewed sorted by year of publication. It represents an upward curve as the literature reviewed was mainly published between 2017 and 2022, which ensures that the references and the conclusions of this thesis are mostly current and updated. As shown in Figure 3, out of the 84 papers included in the literature review, ten were published between the years of 2002 and 2010, 26 of the papers reviewed were published between 2011 and 2016, and the remaining 48 papers were published since 2017. The year with the most papers published is 2021 with 11 papers.

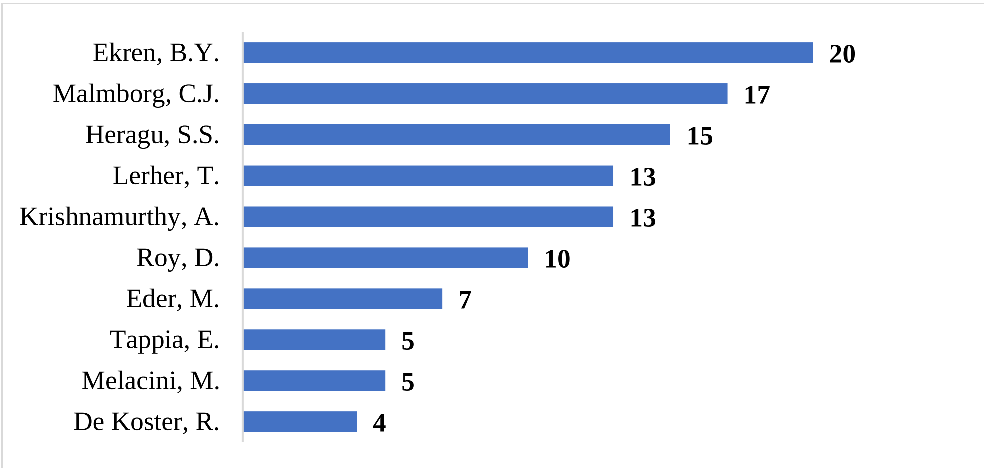
Figure 3 – Number of papers included in the literature review by year of publication.



Source: The author.

Moreover, an analysis of the papers selected reveals that Banu Y. Ekren and Charles J. Malmborg are the two authors responsible for more documents reviewed, with 20 and 17 papers, respectively. Figure 4 shows the 10 authors with more papers reviewed out of 138 authors in total.

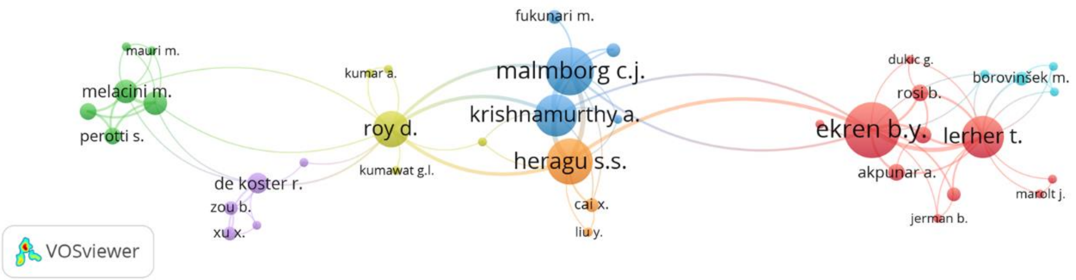
Figure 4 – Number of papers included in the literature review by main authors.



Source: The author.

In addition, an analysis of the co-authorship of the papers selected was performed using VOSviewer, a software tool for constructing and visualizing bibliometric networks. By setting default properties and the minimum number of authors per cluster as three, seven clusters of authors linked by co-authorship were found, as show in Figure 5.

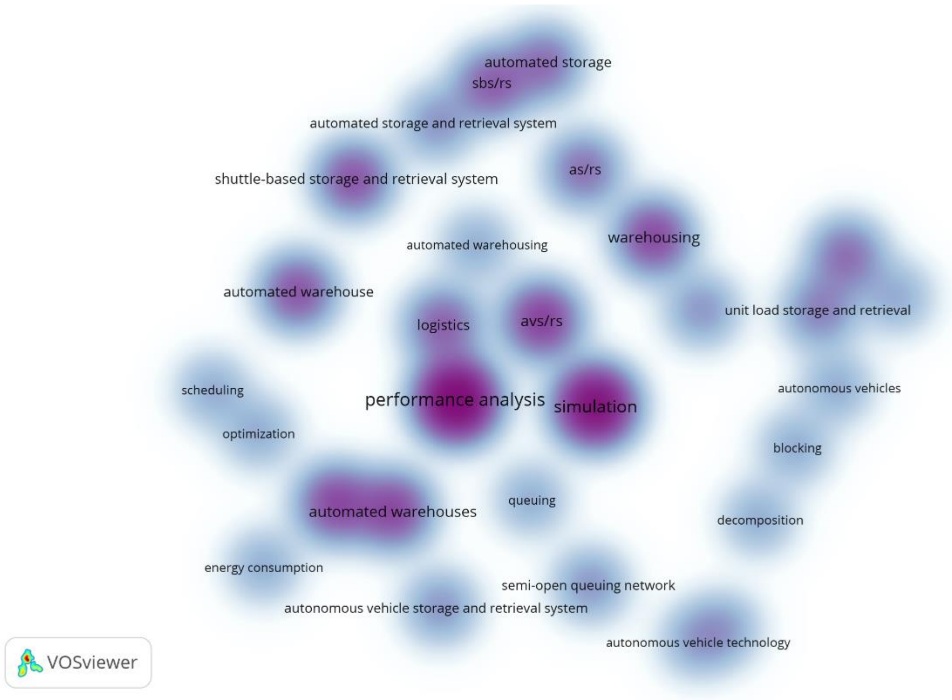
Figure 5 – Co-authorship network for the papers included in the literature review.



Source: The author.

The VOSviewer was also adopted to generate a keyword density map for the papers selected, shown in Figure 6. The minimum number of occurrences of a keyword to be displayed in the map was considered as three in order to limit the number of keywords and allow a proper visualization. *Performance analysis* is the most frequent keyword, with 21 occurrences. Some relevant keywords refer to the AVS/RS and the SBS/RS, such as *autonomous vehicle storage and retrieval system*, *shuttle-based storage and retrieval system*, *AVS/RS* and *SBS/RS*. Some keywords are related to modeling approaches adopted to model the systems, such as *simulation*, *queuing* and *semi-open queuing network*, which will be discussed in detail in Chapter 3.

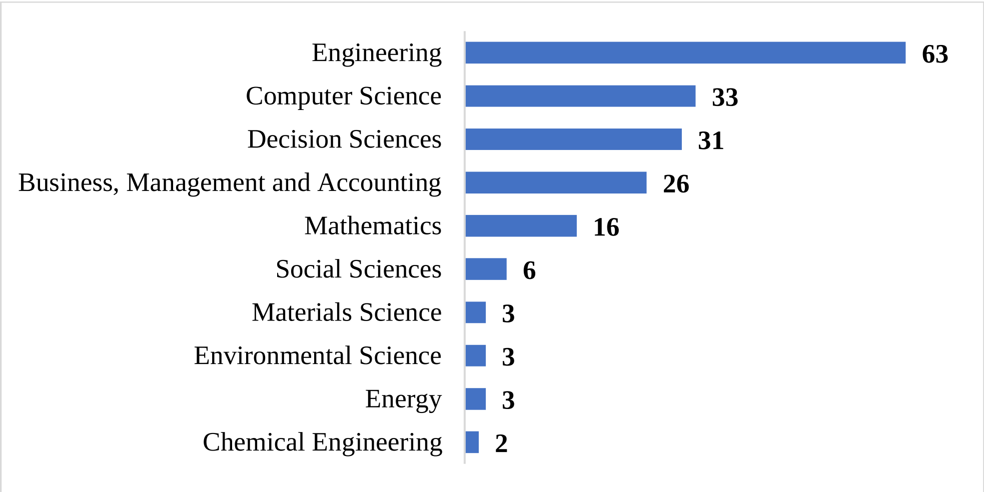
Figure 6 – Keyword density map for the papers included in the literature review.



Source: The author.

Moreover, by sorting the papers according to their subject areas, it can be verified that the literature reviewed in this thesis is mainly on the subject area of *Engineering*, as shown in Figure 7, which depicts the main subject areas into which the 84 papers selected are classified according to Scopus. It is worth mentioning that, since different subject areas can often overlap in a given paper, the final sum of the number of classifications in each of the areas is superior to 84, that is, the number of documents reviewed in total. Although most of the papers are in fact on the subject area of *Engineering*, many of them are also classified in the areas of *Computer Science*, *Decision Sciences* and *Mathematics*, which highlights the importance of computational and mathematical methods to the analysis and design of storage and retrieval systems.

Figure 7 – Number of papers reviewed by main subject areas.



Source: The author.

Finally, as for the sources from which the reviewed papers were withdrawn, only journals were considered, as already mentioned. The main source used was the *International Journal of Production Research* since 16 papers reviewed were published in this journal. This source is followed by the journals titled *International Journal of Advanced Manufacturing Technology*, *Simulation Modelling Practice and Theory* and *FME Transactions*. Table 3 connects each of the 35 journals used as source of papers in this thesis to the number of documents that were respectively withdrawn from each of them.

Table 3 – Number of papers included in the literature review by source title.

Source Title	**Number of Papers**
International Journal of Production Research	19
International Journal of Advanced Manufacturing Technology	8
Simulation Modelling Practice and Theory	5
FME Transactions	4
Applied Mathematical Modelling	3
Computers and Industrial Engineering	3
European Journal of Operational Research	3
Transportation Science	3
Computers and Operations Research	2
European Journal of Industrial Engineering	2
Flexible Services and Manufacturing Journal	2
IEEE Access	2
IEEE Transactions on Automation Science and Engineering	2
IIE Transactions (Institute of Industrial Engineers)	2
International Journal of Simulation Modelling	2
International Transactions in Operational Research	2
Production and Manufacturing Research	2
Annals of Operations Research	1
Applied Sciences (Switzerland)	1
Cleaner Logistics and Supply Chain	1
Expert Systems with Applications	1
ICIC Express Letters	1
International Journal of Advanced Technology and Engineering Exploration	1
International Journal of Computer Applications In Technology	1
International Journal of Production Economics	1
Journal of Applied Engineering Science	1
Journal of Cleaner Production	1
Mathematical Problems in Engineering	1
PLoS One	1
Processes	1
Production Planning and Control	1
Sustainability (Switzerland)	1
Tehnicki Vjesnik	1
Transport	1
Transportation Research Part E: Logistics and Transportation Review	1

Source: The author.

3 Modeling Approaches

As presented in Chapter 2, each paper reviewed in this thesis was classified according to its modeling approach. Therefore, the objective of this chapter is to present and describe the most popular approach used to model and analyze storage and retrieval systems. These modeling approaches can be broadly classified into: ***(i)*** simulation models and ***(ii)*** analytical models.

3.1 Simulation Models

A simulation is the result of solving the equations of a model to imitate an existing process. The model can represent the main aspects of the system, whereas the simulation represents how the model built evolves over time. Thus, simulation models aim at imitating the time evolution of real-world systems (THOMAS; HOOPER, 1991).

However, even though simulation-based models can mimic reality precisely and produce the least number of errors, conceptualizing and designing a detailed and accurate simulation model is quite time-consuming, which makes it difficult to investigate a large number of different warehouse configurations and different types of storage and retrieval systems. Moreover, the optimization of the entire design space may require the development of multiple models (AZADEH; DE KOSTER; ROY, 2019). Therefore, at an early stage, analytical models are preferred over simulation ones, to reduce the design search space and to identify a limited number of promising configurations (AZADEH; DE KOSTER; ROY, 2019). These configurations previously selected could be further evaluated by using simulation models select the final configuration. Besides, even when such configuration is selected based on analytical models, simulation models are frequently used to ultimately validate its performance to verify whether or not the customer requirements are met. For example, many contracts between warehouse companies and system integrators and designers include a clause that requires validating the final design through simulation before the implementation (EKREN et al., 2014).

Many papers reviewed adopt simulation models as modeling approach, as will be presented in Chapter 5. They use simulation models to mimic the operation of the system under study based on design parameters and operating and control policies to evaluate system performance, with the opportunity to draw some design insights to warehouse designers and optimize the system performance.

3.2 Analytical Models

The key advantage of analytical models over simulation models is their computational efficiency (MALMBORG, 2002). Even though simulation models can better represent the process modeled, the error made in the estimated performance measures using analytical models is usually acceptable for the design conceptualization phase (AZADEH; DE KOSTER; ROY, 2019).

As analytical models run faster and can obtain the optimal configuration either directly or with an enumeration over many potential design parameters, they are usually adopted in the design conceptualization (AZADEH; DE KOSTER; ROY, 2019). They can be used to evaluate even hundreds of alternative warehouse configurations and material-handling technologies, estimate the operational performance measures of each of them and allow the selection of a handful of configurations to be extensively tested through a detailed-simulation (EKREN et al., 2014).

According to Azadeh, De Koster and Roy (2019), the most popular analytical models for storage and retrieval systems can be classified into three categories: ***(i)*** linear and mixed-integer programming models; ***(ii)*** travel time models; and ***(iii)*** queuing network models. These three categories will be further described.

3.2.1 Linear and Mixed-Integer Programming Models

A linear programming (LP) model is a mathematical programming model in which the objective function is given by a linear combination of the decision variables and subject to a finite number of constraints given by a system of linear equations and inequalities. A mixed-integer programming (MIP) model, in turn, is one in which some of the decision variables are constrained to be integer values, being called integer programming (IP) model when all these variables must be integers. The integrality constraints allow MIP models to capture the discrete nature of some decisions (CONFORTI et al., 2014).

Many of the design and operational decisions in storage and retrieval systems can be optimized by using LP or MIP models. For instance, they can be used for optimizing the shape of the system, finding the best choice of storage policy, scheduling and sequencing order transactions and defining order batching rules. These models are adopted in a deterministic scenario, while the other two analytical models are preferred in case of stochasticity (AZADEH; DE KOSTER; ROY, 2019).

LP models can be solved exactly in polynomial time, while the adoption of integer variables by MIP models greatly expands the scope of useful optimization problems that can be defined and solved. However, including integer variables to the models enormously increases the modeling power. Therefore, the exact solutions for the majority of the MIP models are intractable and even small problems may be difficult to solve. So, MIP models are usually analyzed by resorting to heuristic algorithms, which are able to quickly provide near-optimal solutions (AZADEH; DE KOSTER; ROY, 2019).

3.2.2 Travel Time Models

Travel time models provide closed-form expressions using probability theory to assess performance in terms of travel distance and travel time. It is frequently adopted when studying storage and retrieval systems based on the design parameters, such as the rack configuration, velocity profile of resources and storage policy. With these models, the warehouse designer can estimate performance measures, including, for example, the average load storage and retrieval time, for the system under study (AZADEH; DE KOSTER; ROY, 2019).

The closed-form expressions for travel time are simple and computationally friendly, which allows the adoption of them to search for system configurations prior to committing extensive time and effort to study the detailed performance of some alternative configurations through simulation, as already explained. Even though these models are simple, they are not able to capture several relevant factors, such as the interaction between multiple resources, the parallel processing by multiple resources or the queueing dynamics within the system. In these scenarios, queuing network models are preferred (AZADEH; DE KOSTER; ROY, 2019), which explains why these models are more adopted in the papers reviewed, as will be further presented.

3.2.3 Queuing Network Models

A queuing network can be broadly classified into three categories: ***(i)*** open queuing network (OQN), where the customers arrive at a specified rate; ***(ii)*** closed queuing network (CQN), where the number of customers in the system is fixed; and ***(iii)*** semi-open queuing network (SOQN), where the customers arrive at a specified rate, but the system can process a maximum number of customers at any time (ROY, 2016). Due to the maximum number of customers being processed, the SOQN is also referred in the literature as OQN with population constraint and OQN with restricted capacity, respectively by Buitenhek, Houtum and Zijm (2000) and Dallery (1990), for example.

In an OQN, customers arrive from an external source and after receiving service in different nodes, they exit the system (AZADEH; DE KOSTER; ROY, 2019). Depending on the network, the customers can return to a node where they previously received service, but the requirement is that eventually every customer must leave. In this type of network, there is no limit on the number of customers that can be processed by the network at a time (WHITT, 1983).

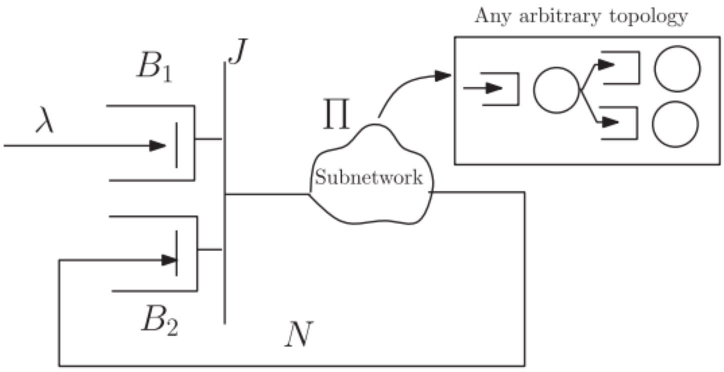
On the other hand, in a CQN, customers do not arrive from an external source and do not leave the network after being served. In this type of network, a limited number of resources are paired with the incoming customers and once a customer is served, the resource becomes available to serve another customer. In this case, the limited number of resources leads to a population constraint in the CQN (AZADEH; DE KOSTER; ROY, 2019), but it is assumed that an infinite number of customers are waiting outside the system, in the external queue (HERAGU et al. 2011).

SOQNs have the properties of both OQNs and CQNs. The network is considered open because customers still arrive from an infinite population set and there is no upper bound on the number of customers waiting in the external queue, whereas the network is deemed closed because the maximum number of resources available to process customers in the network is fixed (ROY, 2016).

SOQNs are a set of queueing networks with additional resources (CAI; HERAGU; LIU, 2014). It is assumed that a customer entering the system requires another resource, for example, a pallet or an operator, before it can be processed. If there is a resource available when a customer arrives, the customer enters the network of servers immediately, along with this resource. Otherwise, the customer waits in the external queue until a resource becomes available (HERAGU; SRINIVASAN, 2011). This resource is denoted as movable because it is required to physically accompany or even transport the customer from one station to another in the network (ROY, 2016). The amount of such resource defines the maximum number of customers the system can process at a time.

Figure 8 shows a general SOQN. Customers arriving to the network wait in the external queue B_1. The network has a fixed fleet size of N movable resources. The resources wait to be allocated to the customers in the resource queue B_2. When there is a customer in the external queue and a resource in the resource queue, they are matched at the synchronization station J and they enter the subnetwork Π, with any arbitrary topology (ROY, 2016). When a customer exits the system, the resource associated with this customer returns to the resource queue, where it waits to be paired with an arriving customer or, if a customer is already waiting in the external queue, it is immediately paired with the customer at the synchronization station and they enter the subnetwork together (HERAGU; SRINIVASAN, 2011).

Figure 8 – Representation of a general SOQN.



Source: Roy (2016).

An OQN can be useful to estimate expected system throughput time. However, in many systems, a limited amount of resources is required by customers during the whole or at least part of the process. In these cases, an OQN is not capable of accurately estimating the system performance as it assumes an infinite availability of resources. A CQN, in turn, is useful to estimate the maximum throughput capacity of the system, because using this type of network to model a system in which the incoming customers and the resources are paired together throughout the process leads to an underestimation of the true customer waiting time and hence an overestimation of the throughtput capacity. This is due to the infinite number of customers waiting outside the system (AZADEH; DE KOSTER; ROY, 2019).

To summarize, unlike an SOQN, an OQN assumes that there are infinite resources in the resource queue so that an arriving customer never has to wait in the external buffer, whereas a CQN assumes infinite customers in the external buffer so that a resource never has to wait in the resource queue. In many real-world systems, neither is a resource readily available for each customer, nor is a customer readily available for each resource. On the contrary, each of them has to wait for the other for some amount of time. Thus, OQNs and CQNs fail to capture the actual way these systems operate and hence these models result in inaccurate performance measures. Heragu and Srinivasan (2011) show that OQN and CQN models could significantly underestimate the expected customer flow time (W_{tot}) due to their limiting assumptions, as exemplified in Table 4.

Table 4 – Comparison of SOQN, OQN and CQN.

Model	L_{ext}	L_1	L_2	L_3	L_4	L_5	W_{tot}
OQN	0	5.00	3.33	2.00	2.50	2.86	1.57
CQN	∞	4.61	3.20	1.98	2.45	2.77	1.44
SOQN	12.03	3.69	2.81	1.88	2.26	2.51	2.52

Notes: λ = 10; μ_1 = 12; μ_2 = 13, μ_3 = 15, μ_4 = 14, μ_5 = 13.5, N = 15, where λ is the customer arrival rate, μ_k is the service rate of the k-th server and N is the maximum number of resources available to process customers.

Source: Heragu and Srinivasan (2011).

In Table 4, it can be seen that L_{ext}, which captures the expected number of customers waiting in the external queue, is zero for the OQN and ∞ for the CQN, while, in reality, about 12 customers wait on average in the external queue when we consider the SOQN. In this case, the total expected flow time of a customer in the system (W_{tot}) of 2.52 time units is underestimated when OQN and CQN models are used. Therefore, modeling some systems using an SOQN model yields better results in estimating system performance.

The adoption of such networks goes back to 1973, when Avi-Itzhak and Heyman (1973) analyzed the performance of a multi-programming computer system, in which several customer jobs could be handled simultaneously, with one job being processed by the central processing unit, while other jobs were being served by the peripheral devices. Today, SOQNs can be potentially applied to analyze the performance of complex manufacturing, health care and logistics systems (ROY, 2016).

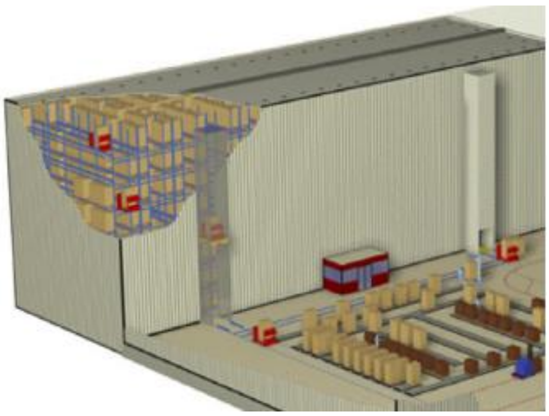
4 Systems Description

In this chapter, the five storage and retrieval systems under study in this thesis are described in depth. The first system addressed is the so-called autonomous vehicle storage and retrieval system (AVS/RS), in which vehicles are responsible for the storage and retrieval processes, relying on lifts for the vertical movement. The second system presented in detail is the shuttle-based storage and retrieval system (SBS/RS), a type of system quite similar to the AVS/RS. Then, the third system addressed is the shuttle-based compact storage system (SBCSS), which is a system that works similarly to the SBS/RS but with a high-density storage area due to multiple-deep storage lanes. Then, the focus moves to the vertical robotic storage and retrieval system (VRS/RS), which is a single-touch system in which robots move independently in the horizontal and vertical directions inside the rack structure, without resorting to a lifting mechanism. Lastly, the fifth system described is the robotic compact storage and retrieval system (RCS/RS), which is a recent automated storage and retrieval system using robotic technology and a high-density storage area due to a vertical stacking approach.

4.1 Autonomous Vehicle Storage and Retrieval System

The AVS/RS is an automation technology for unit load storage and retrieval in which vehicles with function similar to automated guided vehicles (AGVs) operate as storage and retrieval devices (MALMBORG, 2002). As shown in Figure 1, the AVS/RS is classified as a horizontal aisle-based system. Figure 9 brings a representation of this system.

Figure 9 – Representation of the AVS/RS.

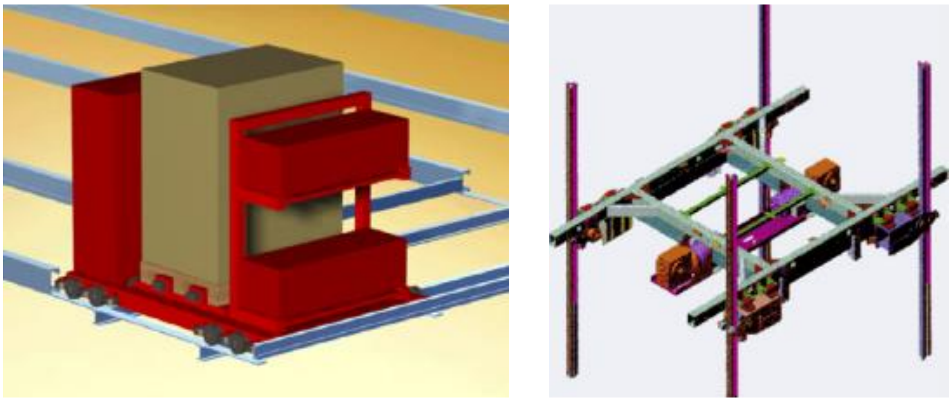


Source: Kuo, Krishnamurthy and Malmborg (2007).

The main components of the AVS/RS are: ***(i)*** autonomous vehicles, responsible for the horizontal movement; ***(ii)*** lifts, responsible for the vertical movement; and ***(iii)*** a system of rails in the rack area (Roy et al., 2012). Figure 10(a) illustrates a vehicle on the system of rails, whereas Figure 10(b) shows a lifting mechanism adopted in AVS/RS.

Figure 10 – Representation of (a) vehicle and (b) lifting mechanism of the AVS/RS.

(a) **(b)**



Source: Kuo, Krishnamurthy and Malmborg (2007).

The system of rails runs in two horizontal dimensions within a storage rack. Vehicles travel horizontally along rails within the storage aisles and within the cross-aisle when transferring between aisles. The lifts, mounted at fixed locations along the periphery of the storage rack, as can be seen in Figure 9, are responsible for the vertical movement of unit loads. Figure 9 also depicts the load buffering area in the bottom right corner, where unit loads are queued after the retrieval process and also before the storage process, while waiting for the lift (MALMBORG, 2002).

Based on the vehicle assignment to storage tiers, two main configurations of the AVS/RS can be found: the tier-to-tier AVS/RS and the tier-captive AVS/RS. In the first configuration, the vehicles move from one tier of the storage rack to another on a lift. In the second configuration, each vehicle is dedicated to a single tier of the system and therefore cannot move to another one. While in the tier-to-tier configuration the unit loads move vertically on the lift loaded by the vehicles, in the tier-captive configuration they move on the lifts without any vehicle (MARCHET et al., 2012). As will be presented in further in this chapter, the SBS/RS is a variation of the tier-captive AVS/RS.

Comparing these two configurations, the tier-captive AVS/RS is more expensive, since it usually adopts a higher number of vehicles, and offers better performances thanks to the fact that vehicle and lift movements are independent. In terms of application, the tier-to-tier and the tier-captive configurations are usually adopted when handling pallet unit loads and product totes, respectively (MARCHET et al., 2012).

Figure 11 illustrates a vehicle of a tier-to-tier AVS/RS during a storage transaction, moving vertically on the lift and horizontally inside the storage rack. This is a real-world example of AVS/RS called Magmatic, which was developed by Savoye Logistics, a France-based equipment manufacturer that was pioneer in the development of this type of system (ROY et al., 2017). Figure 11(a) shows the vehicle on the lift, moving to the first tier to load a unit load, whereas Figure 11(b) exhibits the same vehicle inside the storage rack already carrying the unit load to be stored.

Figure 11 – Vehicle (a) on a lift and (b) inside the storage rack of the AVS/RS.

(a) **(b)**

Source: Savoye (2019).

Besides the configuration with lifts, some systems have also been adopting conveyors as a vertical transfer mechanism, as studied by Roy et al. (2015b) and Roy et al. (2017). While only one unit load can be carried at a time by a lift, multiple unit loads can be transferred simultaneously in a conveyor-based AVS/RS, which enables higher capacity and shorter cycle times (ROY et al., 2015b). However, the choice of this mechanism is subject to other factors rather than performance, such as cost and space (ROY et al., 2017). Since the lift-based system is more traditional than the conveyor-based, the vertical mechanism transfer is generally referred to only as a lift.

In any case, there are different cycle types that can be performed by the vehicles. In a tier-to-tier system, the movement sequence performed by them depends on the type of command cycle, the tier of the storage or retrieval location, the initial tier of the vehicle and its position inside this tier. The command cycle can be either a single command (SC), when either a storage or a retrieval transaction is performed per cycle, or a dual command (DC) cycle, which both a storage and a retrieval transaction per cycle. The initial tier of the vehicle matters since it affects how many times the vehicle will require the lift.

In this regard, Ekren et al. (2013) address a tier-to-tier AVS/RS with only SC cycles and adopt the location of the last service completion as dwell point for vehicles. They identify six different cycle types for storage process and seven for retrieval process. The cycle types for storage process are described by the following scenarios:: ***(i)*** the assigned vehicle and the requested storage position are not on the first tier; ***(ii)*** the assigned vehicle is not on the first tier and the requested storage position is on the first tier; ***(iii)*** the assigned vehicle is on the first tier and the requested storage position is not on the first tier; ***(iv)*** the assigned vehicle is at the input-and-output (I/O) point and the requested storage position is not on the first tier; ***(v)*** the assigned vehicle and the requested storage position are on the first tier; and ***(vi)*** the assigned vehicle is at the I/O point and the requested storage position is on the first tier. In the scenario ***(i)***, for example, the vehicle travels horizontally from its position to the lift, moves on the lift to the first tier, where it can load the unit load to be stored, moves on the lift to the target tier and travels horizontally again to the target storage location, where the unit load is unloaded. The seven scenarios for retrieval process are: ***(i)*** the assigned vehicle and the requested retrieval location are not on the same tier and the retrieval location is not on the first tier; ***(ii)*** the assigned vehicle is at the I/O point and the retrieval location is not on the first tier.; ***(iii)*** the assigned vehicle and the retrieval location are on the same tier other than the first; ***(iv)*** the assigned vehicle is not on the first tier and the retrieval location is on the first tier; ***(v)*** and the assigned vehicle and the retrieval location are on the first tier; ***(vi)*** the assigned vehicle is at the I/O point and the retrieval location is on the first tier; and ***(vii)*** the seized vehicle is on the first tier and retrieval location is not on the first tier.

In a tier-to-tier system, the lifts represent an embedded queuing system, being the waiting time for them a component of total cycle time (MALMBORG, 2002). The number of times that a vehicle requires a lift per cycle also depends on the type of cycle, varying according to the type of command cycle, the tier of storage or retrieval location and the initial tier of the vehicle. SC and DC cycles require a maximum of two and three lift movements, respectively

(MALMBORG, 2002). For example, in case of a SC cycle for a retrieval transaction in which neither the storage location nor the vehicle initial position are on the first tier, the vehicle uses a lift twice: the first time to move unloaded from the initial tier to the target tier, and then from this tier to the first one with the unit load.

The AVS/RS is a direct alternative to the traditional autonomous storage and retrieval system (AS/RS), which is a crane-based automation technology. Malmborg (2002) highlights that the main differences between the AVS/RS and the AS/RS are related to load movement patterns and buffering.

Regarding movement patterns, in the AS/RS, aisle-captive cranes move unit loads simultaneously in both horizontal and vertical dimensions while interfacing with cross-aisle accumulation systems, which are usually conveyors. The AVS/RS uses sequential vehicle movement in the vertical and horizontal dimensions resulting in longer expected travel paths (MALMBORG, 2002). However, differently from storage cranes in the AS/RS, which can access the locations inside a single storage aisle, AVS/RS vehicles can access any storage location in any tier in the tier-to-tier configuration and any storage location in a designated tier in the tier-captive configuration (HERAGU et al., 2011).

Regarding load buffering, differences between the AS/RS and the AVS/RS depend on the rules for dispatching transactions and the storage policy used in the system. Retrieval transactions in the AS/RS create individual queues by storage aisles, whereas storage transactions may or may not be segregated by aisle depending on the storage policy adopted. On the other hand, in the AVS/RS, all buffered loads and retrieval requests are pooled in a single queue, which may allow a higher number of DC cycles compared to SC cycles in the AVS/RS when an opportunistic interleaving discipline is implemented (MALMBORG, 2002).

When comparing the AVS/RS to its counterpart technology, several advantages can be found. In the AVS/RS, it is possible to choose a variable number of vehicles and lifts based on the rack configuration and the requirements in terms of throughput capacity. (MALMBORG, 2003). As vehicles can be added without changing the rack configuration, one advantage of the AVS/RS is its flexibility, which allows the system to better adapt to surges in demand by increasing the number of vehicles (ROY et al., 2012).

Since the AS/RS requires one crane for each storage aisle, this technology could lead to higher capital costs and lower utilization of the material handling devices. Conversely, the number of vehicles in both the tier-to-tier and tier-captive AVS/RS is not strictly dependent on the system configuration as a vehicle can access all locations in the tier-to-tier system and all locations in a given tier in the tier-captive (HERAGU et al., 2011).

Besides, the AVS/RS is more robust to failures than the AS/RS, because maintenance issues related to individual vehicles do not severely impact system performance, as multiple vehicles can access a given storage position and an affected vehicle can be easily replaced by a new one, without shutting the system down (ROY et al., 2012). In the AS/RS, the failure of an aisle-captive crane can affect the system performance significantly more as a crane cannot be quickly replaced, and the ones operating in other aisles cannot access the aisle of the broken crane.

Furthermore, another advantage of the AVS/RS is its modularization. Since expanding the warehouse by adding more aisles necessarily means adding more cranes as well when the AS/RS is adopted, even a small change in the system leads to costly redesign of the entire system. On the other hand, the AVS/RS is highly modular, as different functional areas can be redesigned easily with minimal impact on other areas. For example, one can change the number of lifts while keeping other configuration parameters fixed (HERAGU et al., 2011).

However, the AVS/RS technology also has some disadvantages, such as the longer flow paths from sequential vertical and horizontal travel, the vehicle waiting time for lifts, the transfer time from the vehicle to the lift and vice versa (MALMBORG, 2003). Besides, this technology includes additional operational complexities due to blocking and bottlenecks among the horizontal and vertical load transfer mechanisms (ROY et al., 2017), therefore, it requires more complex control systems to manage the traffic and also avoid collision (MALMBORG, 2003).

The major cost related to the AVS/RS technology is due to the vehicles, with the costs for lifts being around a quarter of those for vehicles. Because of this cost relationship, lifts are usually not the bottleneck in the AVS/RS (KUO; KRISHNAMURTHY; MALMBORG, 2007). However, since the vertical movement is generally slower than the horizontal movement, and depending on the type of cycle the vehicle may require a lift up to three times in a tier-to-tier configuration, the lifts have a considerable impact on the performance of AVS/RS.

Regarding the system performance, two key performance measures are the throughput capacity and the transaction cycle time. These measures are influenced by design decisions as well as operational and control decisions. Design decisions, also referred to as long-term decisions, include the tier configuration parameters, such as: ***(i)*** rack dimensions, that is, the length and width of the system and the number of storage tiers; ***(ii)*** number of vehicles; ***(iii)*** number of lifts; ***(iv)*** location of the cross-aisle; ***(v)*** location of I/O point; ***(vi)*** number of zones; ***(vii)*** velocity profile of vehicles and lifts; and ***(viii)*** system configuration, which can be either tier-to-tier or tier-captive. The operational and control decisions, which are short-term decisions, embrace, for example: ***(i)*** storage policy, that is the rules for assigning items to system storage locations; ***(ii)*** dwell point policy, that is the rules related to the location where vehicles dwell after completing a transaction; ***(iii)*** interleaving policy, that is the rules for choosing between SC and DC cycles; ***(iv)*** vehicle assignment policy, that is the rules for assigning vehicles to tasks waiting to be performed; ***(v)*** task scheduling policy, that is the rules for scheduling the tasks waiting to be performed; ***(vi)*** processing policy, that is the rules that describe the relationship between the processes performed by the vehicle and lifts, which is usually either sequential or parallel; ***(vii)*** block prevention policy, that is the rules for preventing blocking and collision; and ***(viii)*** allocation of devices to zones (ROY et al., 2012).

4.2 Shuttle-Based Storage and Retrieval System

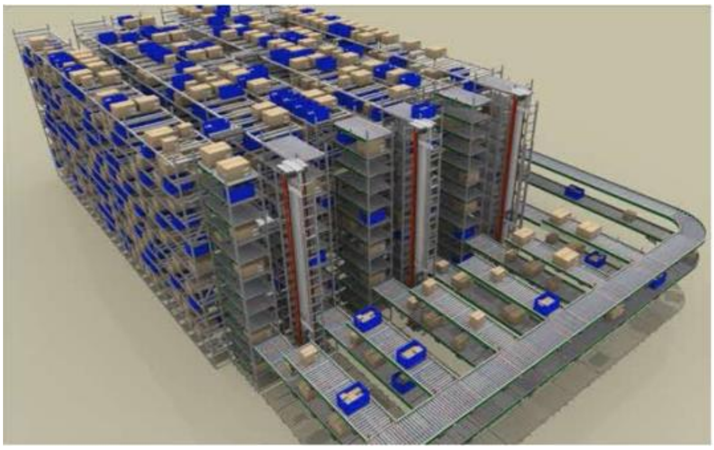
The SBS/RS is quite comparable to the AVS/RS, also being classified as a horizontal aisle-based storage and retrieval system, as shown in Figure 1. In fact, in the literature, the SBS/RS is usually referred to as AVS/RS and vice versa, especially in the oldest papers reviewed since the term *shuttle-based storage and retrieval system* did not exist yet. This confusion can also be explained by the facts that they operate in a similar way and have similar application fields, as will be presented.

Due to increasingly small order sizes with large product variety and faster deliveries, material handling providers invented new warehouse solutions to meet requirements in terms of throughput capacity and constraints regarding delivery times (CARLO; VIS, 2012). In this scenario, the SBS/RS was developed for small transactions carried in small container shipments and is designed to accommodate a wider range of products and shorter response times than the traditional AVS/RS (EKREN, 2020).

Like the AVS/RS, the SBS/RS relies on shuttles for the horizontal movement and lifts for the vertical movement. However, in the SBS/RS there is a lift for each storage aisle and a shuttle can move along only one dimension, within a designated storage aisle of a tier. Thus, as shuttles cannot travel between aisles and each aisle of the system works independently with its own queue of storage and retrieval transactions, the system can be partitioned by aisles with each part being identical (NING et al., 2016). This allows the analysis of the SBS/RS to take into consideration only a single-aisle system, which is done by many papers in the literature.

Figure 12 represents a perspective view of a real-world example of SBS/RS called Multishuttle 2 system, which is developed by Dematic. In this example, the system is composed by double-deep storage racks and it manages both totes and card boxes. Since each lift serves one storage aisle of the system and each vehicle works within a specific aisle of a tier, the number of lifts installed in the system is equal to the number of aisles, whereas the number of vehicles is equal to the product of the number of aisles times the number of tiers (MARCHET et al., 2012). In Figure 12, for example, the exemplified system design is composed by three storage aisles and three lifts.

Figure 12 – Representation of the SBS/RS.

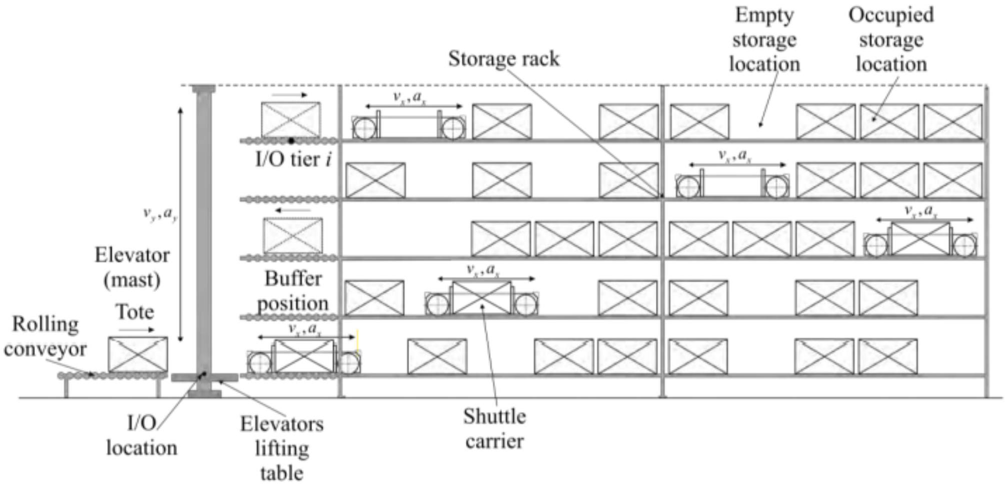


Source: MWPVL International Inc (2013).

Besides parallel aisles of storage racks and lifts, the SBS/RS is also composed of I/O locations, two buffer positions in each aisle of each tier and roller conveyors (LERHER; EKREN; SARI; ROSI, 2015), as represented in Figure 13 and Figure 14, which depict a side view and a top view of the SBS/RS, respectively.

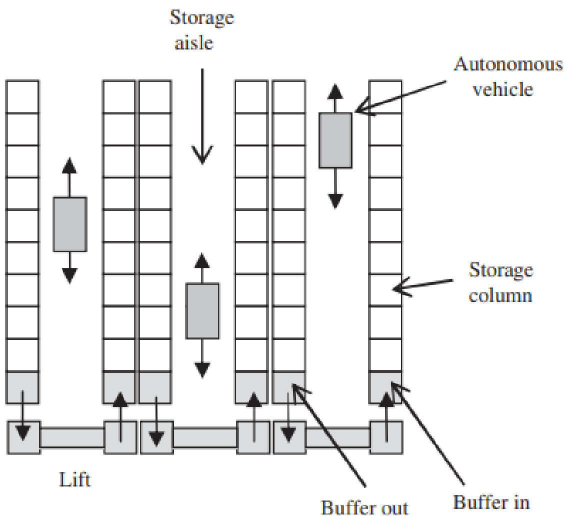
Lifts are mounted at fixed locations along the periphery of the storage racks and the I/O point is located at the first tier beside each lift (MARCHET et al., 2012), as shown in Figure 13. In the I/O point, rolling conveyors are responsible for taking away unit loads, previously retrieved by the shuttles and lifts, and bringing them to be stored in the system, creating a queue of loads waiting for the lift. In Figure 14, it is possible to see that each lift has two rolling conveyors, one to move loads to the I/O point and the other to move goods away from this point.

Figure 13 – Side view of the SBS/RS.



Source: Lerher, Ekren, Sari and Rosi (2015).

Figure 14 – Top view of the SBS/RS.



Source: Marchet et al. (2013).

Figure 14 also represents the buffer positions, which are set at the beginning of each tier of the SBS/RS. These positions are used for buffering totes carried by lifts for storage process, while they wait for shuttles, and by shuttles for retrieval process, while they wait for the lift (BOROVINŠEK et al., 2017). Therefore, the buffer enables a decoupling of shuttle and lift operations, which allows the shuttles to have no waiting time at the lift, improving system performance (EDER; KARTNIG, 2016).

In a storage transaction, a load to be stored waits in the queue on the rolling conveyors at the I/O point until a vertical motion of the lift transports it to the target tier and transfers it to the input buffer position, where it waits for the availability of the shuttle, which then moves the load horizontally and transfers it to the final storage position. In a retrieval transaction, on the other hand, a load to be retrieved waits in the queue at the retrieval location until a horizontal motion of the shuttle moves the load to the output buffer position. After a possible waiting time to empty the buffer position, the load is moved to the output load position, where it waits for the availability of the lift to perform the vertical movement until the I/O point (EDER; KARTNIG, 2016).

Like the AVS/RS competes with the AS/RS, the SBS/RS was introduced in the automated material handling industry as an alternative to the AS/RS where it cannot handle the required throughput capacity (LERHER; EKREN; SARI; ROSI, 2015). The main advantages of the SBS/RS are that it is energy efficient since it is lightweight and it has high transaction throughput capacity due to having a dedicated shuttle in each aisle of each tier (BOROVINŠEK et al., 2017). However, compared to the mini-load CBAS/RS, the capital and maintenance costs of the SBS/RS are relatively high, therefore the application of SBS/RS must be economically justifiable (LERHER, 2016b).

The SBS/RS technology has been widely implemented in many fields of industry, where the basic transport unit load is presented by a tote (LERHER; EKREN; DUKIC; ROSI, 2015). In particular, its adoption has increased significantly from the second half of the past decade, which is expected to continue due to the growth in e-commerce activities (EKREN, 2020).

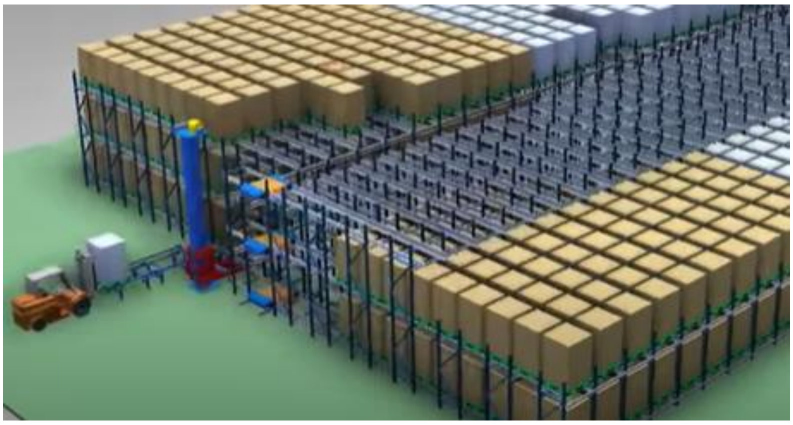
Regarding design decisions and operational and control decisions for the SBS/RS, they are quite similar to the decisions for the AVS/RS. Key design decisions for the SBS/RS are: ***(i)*** rack dimensions; ***(ii)*** number of shuttles; ***(iii)*** location of I/O point; ***(iv)*** velocity profile of shuttles and lifts; and ***(v)*** system configuration, which can be either tier-to-tier or tier-captive. For this system the number of lifts, the location of the cross-aisle and the number of zones are not decisions to be made, since there is one lift per aisle and shuttles operate in only one storage aisle. The only key operational and control decision important to the AVS/RS that is not applicable to the SBS/RS is the allocation of devices to zones, since the SBS/RS is not partitioned into zones (NING et al., 2016).

Since shuttles are dedicated to a storage aisle of a tier, lifts are mostly the bottleneck in the SBS/RS (EKREN et al., 2018). For this reason, newer designs of this system have installations with two lifting tables, which can work independently, allowing a higher throughput capacity (LERHER, 2016b). There is also a variation of the traditional single-lift system with multiple lifts per aisles, introducing new design variables, such as the number of elevators, the elevator position and the buffer position (NING et al., 2016). Moreover, there is another configuration with cross-shuttles on each tier, which allow the loads to move horizontally between aisles (WU et al., 2020).

4.3 Shuttle-Based Compact Storage System

The SBCSS is a third type of aisle-based horizontal system under study. It arose in a context in which warehouses had to respond efficiently and responsively to customer demand with flexible volumes (TAPPIA et al., 2017). This system is characterized by high-density storage as it consists of multiple tiers of multiple-deep storage lanes, each one holding unit loads, a single product, as shown in Figure 15.

Figure 15 – Representation of the SBCSS.



Source: Total Solution Provider Group (2015).

In such system, a vertical transport mechanism carries out the vertical movements moving unit loads across tiers, and shuttles carry out the horizontal movements within the storage lanes moving underneath the unit loads. The horizontal movements of shuttles and loads within the cross-aisle run orthogonally to the storage lanes. On the other hand, they can be performed either by specialized shuttles, which are transported to and from the appropriate storage lanes by a transfer car, or by generic shuttles, that can move in both the horizontal directions (TAPPIA et al., 2017).

Therefore, two subtypes of systems can be distinguished based on the type of shuttles adopted. From the operational point of view, the adoption of generic shuttles implies a shorter total travel distance, since shuttle movements in the cross-aisle without a load are not required. On the other hand, from the economic perspective, a generic shuttle is about twice as expensive as a specialized one, since it can change direction and move in both *x*- and *y*-directions. (TAPPIA et al., 2017). Figure 16 brings examples of a shuttle and a transfer car, being the latter used only in case of specialized shuttles.

Figure 16 – Examples of (a) shuttle and (b) transfer car of the SBCSS.

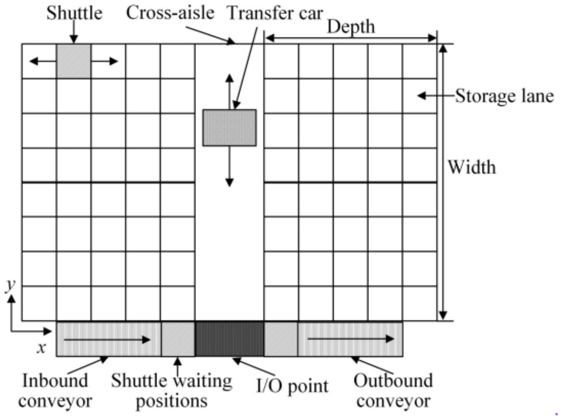
(a) **(b)**

Source: Automha (2021).

The vertical transport mechanism is a lift that can be either continuous or discrete, being the main difference between them the number of unit loads that can be handled simultaneously: a continuous lift, also referred as a conveyor, can move multiple unit loads at the same time, whereas a discrete lift can move only one (TAPPIA et al., 2017).

Figure 17 represents a top view of a SBCSS with specialized shuttles. It is possible to see the that the cross-aisle is located in the middle of the tier, running orthogonally to the storage lanes. The fleet of tier-captive specialized shuttles moves the pallets within the storage lanes (*x*-direction movement) and the shuttles can travel along the cross-aisle (*y*-direction movement) by transfer car, being able to access any storage position in the system (TAPPIA et al., 2017).

Figure 17 – Top view of a SBCSS.



Source: Deng et al. (2021).

Besides, Figure 17 shows that there is only one I/O point per tier, which is located at the end of the cross-aisle, and that the shuttles waiting positions are located next to this I/O point. In the represented system, the vertical transport mechanism is a conveyor, which moves the loads to be stored from the inbound workstation to the shuttle waiting position and the loads to be retrieved from the shuttle waiting position to the outbound workstation (DENG et al., 2021).

As a recent unit load storage and retrieval system, the SBCSS combines the features of the AVS/RS and compact storage systems in general, while being more cost-effective than both of them (DENG et al., 2021). Moreover, this system also has advantages in terms of time saving and flexibility, which means it has a shorter response time for storage and retrieval transactions and can easily modify its throughput capacity by adding or removing shuttles (TAPPIA et al., 2017).

The key decisions on system design relevant to the SBCSS are: ***(i)*** rack dimensions; ***(ii)*** number of shuttles; ***(iii)*** location of I/O point; ***(iv)*** velocity profile of shuttles and lifts; ***(v)*** system configuration, which can be either tier-to-tier or tier-captive; and ***(vi)*** type of shuttles adopted, which can be generic or specialized. Besides these decisions all the key operational and control policies for the SBS/RS are relevant for the SBCSS. Deng et al. (2021) highlights the importance of the processing policy for this type of system. In case of a specialized system this policy may considerably affect the system performance, since there are simultaneous operations of independent resources, shuttles and transfer cars. During a retrieval transaction under the sequential processing policy, for example, the transfer car waits for the shuttle while it retrieves the load inside the storage lane. Thus, as the storage lanes become deeper, it takes more time for the transfer car to wait for shuttles retrieving loads and this may affect the system response time.

4.4 Vertical Robotic Storage and Retrieval System

As shown in Figure 1, the AVS/RS, the SBS/RS and the SBCSS are classified as horizontal aisle-based systems, since they use a combination of autonomous vehicles or shuttles that move only horizontally, relying on lifts to perform the the vertical movement. Unlike these three types of systems, the VRS/RS is a vertical aisle-based system. This vertical system, as well as the diagonal system, are referred to as single-touch systems because they eliminate the multi-touch process of the horizontal systems, without requiring lifts to perform the vertical movement, as a single robot can independently roam throughout the storage rack to transport items.

The difference between the vertical and the diagonal systems is that in the former robots move independently in the horizontal and vertical directions inside the rack structure, with flexible horizontal and vertical paths, while in the latter the robots can move in diagonal directions. Figure 18 shows some examples of robots in single-touch system. Rack Racer, developed by Fraunhofer IML and shown in Figure 18(a), is one example of robot adopted in the diagonal system. iBot, developed by Opex Corporation and part of the Pick Perfect solution, and Skypod, developed by Exotec, are two examples of rack-climbing robots used in the VRS/RS. They are presented in Figure 18(b) and Figure 18(c), respectively.

Figure 18 – Robots of single-touch systems: (a) RackRacer, (b) iBot and (b) Skypod.

(a) **(b)** **(c)**

Source: Fraunhofer IML (2014), OPEX Corporation (2015) and Exotec (2022).

Since the diagonal robotic storage and retrieval system has not been studied in the literature yet, this thesis focuses only on the VRS/RS. In practical terms, the VRS/RS is a storage and retrieval system for small unit loads, usually totes. It is an emerging storage and retrieval solution based on mobile robots which can both navigate the shop floor and enter the storage racks (MORETTI et al., 2022), as exemplified in Figure 19.

Figure 19 – Robots of the VRS/RS (a) inside and (b) outside the storage racks.

(a) **(b)**

Source: Exotec (2022).

The VRS/RS consists of several aisles, each one consisting of two single-deep storage racks separated by an orthogonal cross-aisle in which autonomous robots can move. Each robot can access every storage location by independently moving horizontally and vertically, in sequence. The I/O points are usually located at either one end or both ends of each aisle on the ground tier, but other I/O points can be added on the mezzanine floor to increase the picking capacity (AZADEH; DE KOSTER; ROY, 2019).

Being a single-touch system, the VRS/RS has an advantage compared to a horizontal system, like the AVS/RS, in terms of flexibility and throughput capacity adjustability. In the VRS/RS, the desired throughput capacity can be obtained by only choosing the number of robots in the system, while in the AVS/RS with an already installed racking structure, the number of shuttles and the number of lifts need to be adjusted to achieve a certain throughput capacity. Moreover, the VRS/RS is also more reliable since if one robot breaks down, it can be quickly replaced by a backup robot without affecting the operation, while a failure of an exchange point in the AVS/RS could result in a system shutdown (AZADEH; DE KOSTER; ROY, 2019).

Moretti et al. (2022) highlight that, unlike other storage and retrieval systems which support the automation of either storage, picking or transportation of unit loads, the VRS/RS may allow to seamlessly integrate these activities with the same fleet of robots, as they are able to move both inside and outside the racks, as shown in Figure 19. This characteristic of the robots also allows the adoption of the VRS/RS in a factory environment, as addressed by Moretti et al. (2022). This system can be used to replenish supermarkets with totes from the central warehouse and also as a part-feeding system to assembly stations.

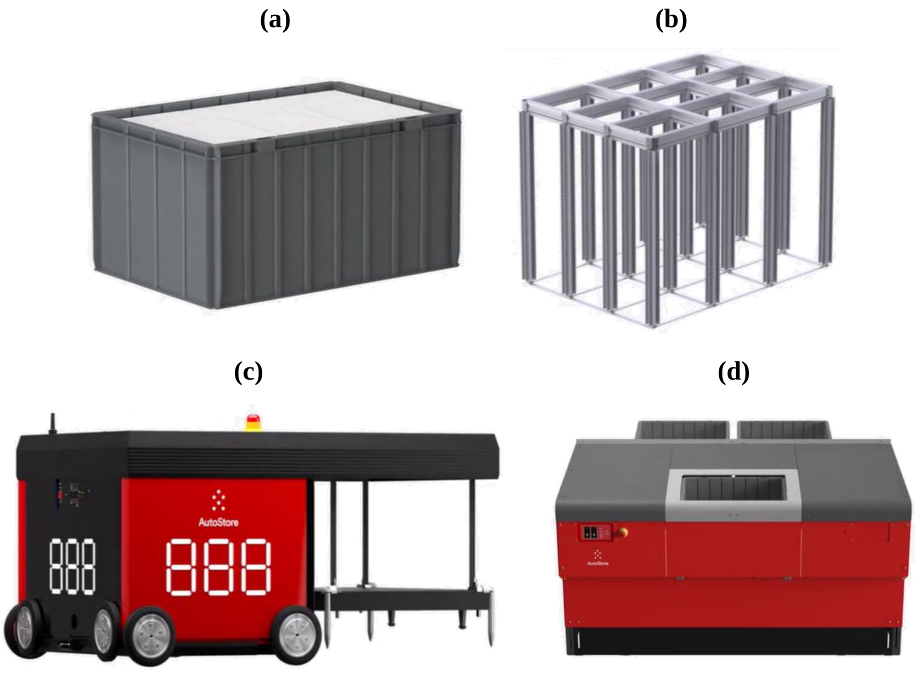
Like the previous systems, specially the AVS/RS, some key design decision to be made for the VRS/RS are: ***(i)*** rack dimensions, that is, the length and width of the system and the number of storage tiers; ***(ii)*** number of robots; ***(iii)*** location of the cross-aisle; ***(iv)*** location of I/O point; ***(v)*** velocity profile of vehicles and lifts. The only key operational and control decision important to the SBS/RS that is not applicable to the VRS/RS is the processing policy, since this latter system relies on only one type of device.

4.5 Robotic Compact Storage and Retrieval System

Unlike the previous four systems, as depicted by Figure 1, the RCS/RS is classified as a grid-based system rather than an aisle-based one. As presented in Figure 20, the RCS/RS is basically composed by four components: bins, grid, robots and workstations. In such system, the items are stored in bins, as exemplified in Figure 20(a), that are organized in a sort of a grid, as shown in Figure 20(b). In each cell of the grid, bins are stored on top of each other, forming a storage stack. Robots with transport and lifting capabilities, as represented in Figure 20(c), move on the grid roof, transporting bins between storage stacks and workstations, as shown in Figure 20(d), that are located on the ground level of the system (ZOU; KOSTER; XU, 2018).

To process a customer order with multiple items, robots first retrieve the bins that store the items from a storage stack, they move on the grid roof to the location above the workstation to which the order was assigned and then they lower the retrieved bins to this workstation. There, a worker picks the items requested by the customer order from the bins and performs packing operations. Then, the bins are returned by the robots to the top layer of the storage stacks from which they were originally retrieved (KO; HAN, 2022).

Figure 20 – Components of the RCS/RS: (a) bin, (b) grid, (c) robot and (d) workstation.



Source: AutoStore (2021).

Zou, Koster and Xu (2018) gathered from two warehouse automation and material handling providers, ElementLogic and Swisslog, some advantages of RCS/RS that explain its popularity:

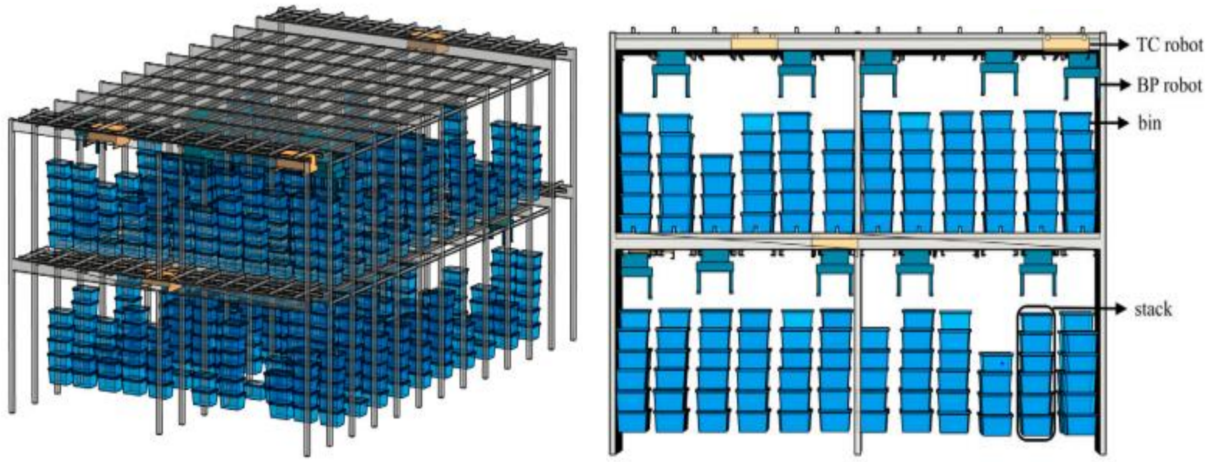
1. Flexible modular structure: it is possible to start with a small grid, which can be gradually expanded over time, without stopping the system operation.
2. Flexible throughput capacity: it is possible to expand the throughput capacity of the system by adding more robots and workstations.
3. Relatively low costs: compared to other automated storage systems available, the robots are small and relatively inexpensive.
4. Compact storage space: bins are stacked and robots transport bins on the grid roof, eliminating travel aisles and reducing system footprint.
5. Short response times: robots can move flexibly, in both *x*- and *y*-directions, which allows them to use congestion-free shortest paths.

These advantages make the RCS/RS particularly suitable for e-commerce-based logistics and distribution companies, which need to process small orders, with a big product assortment and with short response time to fulfill customer demands (KO; HAN, 2022).

There is a particular type of RCS/RS called overhead robotic compact storage and retrieval system (ORCS/RS), which can carry much heavier items compared to the traditional RCS/RS, allowing more industrial applications. In the ORCS/RS, shown in Figure 21, the items are also stored in bins stacked and organized in a grid, and usually the storage area consists of more than one plane (CHEN; YANG; SHAO, 2022).

Figure 21 – ORCS/RS (a) perspective view and (b) front view.

(a) **(b)**



Source: Chen, Yang and Shao (2022).

However, differently from traditional RCS/RS, the ORCS/RS operates with two types of robots: bin-picking robots (BP robots) and track-changing robots (TC robots). These robots work on their own, separate and mutually perpendicular tracks. The lower end of the TC robot has the same structure as the BP robot track, so the BP robots can move to the bottom of the TC robot and then move to another track with the aid of a TC robot (CHEN; YANG; SHAO, 2022) Figure 22, shows examples of BP and TC robots developed by WhaleHouse, a leading logistics technology supplier.

For an inbound task, the control system launches a storage command, which includes information about the product and storage place, and assigns a certain BP robot to complete the task. The BP robot places the inbound bin on top of the designated stack and leaves it there (CHEN; YANG; SHAO, 2022).

Figure 22 – Examples of (a) BP robot and (b) TC robot of ORCS/RS.

(a) **(b)**

Source: WhaleHouse (2022).

For an outbound task, the control system selects a bin that contains the required product from the available bins in all the stacks. First, the system queries for a BP robot on the same track as the target bin. If there is an idle BP robot on the target track, it will be ordered to retrieve the bin. If there are no idle BP robots there, the control system calls a TC robot to move an idle BP robot to the target track. In either case, like in the traditional RCS/RS, if the target bin is not on the top tier of the stack, the BP robot needs to reshuffle this stack in order to move the bins that are blocking the target bin to nearby stacks (CHEN; YANG; SHAO, 2022).

To properly exploit the advantages already presented, valid for both the traditional RCS/RS and the ORCS/RS, appropriate decisions regarding both the physical system design and the operation and control of system components need to be made. As for the key decisions affecting the RCS/RS, the design decisions are the following: ***(i)*** grid dimensions, that is the length and width of the system; ***(ii)*** stack height, that is the maximum number of items that can be stacked; ***(iii)*** number of robots; ***(iv)*** number and location of workstations; and ***(v)*** velocity profile of vehicles and lifts. Concerning the operational and control decisions, one decision that is particular to the RCS/RS is the reshuffling policy, since it might be necessary to reshuffle a stack if the target bin is not on the top (KO; HAN, 2022).

Zou, Koster and Xu (2018) and Ko and Han (2022) highlight the importance of operational and control policies for the RCS/RS. The decisions on storage policy are particularly important for the RCS/RS performance since it is a system using high-level storage stack and the storage policy implemented in the RCS/RS will determine the storage space required and the system throughput time. Specifically, storing one product in one storage stack, that is, a dedicated storage policy, can eliminate the reshuffling need of blocking bins while retrieving a requested bin, but more stacks will be required for products with large inventories, or for new incoming products. On the other hand, allowing multiple products to share the same storage stack, that is, a shared storage policy, can save storage space, but the retrieval time will increase since the robot may need to reshuffle the blocking bins before it can reach the requested bin (ZOU; KOSTER; XU, 2018). Besides, task sequencing also plays a major role in RCS/RS when a shared storage policy is adopted. In this case, to retrieve a target bin that is not on the top of a storage stack, all bins located above it must be reshuffled and, therefore, the amount of work required for a robot to process bins depends heavily on the sequence in which orders are processed (KO; HAN, 2022) (KANG, 2021).

Table 5 summarizes the key design decisions, the key operational and control decisions, the main advantages and the main application field for the five storage and retrieval systems under study.

Table 5 – Summary of the storage and retrieval systems under study.

	AVS/RS	SBS/RS	SBCSS	VRS/RS	RCS/RS
Key design decisions	- rack dimensions - number of vehicles - number bof lifts - location of cross-aisle - location of I/O point - number of zones - velocity profile of devices - tier-to-tier *vs* tier-captive system	- rack dimensions - number of shuttles - location of I/O point - velocity profile of devices - tier-to-tier *vs* tier-captive system	- rack dimensions - number of shuttles - location of I/O point - velocity profile of devices - tier-to-tier *vs* tier-captive system - generic *vs* specialized shuttles	- rack dimensions - number of robots - cross-aisle location - location of I/O point - velocity profiles of robots	- grid dimensions - stack height - number of robots - number and position of workstations - velocity profiles of robots
Key operational and control decisions	- storage policy - dwell point policy - interleaving policy - vehicle assignment policy - task scheduling policy - processing policy - block prevention policy - allocation of devices to zones	- storage policy - dwell point policy - interleaving policy - shuttle assignment policy - task scheduling policy - processing policy - block prevention policy	- storage policy - dwell point policy - interleaving policy - shuttle assignment policy - task scheduling policy - processing policy - block prevention policy	- storage policy - dwell point policy - interleaving policy - robot assignment policy - task scheduling policy - block prevention policy	- storage policy - dwell point policy - interleaving policy - robot assignment policy - task scheduling policy - block prevention policy - reshuffling policy
Main advantages	- flexibility - robustness to failures - modular structure - high throughput capacity - relatively low costs	- flexibility - robustness to failures - modular structure - high throughput capacity - energy efficient	- flexibility - robustness to failures - modular structure - high throughput capacity - compact storage space	- flexibility - robustness to failures - modular structure - high throughput capacity - integration of warehouse activities	- flexibility - robustness to failures - modular structure - relatively low costs - compact storage space - short response time
Main application fields	High requirements in terms of throughput performance when flexibility, robustness and modularization are desired	Similar to the AVS/RS, but managing a wider range of product, small unit load handled (e.g. tote) and shorter response times required	Similar to the AVS/RS, but managing small unit loads (e.g. tote), shorter response times required and stricter space constraints	Similar to the AVS/RS, but managing small unit loads (e.g. tote) and integrating other warehouses activities (e.g. replenishment of supermarkets)	Similar to the AVS/RS, but managing a wider range of product, small unit load handled (e.g. tote) and short response times required

Source: The author.

5 Systematic Literature Review and Research Agenda

In this chapter, all the papers included in the systematic literature review are briefly presented and the outcome data of the literature review process is synthesized in tables to present the current state of the literature for each storage and retrieval system under study, as explained in Chapter 2. Based on the current state mapped, research gaps are identified and opportunities for future study are proposed.

5.1 Autonomous Vehicle Storage and Retrieval System

The literature on the AVS/RS is relatively vast when compared to the other automated storage and retrieval systems under study, as will be further presented. There are several studies focusing on this type of system. As presented in Chapter 2, **28 papers** on this system were included in the literature review.

Malmborg (2002) is the first to address the AVS/RS in the literature. He develops a state equation model to estimate system performance, in terms of expected vehicle utilization and cycle time, based on key system parameters, including storage capacity, rack configuration and number of vehicles and lifts. The model built is validated through simulation and compared with analytical conceptualizing tools previously developed for the AS/RS technology.

Malmborg (2003) extends this state equation model by including the number of pending transactions in the state space description in order to predict the proportion of DC cycles in the AVS/RS when implementing opportunistic interleaving (i.e. matching a retrieval transaction with a storage transaction at the start of the storage and retrieval cycle when one or more of both types are waiting in the queue). The model is validated through simulation and used to estimate cycle time, system utilization and throughput capacity for different system profiles based on the number of aisles, the rack dimensions and the number of vehicles and lifts. One of his conclusions is that the model allows warehouse designers to explicitly trade off accuracy and computational cost.

Kuo, Krishnamurthy and Malmborg (2007) propose an analytical model to overcome the computational inefficiency related to the state equation approach adopted by Malmborg (2002) and Malmborg (2003). They model the lift system as a CQN which is nested within a separate vehicle CQN to estimate cycle time, transaction waiting time and vehicle utilization based on the number of storage tiers, aisles, columns, lifts and vehicles. The nested queuing network (NQN) model built is validated through simulation and illustrated in the context of design conceptualization, for example, by comparing the AVS/RS to the AS/RS in terms of costs.

Kuo, Krishnamurthy and Malmborg (2008) investigate the effect of a class-based storage policy on the cycle time of the AVS/RS. They develop a CQN model to estimate the performance of the AVS/RS with class-based storage policy in terms of cycle time, transaction waiting time and vehicle utilization. They conclude that the adoption of this policy can mitigate the cycle time inflation effect of vertical storage, while maintaining most of the space efficiency offered by the random storage policy.

Fukunari and Malmborg (2008) develop a computationally efficient cycle time model based on NQN, similarly to Kuo, Krishnamurthy and Malmborg (2007), with the lift queuing system modeled as a system nested within the vehicle queuing system. The model is validated and used to perform a direct comparison between the AVS/RS and the AS/RS. Optimal configurations of both systems are compared in terms of operational performance and costs and it is found that the technology selection has a significant impact on the initial costs of the system.

Fukunari and Malmborg (2009) propose a CQN model for estimating cycle time and resource utilization in the AVS/RS. This approach not only overcomes the computational disadvantage of the state equation models, as proposed by Malmborg (2002) and Malmborg (2003), but also provides flexibility for modeling the interfaces between a storage system and the overall material flow system, unlike nested queuing models. The model is validated through simulation and the results obtained show that it provides accurate estimates of the utilization of vehicles and lifts.

He and Luo (2009) address the deadlock control problem for the AVS/RS via colored timed Petri nets. Their focus is on deadlock avoidance because of its efficiency in solving the deadlock control problem. They build a dynamic model of the AVS/RS control system using colored petri nets, present the conditions of deadlock-free in vehicle travelling processes and, lastly, they propose and validate effective control policies for conflict and deadlock avoidance through a case study on a single-tier AVS/RS.

Zhang et al. (2009) are the first to develop an effective model to estimate transaction waiting times, as the previous models are quite inaccurate in this estimate, even though they compute vehicle utilization with reasonable accuracy. They build a NQN for estimating waiting times by dynamically choosing three alternative queuing approximations based on the squared coefficient of variation of transaction inter-arrival times. The simulation-based validation shows that the approach can reduce errors in this estimate by around 80% compared to static approximations.

Ekren and Heragu (2010) perform a simulation-based regression analysis to study rack configuration of the AVS/RS. They build a regression model considering as output variable the average cycle time for storage and retrieval transactions and as the input variables the design factors, namely the number of tiers, aisles and bays of the system. Then, they check whether or not the regression model adequacy is met, and they conclude that the regression function found is a good fit for expressing the relationship intended. Lastly, they present optimal points of this function using an optimization software.

Ekren et al. (2010) also perform simulation-based experiments for the AVS/RS, but their goal is to identify factors affecting system performance. They first select near-optimal combination of the number of vehicles and lifts from predefined scenarios. Then, they develop a design of experiment with these scenarios and the near-optimal number of vehicles and lifts, including several input factors, namely the dwell point policy, the scheduling rule, the I/O location and the interleaving rule. They investigate the effect of these factors and their interactions on the performance of the system using ANOVA, whereas a Tukey's test is used to obtain the best combination of factor levels for each scenario.

Ekren (2011) adopts simulation to evaluate the performance of the AVS/RS with zones under predefined design scenarios, which are determined by the number of aisles, bays, tiers, vehicles and lifts. Several performance measures are calculated, namely the cycle time, utilization of vehicles and lifts, lift and vehicle waiting times and number of transactions waiting for vehicle and lift. Finally, he also integrates into his analysis the total cost of the system, which is an important dimension to be taken into account by warehouse designers during the design conceptualization.

Ekren and Heragu (2011) present a simulation-based performance analysis of the AVS/RS. They consider that the system is divided into zones, with each zone having its own lift, so that the number of zones is given by the number of lifts and vice versa. Their aim is to find out near-optimal values for the number of vehicles and lifts in the system that lead to high performance under several predefined scenarios, defined in terms of rack configurations, number of lifts and number of vehicles per zone.

Heragu et al. (2011) develop analytical models for evaluating the performance of both tier-captive AVS/RS and AS/RS. The two competing systems are modeled using OQN and then an existing tool, called Manufacturing Performance Analyzer (MPA), is used to compare their performances. They run numerical experiments to show that the MPA is a better procedure than simulation to quickly evaluate different configurations of the two systems. Lasty, they examine the effect of dividing the AVS/RS into zones.

Ekren and Heragu (2012) compare the performance of the AVS/RS to the traditional CBAS/RS by using simulation models. Four performance measures are considered, namely the average flow time, the S/R device utilization, the average waiting time in the S/R device queue and the average number of jobs waiting in the S/R device queue. They also perform a T-test to find out the best warehouse configuration. Lastly, they conclude that in many cases the AVS/RS outperforms the CBAS/RS in terms of throughput performance.

Roy et al. (2012) are the first to model the AVS/RS using an SOQN. They model a single tier of the system as a multi-class SOQN with class switching, and a decomposition-based approach is implemented to evaluate the system performance. The model is validated through simulation and used to perform numerical examples to draw design insights. First, the model is used to analyze systems with different shape ratio, which suggests the optimal value to provide the best system performance. Then, they investigate vehicle assignment rules, and they find that the random vehicle assignment rule is quite effective. Lastly, they examine the effect of partitioning the storage area into zones and the results show that adopting multiple zones leads to a better performance due to the reduction in travel time along the cross-aisle.

Ekren et al. (2013) also model the AVS/RS as an SOQN and present an analytical model to assess system performance. They define all possible types of storage and retrieval cycles, as already presented, and the occurrence probabilities of each one of them. They derive general travel times for vehicles and lifts by considering all possible types of cycles identified. Then, they model the types of cycles as types of customers and they are all aggregated into a single class. Lastly, to find the performance measures, they solve the SOQN using an approximate method, which is later validated through simulation.

Cai, Heragu and Liu (2014) model the AVS/RS as a multi-class multi-stage SOQN, also implementing the so-called Matrix-Geometric Method (MGM) to analyze it and obtain performance measures. Besides, they also compare two synchronization policies: the virtual synchronization, which allows an available vehicle to be assigned to transaction regardless of its actual physical location, and the physical synchronization, which requires the return of the vehicle to the I/O point to be assigned to a transaction. They show that when the virtual synchronization is adopted the system achieves a better performance.

Ekren et al. (2014) model again the AVS/RS as an SOQN, but they solve it by applying the MGM. Firstly, the system is modeled as an SOQN with three stations. They reduce the network by aggregating the last two stations and obtain load-dependent throughput rates for these aggregated stations, assuming it as a single exponential server. Then, the reduced network is solved using the MGM to find main performance measures of the system. Lastly, the model is validated through simulation, and it is found that this approach improves the estimate of the number of transactions waiting for a vehicle from their previous study (EKREN et al., 2013).

Kumar, Roy and Tiwari (2014) study a zone-captive AVS/RS, which is a system partitioned into vertical and horizontal zones with dedicated vehicles. Their goal is to understand the effect of vertical zones and cross-aisle location on system performance measures. For this purpose, a detailed simulation model of a multi-tier zone-captive system is built to capture the dynamics of the system. As a conclusion, they found that an optimal vertical zoning can reduce transaction cycle times up to 12% in comparison to a system without zoning, but the horizontal zoning brings more benefits in cycle time reduction than the vertical one. Moreover, it is possible to further reduce the transaction cycle times by up to 15% with a better cross-aisle location.

Roy et al. (2014) devise blocking protocols to determine rules for usage of aisles and cross-aisles of the AVS/RS and propose an SOQN to model a single tier of the system. They adopt a decomposition-based approach to solve this network, similarly to Roy et al. (2012), validate the model through simulation and use it to evaluate the effect of vehicle blocking. They show that the blocking delays could contribute significantly to the transaction cycle time. Furthermore, they find that the percentage of blocking delays goes up as the number of vehicles increases, but the relevance of blocking is reduced as the utilization of vehicles increases, since the transaction waiting time in vehicle queue grows significantly.

Roy et al. (2015a) extend the model developed by Roy et al. (2012) to study the effect of the choice of vehicle dwell point policy and location of cross-aisles on system performance. They propose customized SOQN models for performance analysis of the AVS/RS with varying cross-aisle location and dwell point policies. The models are evaluated using a decomposition-based approach and later validated through simulation. They conclude that positioning the cross-aisle at the end of the storage aisles is an efficient choice if not optimal and that the I/O point dwell point policy is the best one.

Roy et al. (2015b) use SOQN to evaluate congestion effects in a multi-tier AVS/RS. They are the first to consider a conveyor-based AVS/RS, in which conveyors rather than lifts are responsible for the vertical movement. Their model provides the state distribution of vehicles at the cross-aisles and aisles of each tier, conveyor loops and I/O point. The queuing network is again solved using a decomposition-based approach and validated through simulation.

Roy et al. (2016) find a similar conclusion to Roy et al. (2014) using a simulation model. They also investigate the effect of blocking on system performance by analyzing a single tier of the AVS/RS. They develop protocols to address vehicle blocking that are incorporated in the simulation model, which is used to study blocking effects for a variety of tier configurations, defined in terms of shape ratio, number of storage locations, number of vehicles and transaction arrival rates. They show that blocking delays have a significant impact on transaction cycle time, representing up to 20% of this time.

Roy et al. (2017) adopt a multi-stage SOQN to model a multi-tier AVS/RS. Each tier of the system is modeled using an SOQN and the vertical transfer subsystem is modeled using an OQN. These subsystems are combined into an integrated queuing network model, consisting of multiple interconnected SOQNs. This model is solved using an iterative algorithm, validated through simulation and used to evaluate the performance of the system with alternate vertical mechanisms. They find that the conveyor-based system outperforms the lift-based system in terms of throughput capacity and expected transaction cycle time.

Akpunar, Ekren and Lerher (2017) take into account the environmental perspective to provide an energy efficient design of the AVS/RS. They use simulation models to analyze energy consumption per transaction based on warehouse design of the system, including the number of aisles, tiers and bays as well as the number of vehicles. They run some simulation experiments aiming to find the system with minimal energy consumption.

Lerher (2018) proposes analytical travel time models for the AVS/RS. The expressions of the travel times for both SC and DC cycles have been developed based on probability theory and the assumption of uniform distributed storage locations. A simulation model has been applied for the performance analysis of the proposed analytical models, which yields good performances.

Ekren (2021) develops a hierarchical solution approach for multi-objective optimization of the AVS/RS. He aims to minimize two conflicting performance measures, that are the expected transaction cycle time and the energy consumption per transaction, by working on some design variables, namely the number of tiers, the shape ratio and the velocity profile of vehicles and lifts. He uses simulation and performs a design of experiment, using ANOVA to identify statistically significant design factors and interactions among them affecting the performance measures, and the Tukey's test to search the best levels of such factors. Lastly, the multi-objective optimization work is completed by finding Pareto-optimal solutions.

Jerman et al. (2021) study a a novel AVS/RS design with movable lifts. They develop simulation models to investigate two alternative system designs with different rack configurations. The two system designs considered are the design with a single I/O point and the one with two I/O point, one at each end of the aisle. Their results show that designs with two separate I/O points provide a better throughput rate, and that a lower number of columns in the system improves system performance.

Table 6 presents the overview of the literature studied on the AVS/RS. Most of the papers reviewed are categorized as *system analysis*, being 13 of them classified only into this research category. This is especially true for older studies, from 2002 to 2009, as they focus on the development of models to estimate the system throughput performance, except for Kuo, Krishnamurthy and Malmborg (2008), which also investigate the effect of class-based storage policies. On the other hand, papers published in the last decade consider proportionally more design parameters and operational and control policies.

Regarding the modeling approach, most of the papers reviewed propose analytical models. The first two adopt state equation models, while queuing network models are the most used to analyze the AVS/RS. The papers started to model the system using NQN, CQN and OQN, but since SOQN models were proposed by Roy et al. (2012), no other type was used, showing a trend to use SOQN, which is explained by better results achieved with SOQN models due to the simplifying assumptions of OQN and CQN, as explained in Chapter 3. Moreover, all papers consider the AVS/RS in a distribution environment and only two papers address the environmental dimension, namely Akpunar, Ekren and Lerher (2017) and Ekren (2021).

One potential area of future research could be to further explore operational and control policies, since they are addressed by only six papers. Blocking prevention policy is one example of policy that can be studied. Roy et al. (2014, 2015b, 2016) investigate the effect of vehicle blocking on the system performance, but they do not seek any optimization of the system. Thus, future studies could explore different block prevention policies to mitigate the negative impact of blocking and optimize system performance.

Moreover, following the recent trend of environmental concern, the system design should not only consider minimization of cycle time, but also consider the minimization of energy consumption in the system. Therefore, studies on multi-objective optimization, similarly to Ekren et al. (2021), could be developed, considering other design parameters that affect system performance, for example, different zoning designs.

Table 6 – Overview of the literature on the AVS/RS.

Paper	Environment of Adoption	Research Category	Research Issue	Modeling Approach	Environmental Perspective
Malmborg (2002)	Distribution	SA	Estimate throughput performance	State equation	No
Malmborg (2003)	Distribution	SA	Estimate throughput performance	State equation	No
Kuo, Krishnamurthy and Malmborg (2007)	Distribution	SA	Estimate throughput performance	NQN	No
Kuo, Krishnamurthy and Malmborg (2008)	Distribution	SA OP&C	Estimate throughput performance Effect of class-based storage on performance	CQN	No
Fukunari and Malmborg (2008)	Distribution	SA	Estimate throughput performance	NQN	No
Fukunari and Malmborg (2009)	Distribution	SA	Estimate throughput performance	CQN	No
He and Luo (2009)	Distribution	OP&C	Investigation of deadlock-free policies	Colored Timed Petri Nets	No
Zhang et al. (2009)	Distribution	SA	Estimate transaction waiting times	NQN	No

Table 6 – Overview of the literature on the AVS/RS (continuation).

Paper	Environment of Adoption	Research Category	Research Issue	Modeling Approach	Environmental Perspective
Ekren and Heragu (2010)	Distribution	SA SD	Estimate throughput performance Optimal rack configuration	Simulation	No
Ekren et al. (2010)	Distribution	SA SD OP&C	Estimate throughput performance Effect of I/O point location on performance Effect of dwell point, scheduling and interleaving policies on performance	Simulation	No
Ekren (2011)	Distribution	SA	Estimate throughput performance	Simulation	No
Ekren and Heragu (2011)	Distribution	SA SD	Estimate throughput performance Optimal number of vehicles and lifts	Simulation	No
Heragu et al. (2011)	Distribution	SA SD	Estimate throughput performance Effect of system zones on performance	OQN	No
Ekren and Heragu (2012)	Distribution	SA SD	Estimate throughput performance Optimal rack configuration	Simulation	No
Roy et al. (2012)	Distribution	SA SD OP&C	Estimate throughput performance Optimal rack configuration Effect of system zones on performance Comparison between vehicle assignment policies	SOQN	No
Ekren et al. (2013)	Distribution	SA	Estimate throughput performance	SOQN	No
Cai, Heragu and Liu (2014)	Distribution	SA OP&C	Estimate throughput performance Comparison between synchronization policies	SOQN	No
Ekren et al. (2014)	Distribution	SA	Estimate throughput performance	SOQN	No
Kumar, Roy and Tiwari (2014)	Distribution	SA SD	Estimate throughput performance Effect of cross-aisle location of performance Effect of system zones on performance	Simulation	No
Roy et al. (2014)	Distribution	SA	Estimate throughput performance with blocking delays	SOQN	No
Roy et al. (2015a)	Distribution	SA SD OP&C	Estimate throughput performance Effect of cross-aisle location of performance Comparison between dwell point policies	SOQN	No
Roy et al. (2015b)	Distribution	SA	Estimate throughput performance with blocking delays	SOQN	No
Roy et al. (2016)	Distribution	SA	Estimate throughput performance with blocking delays	Simulation	No
Roy et al. (2017)	Distribution	SA SD	Estimate throughput performance Comparison between lifts and conveyors	SOQN	No
Akpunar, Ekren and Lerher (2017)	Distribution	SA SD	Estimate throughput performance Estimate energy consumption Optimal rack configuration and number of vehicles	Simulation	Yes
Lerher (2018)	Distribution	SA	Estimate throughput performance	Travel time	No
Ekren (2021)	Distribution	SD	Optimal rack configuration and velocity profiles	Simulation	Yes
Jerman et al. (2021)	Distribution	SA SD	Estimate throughput performance Effect of rack configuration and I/O point location on performance	Simulation	No

Notes on Research Category: SA: system analysis; SD: system design; OP&C: operations planning and control.

Source: The author.

5.2 Shuttle-Based Storage and Retrieval System

The literature on the SBS/RS is quite vast like the literature on the AVS/RS, even though the oldest studies found on the SBS/RS are more recent. In total, **38 papers** on this system were included in the literature review, as presented in Chapter 2. It is important to note that many of these papers refer to this system as AVS/RS, mainly the oldest ones, for example, Marchet et al. (2012), as the term *shuttle-based storage and retrieval system* is more recent than these studies.

Carlo and Vis (2012) are the first authors to study the SBS/RS. They analyze a particular type of system developed by the Vanderlande Industries consisting of a conveyor, two non-passing lifts that share a mast, multiple transfer shuttles, and a storage rack. Since the system has two lifts which share a mast, there is the possibility of blockage, so they focus on the scheduling problem of the two lifts in order to prevent blockages and reduce waiting times. They introduce two innovative functions to evaluate candidate solutions and an integrated look-ahead heuristics for the solution procedure that achieves improvements in terms of total handling times.

Marchet et al. (2012) analyze the performance of the SBS/RS expanding on previous contributions in the literature about the AVS/RS with tier-to-tier configuration. They model the SBS/RS via OQN to estimate the performance of the system in terms of utilization of lifts and shuttles as well as waiting times for lifts and queues. They validate the analytical models through simulation and show that these models provide good estimates for the performance measures.

Later, Marchet et al. (2013) present main design trade-offs for the SBS/RS using simulation. To evaluate system performance, a simulation model is developed considering both storage and retrieval transactions. They present several performance measures from the system, namely the utilization of lifts and shuttles, the average cycle time, the waiting times and the cost, for predefined rack designs. By varying the rack configuration and observing the performance impact, they analyze the effect of the rack configuration on system performance. Lastly, they develop a design framework for SBS/SR which is a useful tool to identify the optimal design layout, as it allows a quick identification of the most appropriate rack configuration in the conceptualization phase, given the physical and service constraints.

Lerher, Ekren, Dukic and Rosi (2015) propose an analytical travel time model for the computation of cycle time for the SBS/RS. They study closed-form solutions for travel time estimation of lifts and shuttles, taking into consideration their acceleration and deceleration. Based on the rack configuration and velocity profiles of shuttles and lifts, they develop models that can estimate the mean cycle time of lifts and shuttles under SC and DC scheduling rules, separately. They perform a validation using simulation which shows that the results of the developed travel time model correlate with the ones obtained through simulation.

Lerher, Ekren, Sari and Rosi (2015) adopt a simulation modeling approach to evaluate the performance of the SBS/RS. The objective of their study is to show which warehouse design leads to a reduction of the average transaction cycle time, hence an increase of system throughput capacity. They compare the performance of systems with different storage rack configurations and velocity profiles of shuttles and lifts. The results show that warehouse design is significant in reducing average transaction cycle time. More specifically, they conclude that the system throughput capacity depends considerably on the throughput performance of the lift.

Tappia et al. (2015) presents a mathematical model to evaluate the energy consumption and environmental impact of automated warehouse systems to fill a gap in both practice and theory since the selection of automated warehouse solutions were previously made based only on operational and economic performance. They build models to analyze both the SBS/RS and the AS/RS, and they use real data provided by material handling providers to validate them. They confirm the importance of considering the environmental dimension in design conceptualization phase since the monetization of the environmental impact may change the system selection. Moreover, they show that the SBS/RS is suitable for high values of the ratio of throughput capacity to storage capacity.

Eder and Kartnig (2016) introduce an analytical approach to calculate throughput capacity of the SBS/RS, being validated through simulation. The analytical model, developed using single queue with limited capacity (SQLC), allows to determine the optimal rack geometry for the system, given a rack height and a storage capacity to meet, in order to maximize the throughput capacity of the system, whether it is a single-depth or a multi-depth one.

Lerher (2016a) develops an analytical travel time model for the computation of cycle times and throughput performance of the multi-tier SBS/RS. The multi-tier SBS/RS is a variation of the traditional SBS/RS, described in Chapter 4, as it allows aisle-captive shuttles to travel between aisles using lifts deployed in the middle of the aisles, while in the traditional system the elevator lifting table in the beginning of the aisle only manipulates totes. The multi-tier model developed enables the calculation of the expected cycle time for dual command cycles, which allows an evaluation of the throughput capacity of the shuttle and the system as a whole.

Lerher (2016b), similarly to Lerher (2016a) and Lerher, Ekren, Dukic and Rosi (2015), also develops an analytical travel time model for the computation of cycle time for the SBS/RS but considers a double-deep system. The developed models can estimate average cycle time of lifts and shuttles under SC and DC scheduling rules, based on rack configuration, lifts configuration and velocity profiles of shuttles and lifts. The advantage of the proposed double-deep SBS/RS is that fewer aisles are required to satisfy a given storage capacity resulting with a decreased footprint.

Lerher et al. (2016) develop a simulation model like the one proposed by Lerher, Ekren, Sari and Rosi (2015), presenting an efficient approach for evaluating the throughput performance of the SBS/RS. They also investigate the impact of decision variables on system performance, such as the number of tiers, number of aisles, number of columns and velocity of lifts and shuttles. One of the conclusions drawn is that in case of a small number of columns and a large number of aisles, the system performance is expressively higher compared to other rack configurations.

Ning et al. (2016) develop a simulation model that can be used to efficiently test a large number of rack alternatives and search for the optimal design solution. Differently from previous studies, they analyze a new type of SBS/RS with multiple elevators because the lifts are considered the bottleneck of the traditional SBS/RS as the number of lifts is determined by the number of aisles. They validate the simulation model by comparing the simulation results to those obtained by Marchet et al. (2012). After validation, they use the model to identify optimal rack alternatives trying to maximize the throughput capacity and minimize the cycle time.

Zou et al. (2016) investigate a scenario in which the lift and vehicles of the SBS/RS are requested simultaneously to move a load rather than sequentially, unlike previous studies. To analyze the performance of this policy, they formulate a fork-join queuing network (FJQN) where a transaction is split into a horizontal movement task served by the vehicle and a vertical movement task served by the lift. They develop an approximation method based on decomposition to estimate system performance and they build simulation models to validate the effectiveness of the analytical models. They conclude that in small systems the parallel processing policy always outperforms the sequential processing policy in terms of system response time for retrieval transactions.

Borovinšek et al. (2017) present a multi-objective optimization solution procedure for design of the SBS/RS by using the non-dominated sorting genetic algorithm II (NSGA II) for facilitating the solution. The procedure considers three independent objective functions in the design concept: minimization of the average cycle time of transactions, the energy consumption and the total investment cost. They consider several design variables: number of aisles, tiers and columns, velocities and acceleration profile of shuttles and lifts. Lastly, they seek Pareto optimal solutions.

Ekren (2017) uses simulation to model the system and provide a graph-based solution for performance evaluation, considering utilization of lifts and cycle time. The model built is used to run some experiments varying design scenarios, such as number of bays, aisles and tiers and arrival rate of storage and retrieval transactions. The solution via graphs aims to support warehouse designers in the design conceptualization phase by providing a tool to evaluate the performance of predefined systems.

Epp, Wiedmann and Furmans (2017) present a model for performance evaluation of the SBS/RS applying a discrete-time OQN approach. The model is validated through discrete-event simulation and allows the computation of the retrieval transaction time distribution, as well as the distribution of the number of transactions waiting to be stored, so not only expected values and variance can be obtained, but also quantiles of these performance measures.

Lerher et al. (2017) develop a parametric simulation model that enables to calculate the cycle time of shuttles and lifts under both SC and DC cycles, besides the system throughput capacity. Differing from previous studies on the SBS/RS, they implement a design of experiment, similarly to Ekren et al. (2010) on the AVS/RS, which aims to identify factors affecting system performance. The factors included and analyzed in the experiments are the number of bays and the minimum volume of the system. They conclude that warehouse designers aiming to minimize the average cycle time should consider designing the SBS/RS with long storage racks and relatively small numbers of tiers.

Eder and Kartnig (2018) present analytical models to calculate the throughput capacity similar to the one presented by Eder and Kartnig (2016), but they also develop a model to compute the energy consumption of the SBS/RS. This model takes into account acceleration, deceleration, rides with constant speed, lifting movements and storage and retrieval processes.

Ekren et al. (2018) propose a tool based on an analytical model to compute performance measures of the SBS/RS, including the mean and the variance of travel time of lifts and shuttles, as well as the mean amount of energy consumption and energy regeneration per transaction. The analytical model presented is validated through simulation for different design scenarios and it is verified that the results obtained with the tool are highly accurate. This tool allows a quick performance evaluation of the SBS/RS by changing the input parameters, such as velocity, acceleration and deceleration of shuttles and lifts and number of tiers and bays.

Ha and Chae (2018) study control policies to prevent collision and balance workload in the SBS/RS. They suggest system controls to prove the effectiveness of free balancing, that is, when each shuttle’s position is constantly monitored to avoid collisions or blockages, as well as to make sure jobs are evenly assigned and the required throughput is maintained. They develop and run simulation models to assess system performance and they show free balancing achieves better performances, in terms of throughput and utilization, compared to a basic system control.

Kriehn et al. (2018) demonstrate that class-based storage policy, sequencing of retrieval requests and warehouse reorganization have a considerable potential to increase the throughput capacity of the SBS/RS. They use a simulation model to obtain the system throughput capacity for the selected parameter combinations. They conclude that class-based storage and the sequencing of retrieval requests also leads to a lower energy consumption due to shorter travel time.

Zhao, Luo and Lodewijks (2018) study the SBS/RS with two non-passing elevators on a common rail, like Carlo and Vis (2012). They focus on the scheduling of the lifts, including the storage and retrieval requests sequencing, assignment of lifts and collision avoidance. Differently from Carlo and Vis (2012), they consider the acceleration and deceleration. They propose a function to predict the lift trajectory and a scheduling genetic algorithm. Lastly, experimental results show that the proposed approach achieves significant improvement in system performance compared to the approach considering constant velocity.

Eder (2019) addresses a method for measuring system performance using continuous-time open SQLC. The main novelty of the approach presented is the use of a time-continuous queuing model to take into account the interactions between lifts and shuttles combined with a spatial discrete approach for the processes of lifts and shuttles. A discrete event simulation is adopted to validate the developed model. Lastly, it is outlined how the presented model can be used to optimize the SBS/RS in order to satisfy given requirements, such as storage capacity, throughput capacity, height and length constraints.

Ha and Chae (2019) propose a decision model to determine the number of shuttles in the SBS/RS. The decision model is based on a travel time model and it considers parameters such as the system configuration, the velocity profile and the probability of performing a dual command cycle. The decision model is validated by comparing its results with that from simulation. One of the conclusions drawn is that the proposed model is able to help in the system design process by assessing the number of shuttles according to the requirements in terms of throughput capacity.

Zhao et al. (2019) study the tier-to-tier SBS/RS focusing on the task scheduling. Aiming at minimizing total task time by decreasing idle time of lifts and the waiting time of shuttles, they develop an integer programming (IP) model. Then, simulation is used to verify the proposed model, and it is shown that the overall system efficiency is improved using this model.

Eder (2020a), like Eder (2019), also presents a model to determine the performance of the SBS/RS using a continuous-time open SQLC. However, the first adopts this modeling approach to analyze the SBS/RS with class-based storage policy. Again, the developed approach is validated by a comparison with a discrete event simulation. Moreover, he provides an example to outline how his model can be used for optimizing an already existing system through the adoption of a class-based storage policy.

Ekren (2020) performs an experiment study that aims to identify significant factors affecting the performance measures of the SBS/RS, such as average cycle time, energy consumption for a transaction and amount of energy regeneration for a transaction. A simulation model is built, and a design of experiment is implemented with a full factorial design, considering as factors the maximum velocity and acceleration of shuttles and lifts and the number of tiers and bays. Lastly, ANOVA is used to identify significant factors and interaction effects among them, and the Tukey's test is adopted to find out the best levels of those design factors previously identified significant.

Lei et al. (2020) aim to improve the efficiency of the tier-to-tier SBS/RS by considering a mixed storage of goods, that is, multiple goods stored in the same unit load. They build an optimization model consisting of two stages: location allocation and job scheduling. A two-layer genetic algorithm is designed to solve this model considering the shortest outbound time of all outbound orders in a certain period. Lastly, they validate the optimization model and algorithm with the data of a company.

Wu et al. (2020) consider the SBS/RS as a part-to-picker order fulfilment system used to feed workstations. They develop an OQN model to estimate the performance of the SBS/RS and they use simulation to validate this model. Moreover, they present a search algorithm that aims to find the minimum cost configurations to satisfy given requirements in terms of throughput capacity, storage capacity and order cycle time. Lastly, they compare this technology with the competing robotic mobile fulfilment system.

Zhao et al. (2020) analyze the tier-to-tier configuration of the SBS/RS by modeling the system as a SOQN. The network is then transformed into two different CQNs, and the approximate mean value analysis (AMVA) algorithm is applied to solve the model and estimate its performance. The performance measures considered are the utilization of shuttles, the utilization of lift, and the cycle time. They use simulation to validate the effectiveness of the queuing network model proposed and find that it can accurately estimate cycle time.

Bahurdin et al. (2021) develop simulation models in order to compare dwell point policies, that is the optimal location in the system for an idle shuttle to park. They consider two dwell points: the first at the I/O point and the second in the middle of the aisle. The results obtained from the models were statistically analyzed using the T-test method, and they find that the dwell point in the middle of the aisle outperforms the dwell point on the I/O point in terms of travel time.

Dong and Jin (2021) propose travel time models to investigate different storage policies and shuttle dispatching rules for the tier-to-tier configuration of the SBS/RS. They analyze both random and class-based storage policies and three shuttle dispatching rules: random, distance-based, and demand-rate based. They develop travel time models for both SC and DC cycles, and these models are validated through simulation. One of the conclusions drawn is that the decision on the best operational policies significantly depends on demand patterns.

Ekren and Akpunar (2021) develop two approaches based on OQN to assess the performance of the SBS/RS. The approaches are validated with a simulation model and the one with more accurate results is integrated to a software tool that can quickly estimate some important performance measures for predefined SBS/RS warehouse designs. More specifically, based on input data, such as arrival rate of transactions, rack configuration and velocity profiles of devices, the tool estimates the mean cycle time, the mean energy consumption and energy regeneration per transaction, the mean waiting time of a transaction, the mean queue length of lifts and shuttles, and the mean utilization of these devices.

Küçükyaşar, Ekren and Lerher (2021) compare two system configurations of SBS/RS: the one with tier-captive shuttles and the one with tier-to-tier shuttles. These configurations were compared on the following performance measures: initial investment costs, throughput rates per hour, and average energy consumption per transaction when there is a regeneration mechanism in the system. They adopt simulation models and conduct several experiments by changing the rack configuration. They conclude that the tier-to-tier configuration may outperform the tier-captive one in terms of initial investment and throughput performance. Therefore, it must be considered in the system designing phase.

Liu et al. (2021) consider the environmental dimension by investigating environmentally friendly velocity and acceleration configurations for the SBS/RS. They develop an analytical model to estimate the throughput capacity, travel time and energy consumption. Then, they run experiments to find the optimal velocity profiles for given throughput capacities. Their results show that the lift velocity and acceleration are the leading factors affecting energy consumption and that increasing the acceleration of shuttles can moderately reduce travel times and improve storage efficiency, without significantly increasing the energy consumption.

Lin et al. (2021) study task scheduling for the double-deep tier-captive SBS/RS with alternative elevator patterns. They develop a simulation model to support analyzing the performance of the system, considering shuttle waiting time, elevator idle time and total outbound time, with both the single-elevator and the double-elevator design, one at each end of the aisle. Then, they design an optimization model and a non-dominated sorting genetic algorithm II (NSGA II) for task scheduling, which is shown to be able to improve system performance.

Ekren and Arslan (2022) apply a machine learning approach, called Q-learning, on a newly proposed tier-to-tier SBS/RS design, which has two lifts, one at each end of the aisle. The solution based on machine learning is used to study a reinforced learning algorithm for the scheduling rule, and the proposed algorithm is compared with traditional scheduling approaches: first-in-first-out and shortest process time scheduling rules. Their results indicate that, in most cases, the proposed approach outperforms the two static scheduling approaches mentioned.

Li et al. (2022) investigate the multi-item order batching and retrieving problem for the SBS/RS, in which orders containing different items are batched and processed by the system. A mixed-integer linear programming model is proposed to jointly optimize the batching and retrieving assignment considering carbon emission reduction. A tabu search-based algorithm along with an efficient algorithm for generating retrieving assignments are developed for problem-solving. Then, numerical experiments are conducted to validate the efficiency of the proposed algorithm as well as the carbon emission reduction.

Wang et al. (2022) provide a significant contribution towards automated warehouse planning by taking into consideration the environmentally friendly design concept. They present a decision support system based on an analytical model that estimates design indicators, namely mean service time, mean energy consumption per transaction, mean energy regeneration per transaction, and overall system cost. The model is validated through simulation and used to run numerical experiments to study the impact of rack design and equipment parameters on system performance.

Table 7 illustrates the overview of the literature on the SBS/RS, including the 38 papers reviewed. Out of them, 32 assess system performance, either in terms of throughput or energy consumption, 15 perform design optimization or study the relationship between design parameters and system performance, and, lastly, 12 study operational and control policies. In particular, many papers develop models to estimate system performance and then apply them to optimize system design, especially the rack dimensions.

Table 7 also shows that a high variety of modeling approaches is used to analyze the SBS/RS. Only 13 papers adopt simulation models, so analytical models are the most frequently adopted ones, including queuing network model, travel time model, IP model and heuristics. Regarding queuing network models, there are two different main approaches: the first possibility is to model an OQN, the other option is to model an open SQLC. According to Eder (2019), OQN models are able to calculate the waiting times per cycle, but the maximum throughput cannot be derived from such approach, being the SQLC model used to approximate the real system as much as possible and to consider the interactions between lifts and shuttles.

Similarly to the AVS/RS, all papers on SBS/RS consider the system in a distribution environment. However, 10 papers take into account the environmental perspective. Most of them adopt analytical models to estimate the energy consumption of the system, even though simulation models are used for this purpose as well. It is possible to see that this perspective is considered mainly by the most recent papers, with eight out of the 10 papers that considered this perspective being published since 2018, which suggests a research trend.

Besides the research trend to consider the environmental perspective, recent papers also consider the system cost. For instance, Wu et al. (2020) aim at finding minimum cost configurations of SBS/RS to satisfy performance requirements, whereas Wang et al. (2022) present a tool to design the system considering throughput performance, energy consumption and overall system cost. In this perspective, for example, the work by Liu et al. (2021) could be extended to include the cost perspective by incorporating both fixed and operating costs in addition to the throughput capacity and the energy consumption.

Since only 12 out of the total 38 papers reviewed analyze operational and control policies, this seems to be an opportunity for future research. Policies that have been extensively studied for the traditional AVS/RS could be further investigated for the SBS/RS, for example, dwell point policies, which is addressed by only one paper on SBS/RS. A future study could compare different dwell point policies based on the system throughput and environmental performances.

Lastly, as there are already many papers on the SBS/RS, another potential area of research could be to compare its performance with that of other advanced logistics systems. In this regard, both Liu et al. (2021) and Wang et al. (2022) point out that future research could compare this system to to other systems, such as the so-called robotic mobile fulfillment system, in order to support warehouse managers in the technology selection. Such comparison could include not only the system performance in terms of throughput time and energy consumption, but also considering costs.

Table 7 – Overview of the literature on the SBS/RS.

Paper	Environment of Adoption	Research Category	Research Issue	Modeling Approach	Environmental Perspective
Carlo and Vis (2012)	Distribution	OP&C	Optimal scheduling of lifts	Heuristics	No
Marchet et al. (2012)	Distribution	SA	Estimate throughput performance	OQN	No
Marchet et al. (2013)	Distribution	SA SD	Estimate throughput performance Optimal rack configuration	Simulation	No
Lerher, Ekren, Dukic and Rosi (2015)	Distribution	SA	Estimate throughput performance	Travel time	No
Lerher, Ekren, Sari and Rosi (2015)	Distribution	SA SD	Estimate throughput performance Effect of rack configuration and velocity profile on performance	Simulation	No
Tappia et al. (2015)	Distribution	SA	Estimate energy consumption	Energy consumption	Yes
Eder and Kartnig (2016)	Distribution	SA SD	Estimate throughput performance Optimal rack configuration	SQLC	No
Lerher (2016a)	Distribution	SA	Estimate throughput performance	Travel time	No
Lerher (2016b)	Distribution	SA	Estimate throughput performance	Travel time	No
Lerher et al. (2016)	Distribution	SA SD	Estimate throughput performance Effect of rack configuration and velocity profile on performance	Simulation	No
Ning et al. (2016)	Distribution	SA SD	Estimate throughput performance Optimal rack configuration	Simulation	No
Zou et al. (2016)	Distribution	SA OP&C	Estimate throughput performance Comparison sequential *vs* parallel processing policies	FJQN	No
Borovinšek et al. (2017)	Distribution	SD	Optimal rack configuration and velocity profiles of vehicles and lifts	Heuristics	Yes
Ekren (2017)	Distribution	SA	Estimate throughput performance	Simulation	No
Epp, Wiedmann and Furmans (2017)	Distribution	SA	Estimate throughput performance	OQN	No
Lerher et al. (2017)	Distribution	SA SD	Estimate throughput performance Effect of number of bays and minimum warehouse volume on performance	Simulation	No
Eder and Kartnig (2018)	Distribution	SA	Estimate throughput performance Estimate energy consumption	SQLC Energy consumption	Yes
Ekren et al. (2018)	Distribution	SA	Estimate throughput performance Estimate energy consumption	Travel time Energy consumption	Yes
Ha and Chae (2018)	Distribution	SA OP&C	Estimate throughput performance Effect of system control and free balancing on performance	Simulation	No

Table 7 – Overview of the literature on the SBS/RS (continuation).

Paper	Environment of Adoption	Research Category	Research Issue	Modeling Approach	Environmental Perspective
Kriehn et al. (2018)	Distribution	SA OP&C	Estimate throughput performance Effect of class-based storage and order sequencing on performance	Simulation	No
Zhao, Luo and Lodewijks (2018)	Distribution	OP&C	Optimal scheduling of lifts	Heuristcs	No
Eder (2019)	Distribution	SA SD	Estimate throughput performance Optimal rack configuration	SQLC	No
Ha and Chae (2019)	Distribution	SA SD	Estimate throughput performance Effect of rack configuration and velocity profile on performance	Travel time	No
Zhao et al. (2019)	Distribution	OP&C	Optimization of task scheduling	IP model	No
Eder (2020a)	Distribution	SA OP&C	Estimate throughput performance Effect of class-based storage on performance	SQLC	No
Ekren (2020)	Distribution	SA SD	Estimate throughput performance Estimate energy consumption Effect of rack configuration and velocity profile on performance	Simulation	Yes
Lei et al. (2020)	Distribution	SA SD	Estimate throughput performance Effect of mixed storage, location allocation and job scheduling rules on performance	Heuristics	No
Wu et al. (2020)	Distribution	SA SD	Estimate throughput performance Optimal rack configuration profiles	OQN	No
Zhao et al. (2020)	Distribution	SA	Estimate throughput performance	SOQN	No
Bahurdin et al. (2021)	Distribution	SA OP&C	Estimate throughput performance Comparison between dwell point policies	Simulation	No
Dong and Jin (2021)	Distribution	SA OP&C	Estimate throughput performance Comparison between storage policies and shuttle assignment policies	Travel time	No
Ekren and Akpunar (2021)	Distribution	SA	Estimate throughput performance Estimate energy consumption	OQN Energy consumption	Yes
Küçükyaşar, Ekren and Lerher (2021)	Distribution	SA	Estimate throughput performance Estimate energy consumption	Simulation Energy consumption	Yes
Liu et al. (2021)	Distribution	SA SD	Estimate throughput performance Estimate energy consumption Optimal velocity profiles	Travel time Energy consumption	Yes
Lin et al. (2021)	Distribution	SD OP&C	Comparison between single-lift and double-lift designs Optimization of task scheduling	Simulation Heuristics	No
Ekren and Arslan (2022)	Distribution	SA OP&C	Estimate throughput performance Investigation of scheduling rule based on reinforcement learning algorithm	Simulation	No
Li et al. (2022)	Distribution	OP&C	Optimization of multi-item batching and retrieval process	MIP model Heuristics	Yes
Wang et al. (2022)	Distribution	SA SD	Estimate throughput performance Estimate energy consumption Effect of rack configuration and velocity profile on performance	Travel time Energy consumption	Yes

Notes on Research Category: SA: system analysis; SD: system design; OP&C: operations planning and control.

Source: The author.

5.3 Shuttle-Based Compact Storage System

The literature on the SBCSS is not as vast as the literature on the AVS/RS and the SBS/RS, notwithstanding its better volume flexibility, lower operational cost and shorter response time. This system is more recent, not as widely adopted and it also benefits from previous studies on the two other types of systems. Thus, **12 papers** on this system were included in the literature review, as shown in Chapter 2.

Manzini et al. (2016) study a single tier of the SBCSS but referring to it as deep-lane unit load AVS/RS. They build analytical travel time models to estimate travel distance and travel time for both SC and DC cycles in different layout configurations, which differ in terms of the shape ratio and the location of the I/O points. They also develop analytical expressions to compute the optimal shape ratio to minimize travel distance and travel time. Then, the analytical models are validated through simulation and applied to a real case study.

Tappia et al. (2017) are the first to model a multi-tier SBCSS with lifts, using queuing network models. They model a single-tier system as a multi-class SOQN with class switching, which is solved by using the MGM-based approach. Then, the queuing network model for the multi-tier system is proposed by merging the single-tier systems and is solved by using parametric decomposition. The models built can handle both specialized and generic shuttles and both continuous and discrete lifts. The accuracy of the models is validated through both simulation and a real case. They use the models to optimize the shape ratio and the number of tiers of the system in order to minimize throughput time and, lastly, they compare systems with generic and specialized shuttles in terms of cost and throughput capacity.

D'Antonio et al. (2018) analyze a tier-to-tier single-sided SBCSS, with one lift, one shuttle and one satellite. More specifically, they develop analytical travel time models to calculate the cycle time and its standard deviation, considering the unit load allocation rule as a model variable in order to obtain more accurate estimations of the cycle time. Lastly, the presented models are validated through simulations performed on different warehouse layouts.

D'Antonio and Chiabert (2019) also study a tier-to-tier single-sided SBCSS like D'Antonio et al. (2018). They adopt a similar modeling approach, but they take a step forward to model a multi-shuttle system, rather than a system with only one shuttle. The proposed models are validated against simulations varying parameters, such as rack layouts and fleet size.

Guerrazzi et al. (2019) also refer to the SBCSS as deep-lane AVS/RS. They study a system equipped with energy recovery systems using simulation. Their aim is to provide an energy evaluation considering the energy recovered from the braking phase of the lift. They conclude that about 28% of the energy consumption of the SBCSS can be recovered and that the energy consumption of this system is nearly 40% of that of a traditional AS/RS.

Eder (2020b) and Eder (2020c), similarly to Eder (2019), present an analytical approach to determine the performance of the SBCSS using a continuous-time open SQLC, but, differently from Eder (2019) which analyze the SBS/RS, they consider a system with multiple-deep storage. Again, the invented approach is validated by a comparison with a discrete event simulation. They also give an example to show how the model can be applied to design optimal SBCSS subject to predefined requirements. Both studies analyze the footprint required based on the number of tiers and storage depth of the system and their results show that an increase of the storage depth allows to improve system throughput performance and also reduce its costs, by reducing the footprint required.

Kumawat and Roy (2021) work on a new solution approach for multi-stage SOQN. While the approach developed by Tappia et al. (2017) is based on the multi-server approximation of the subnetwork, their approach is based on two-moment approximation for estimating the job departure process parameters from a single-stage SOQN, which can serve as an input to link multi-stage SOQN. The approach is validated using numerical experiments through simulation and then is applied to a multi-tier SBCSS with specialized shuttles to estimate expected cycle time and average queue length at the lift.

Deng et al. (2021) estimate the performance of a single-tier of the SBCSS under parallel processing policy. They develop a multi-class SOQN with class switching to model the system and a fork-join queueing network (FJQN) to model the concurrent movement of shuttles and transfer car. The model is validated through simulation and is used to investigate the scenarios in which the parallel processing policy outperforms the sequential one. The results suggest the adoption of parallel processing policy in cases of large transaction arrival rates. Finally, they find the optimal shape ratio for minimizing the expected throughput time of the system.

Battarra et al. (2022) propose a hierarchical analytical-simulative hybrid approach to quantify the performance of the SBCSS and compare different system configurations. They consider that two of the most critical issues in current research studies are the random arrival time of storage and retrieval transactions and the random storage policy. Their hybrid model is applied to a case study according to a what-if analysis, and they investigate the effect of the number and typology of shuttles on system performance.

Eder (2022) proposes an analytical approach to determine the performance of the SBCSS using a continuous-time open SQLC similar to the one presented by Eder (2020b) and Eder (2020c) but also considering class-based storage. The approach presented allows to evaluate the improvement in the performance of the SBCSS by applying a class-based storage policy. This approach can be used both in the design process of a new system and in the upgrading process of an existing one.

Marolt, Sinko and Lerher (2022) study the SBCSS allowing more than one SKU to be stored in the same depth lane. They follow a depth-first storage and a depth-first relocation strategy, which ensures that the SKU will be stored or relocated in the storage rack's deepest possible empty storage location. They propose an analytical model based on a novel approach that adopts the Markov chain stochastic steady-state model and they develop numerical simulation models to validate the analytical model.

Table 8 brings the overview of the literature on the SBCSS. It is possible to see that multiple modeling approaches were used to study this type of system, mainly analytical models. Since D'Antonio and Chiabert (2019), which adopt a travel time model, papers with analytical-based approaches mostly use models based on queuing networks (SOQN) or queuing systems (SQLC). This trend is aligned to what was seen for the AVS/RS and the SBS/RS, which was expected because these three systems are similar and both OQN and CQN fail to capture the way they operate, as explained in Chapter 3. Therefore SOQN and SQLC models are used to approximate the real system as much as possible and to consider the interactions between lifts and shuttles.

Guerrazzi et al. (2019) are the only ones to model the SBCSS using simulation, but they have a research issue quite different from the others. While the other papers categorized as *system analysis* estimate performance measures, such as average shuttle and transfer car utilization, average queue length at the lift and average cycle times, they focus on assessing the system performance in terms of energy consumption. In this sense, they are the only ones to consider the environmental perspective for this system.

Table 8 – Overview of the literature on the SBCSS.

Paper	Environment of Adoption	Research Category	Research Issue	Modeling Approach	Environmental Perspective
Manzini et al. (2016)	Distribution	SA SD	Estimate throughput performance Optimal shape ratio Optimal I/O point location	Travel time	No
Tappia et al. (2017)	Distribution	SA SD	Estimate throughput performance Optimal shape ratio Comparison generic *vs* specialized shuttles	SOQN	No
D'Antonio et al. (2018)	Distribution	SA SD OP&C	Estimate throughput performance Effect of rack configuration on performance Effect of location allocation rule on performance	Travel time	No
D'Antonio and Chiabert (2019)	Distribution	SA SD OP&C	Estimate throughput performance Effect of rack configuration on performance Effect of location allocation rule on performance	Travel Time	No
Guerrazzi et al. (2019)	Distribution	SA	Estimate energy consumption	Simulation	Yes
Eder (2020b)	Distribution	SA SD	Estimate throughput performance Optimal rack configuration	SQLC	No
Eder (2020c)	Distribution	SA SD	Estimate throughput performance Optimal rack configuration	SQLC	No
Kumawat and Roy (2021)	Distribution	SA	Estimate throughput performance	SOQN	No
Deng et al. (2021)	Distribution	SA SD OP&C	Estimate throughput performance Optimal shape ratio Comparison parallel *vs* sequential processing policies	SOQN FJQN	No
Battarra et al. (2022)	Distribution	SA SD	Estimate throughput performance Effect of the number and typology of shuttles on system performance	Hybrid model	No
Eder (2022)	Distribution	SA SD OP&C	Estimate throughput performance Optimal rack configuration Effect of class-based storage on performance	SQLC	No
Marolt, Sinko and Lerher (2022)	Distribution	SA OP&C	Estimate throughput performance Investigation of depth-first storage policy	Markov chain-based	No

Notes on Research Category: SA: system analysis; SD: system design; OP&C: operations planning and control.

Source: The author.

Furthermore, only five papers analyze operational and control policies for this type of system, being categorized as *operations planning and control*. The policies investigated are storage policies, processing policy, and location allocation rule. Given the wide range of operational and control decions that affect the performance of the SBCSS, as show in Table 5, new studies on this system are expected to address other policies, for example, dwell point policies, transaction scheduling policies and shuttle assignment policies. Even though they have been studied for the AVS/RS and the SBS/RS, research focusing on these policies and considering the particularities of the SBCSS could provide new insights for warehouse managers and allow the improvement of system performance.

In addition, future studies on the shuttle-based storage and retrieval system could deepen the environmental perspective to meet the rise of consciousness in warehouse sustainability. Guerrazzi et al. (2019) evaluate the energy consumption of a system with regenerative braking system to recover energy from each lift, so the study could be expanded considering regenerative braking system for the shuttles as well. Moreover, they only consider SC cycles, therefore an evaluation also considering DC cycles would be value-adding to investigate whether adopting this command cycle leads to a significative lower energy consumption. The same energy evaluation could be performed again considering different operational and control policies, for example, by studying the impact of the adoption of a class-based storage policy on the amount of energy consumed by reducing the expected travel time.

5.4 Vertical Robotic Storage and Retrieval System

Like the literature on the SBCSS, the literature on the VRS/RS is not so vast, notwithstanding its advantages in terms of flexibility and reliability. Only **two papers** on the VRS/RS were found and included in the literature review.

Azadeh, Roy and De Koster (2019) are the first to investigate the VRS/RS. They take into consideration that increasing the number of robots increases the system throughput capacity, but it can simultaneously lead to increased blocking delays and a reduced throughput capacity. First, they model a single aisle of the VRS/RS using a CQN to assess system performance in terms of throughput capacity. The model is used to optimize the heigh-to-width ratio of the system and to analyze how different robot blocking policies can mitigate blocking effects on the performance of the system. Besides, they also compare the performances and costs of the AVS/RS and the VRS/RS.

Moretti et al. (2022) are the first to model the VRS/RS as automated part feeding to supermarkets in a factory environment. They develop an analytical model based on an SOQN to analyze the system performance, including robots utilization, replenishment lead time, queue length of transactions waiting for robots and number of idle robots. This model is used to perform numerical experiments and to evaluate the design trade-offs referencing a real case in the automotive industry regarding the impact of number of robots, size and number of supermarkets on the replenishment lead-time. Results show that an increase in the number of robots always leads to better performance and that a configuration with multiple small supermarkets improves the efficiency of the replenishment process.

Table 9 – Overview of the literature on the VRS/RS.

Paper	Environment of Adoption	Research Category	Research Issue	Modeling Approach	Environmental Perspective
Azadeh, Roy and De Koster (2019)	Distribution	SA	Estimate throughput performance	CQN	No
		SD	Optimal heigh-to-width ratio		
		OP&C	Comparison between block prevention policies		
Moretti et al. (2022)	Factory	SA	Estimate throughput performance	SOQN	No
		SD	Effect of number of robots and supermarkets size on performance		

Notes on Research Category: SA: system analysis; SD: system design; OP&C: operations planning and control.

Source: The author.

Table 9 represents an overview of the papers on the VRS/RS. It is possible to see that Azadeh, Roy and De Koster (2019) address the system in a distribution environment, while Moretti et al. (2022) considers the system in a factory environment by addressing the replenishment of supermarkets from the central warehouse. Besides, the two papers reviewed develop analytical models based on queuing networks, each paper proposing a model to estimate the performance of the VRS/RS and using this model to perform further analysis on factors potentially affecting the system performance. More precisely, Moretti et al. (2022) use the proposed models to study the number of robots and the supermarket sizes, as they consider a factory environment. On the other hand, Azadeh, Roy and De Koster (2019) optimize the height-to-width ratio of the system and investigate alternate control policies related to robot lock prevention policies. Lastly, none of the two papers address the environmental dimension.

Regarding future research agenda, there are many potential areas of research on the VRS/RS, both for distribution and factory environments, since it has been studied in the literature only since 2019. Azadeh, Roy and De Koster (2019) was the only paper classified as *operations planning and control*. Therefore, a potential research opportunity of research on the VRS/RS is to further explore operational and control policies. In other words, future research could address other policies besides block prevention policies that are key to the VRS/RS, such as storage policies, dwell point policies, transaction scheduling policies and robot assignment policies.

In this sense, it would be interesting to also address the routing of robots. As highlighted by Azadeh, Roy and De Koster (2019), one of the unique features of the VRS/RS is the flexibility of the robots to choose different paths to follow. Therefore, a possible aim of future studies could be finding the routing trajectories for the robots to improve system performance. These studies could also consider smart sensors, which enable robots to interpret environmental changes and choose paths to follow accordingly.

Moreover, since none of the papers reviewed on the VRS/RS considered the environmental dimension, it represents an opportunity for future studies. They could develop models to estimate the energy consumption and the environmental impact of the VRS/RS and compare it with horizontal systems. These studies could also analyze how distinctive design parameters, such as rack dimensions and velocity profile of robots, and operational and control policies, for example, storage policies and robot assignment policies, affect the system performance in terms of environmental measures.

Lastly, as the VRS/RS allows the integration of several warehouse activities, another area of potential research for the VRS/RS is to compare it with a system that uses more than one material handling technology: one for the storage and retrieval of unit loads, and another for the movement of unit loads outside the storage rack, for example, mobile robots or forklifts. In this comparison both system performance and costs could be considered in order to support warehouse managers in the technology selection.

5.5 Robotic Compact Storage and Retrieval System

Like the literature on the SBCSS and the VRS/RS, the literature on the RCS/RS is also limited. The oldest paper found on this system (ZOU; KOSTER; XU, 2018) is still quite recent showing that this literature is still incipient. Only **four papers** on RCS/RS were included in the literature review. Three of them address the traditional system, whereas the fourth (CHEN; YANG; SHAO, 2022) focuses on the ORCS/RS.

Zou, Koster and Xu (2018) estimate RCS/RS performance with different storage policies, considering both dedicated and shared storage policies coupled with random and zoned storage stacks. SOQN models are built to estimate system performance, which can handle both immediate and delayed reshuffling processes. The analytical models are solved using the MGM-based approach and both simulations and a real case are used to validate them. Then, they use these models to find optimal system dimensions and stack height for a system with a certain number of stored products under different storage policies aiming at minimizing throughput time and cost. Lastly, they conclude that the shared storage policy dominates the dedicated storage policy in terms of cost, while the dedicated storage policy outperforms the shared storage policy in terms of system throughput time.

Kang (2021) aims at minimizing the impact of reshuffling activities on the retrieval time of the RCSRS. Instead of finding the optimal sequence among exponentially many sequences, his study proposes an efficient greedy algorithm to determine a sequence of orders that achieves a heuristic solution to minimize reshuffling. Numerical experiments are developed to evaluate the performance of the algorithm proposed, using as objective function the number of reshuffling moves. He concluded that the efficiency induced by the heuristic algorithm is nearly impossible to attain by an unplanned random sequence.

Ko and Han (2022) address the problem of determining the processing sequence for a given set of orders in the RCS/RS to minimize the total number of bins processed. Due to the complexity of this problem, instead of solving the MIP model presented, they propose a rollout heuristic algorithm to find within a short computation time a high-quality solution, within 3% to 4% from the unknown optimal value. They also present some strategies to improve the performance of this algorithm by considerably reducing the computational effort. Through simulation experiments, they show that the algorithm can be effectively applied to real-world instances.

Chen, Yang and Shao (2022) develop a discrete event simulation model to analyze the performance of the ORCS/RS in terms of efficiency and energy consumption. Performance measures, such as throughput capacity, robot utilization and system energy consumption are obtained for both single-product and multi-product cases and for both dedicated and shared storage policies coupled with random and zoned stacks. There is a design of experiment to analyze the effect of shape ratio, storage policy and number of BP robots. Then, ANOVA is used to verify whether these factors are statistically relevant, and the Tukey's test is adopted to find out the best levels of these design factors. The results obtained provide insightful suggestions for the optimal design of an ORCS/RS, such as the best layout shape for optimizing throughput, the number of robots to achieve a given throughput capacity and the maximum number of bins that should be stored in one storage stack.

Table 10 shows an overview of the papers analyzed on the RCS/RS. As explained, Chen, Yang and Shao (2022) focus on a particular type of this system called ORCS/RS, while the other three papers address the traditional system. Two papers reviewed cover all the three predefined research categories, while the other two are categorized only as *operations planning and control*. Moreover, all the four papers analyzed cover different modeling approaches, including queuing network model, simulation model, MIP model and heuristics, which shows that many different approaches can be used to model and study this storage and retrieval system. More specifically, the MIP model and the heuristics are adopted when investigating the order sequencing problem. Lastly, only one paper addresses the environmental perspective, namely Chen, Yang and Shao (2022).

Table 10 – Overview of the literature on the RCS/RS.

Paper	Subsystem	Environment of Adoption	Research Category	Research Issue	Modeling Approach	Environmental Perspective
Zou, Koster and Xu (2018)	Traditional RCS/RS	Distribution	SA SD OP&C	Estimate throughput performance Optimal system dimensions Optimal storage stack height Comparison between storage policies	SOQN	SOQN
Kang (2021)	Traditional RCS/RS	Distribution	OP&C	Optimal order sequencing policies	Heuristics	Heuristics
Ko and Han (2022)	Traditional RCS/RS	Distribution	OP&C	Optimal order sequencing policies	MIP model Heuristics	MIP model Heuristics
Chen, Yang and Shao (2022)	ORCS/RS	Distribution	SA SD OP&C	Estimate throughput performance Estimate energy consumption Optimal layout and number of robots Comparison between storage policies	Simulation	Simulation

Notes on Research Category: SA: system analysis; SD: system design; OP&C: operations planning and control.

Source: The author.

Even though all the four papers study operational and control policies, future studies could further explore this issue. Since two papers perform a comparison between storage policies and other two investigate order sequencing policies, the future research agenda could include other key operational and control policies for the RCSRS, as shown in Table 5, such as dwell point policies, robot assignment policies and block prevention policies. Although order sequencing policies is already addressed by Kang (2021) and Ko and Han (2022), considering that this policy has a massive impact on system performance due to its impact on reshuffling moves, future studies could extend their work by removing some simplifying assumptions, for example, considering a system with multiple workstations rather than only one.

Regarding the environmental dimension, Chen, Yang and Shao (2022) estimate energy consumption and considers the trade-off between time and energy efficiency, for both shared and dedicated storage policies for the ORCS/RS. A study with similar aim could be performed for the traditional RCS/RS, and, in addition, the effect of other operational and control policies on the environmental perspective could be investigated for both systems.

6 Conclusion and Future Research

This thesis studied five distinct types of storage and retrieval systems, namely: ***(i)*** the autonomous vehicle storage and retrieval system (AVS/RS); ***(ii)*** the shuttle-based storage and retrieval system (SBS/RS); ***(iii)*** the shuttle-based compact storage system (SBCSS); ***(iv)*** the vertical robotic storage and retrieval system (VRS/RS); and ***(v)*** the robotic compact storage and retrieval system (RCS/RS). The current state of the literature for each of the systems is brought forward and research areas for future studies are identified. For these purposes, this thesis reviews the main contributions in the existent literature for each system under study, analyzing them according to several aspects, identifying research trends and searching for gaps that can be exploited by future studies.

In this sense, one of the main implications of this thesis is that it provides insights on the current literature on storage and retrieval systems about environment of adoption, modeling approaches, research categories, research issues and consideration of the environmental perspective. For example, analytical models are frequently based on queuing network models, being the SOQN the most adopted, especially by recent papers. The trend to adopt this type of queuing network is shown by the overview of the literature on the AVS/RS, as presented in Table 6, even though it is also used recently by papers studying the SBCSS, the VRS/RS, and RCS/RS.

Moreover, another implication of this thesis is to stimulate and support future research on storage and retrieval systems, mainly by identifying research gaps and opportunities that could be explored in the future research agenda. The main opportunities identified are: ***(i)*** study of operational and control policies; ***(ii)*** consideration of the environmental perspective; and ***(iii)*** comparison between distinct types of systems.

Regarding operational and control policies, there is the opportunity to investigate diverse types of policies for storage and retrieval systems and their impact on system performance. For example, the papers reviewed on the AVS/RS and the SBS/RS mostly focus on the assessment of system performance and on long-term decisions regarding system design, being some operational and control policies not addressed by the current literature. On the other hand, the literature on the SBCSS, the VRS/RS and the RCS/RS is quite insipient, having the opportunity to further explore operational and control policies as well.

In addition, a trend to address the environmental perspective in the literature by estimating the energy consumption was identified, following an increasing environmental concern. Such trend is quite clear according to the overview of the literature on the SBS/RS, shown in Table 7, as most of the papers that consider this perspective were published since 2018. Besides, recent papers on the AVS/RS, the SBCSS and the RCS/RS also take into consideration such perspective.

Furthermore, the future research agenda on storage and retrieval systems could include a comparison between different types of systems in order to support warehouse designers in the technology selection. This comparison could include not only system performance, in terms of throughput and environmental impact, but also system costs. One example of promising research issue is to compare the VRS/RS, which adopts vehicles able to move both inside and outside the storage racks, to a system that uses more than one material handling technology, for instance, the AVS/RS for the storage and retrieval transactions and AGVs for moving the unit loads outside the storage racks.

One limitation of the current thesis is that not all types of novel storage and retrieval systems were addressed. As shown in Figure 1, grid-based systems with dynamic storage and systems based on AGVs, for example, were out of scope. Therefore, future works on this subject could extend the object of analysis to include other storage and retrieval systems, performing a literature review following the same methodology adopted in this thesis.

Moreover, even though a consistent literature review methodology was adopted, resorting to papers focused on this research design, the steps in this process involve some subjectivity, especially the selection of keywords and the definition of criteria of exclusion for choosing the papers to be included in the literature review. Therefore, it was decided to extensive and transparently present in Chapter 2 the methodology adopted and to document all the papers found during the literature review, as shown in Annex 1. In addition, only papers in English and published in journals were included in the review, so future research could also extend this work by considering papers in other publication languages and published in different source types.

As final considerations, from a pedagogical and personal point of view, the development of this thesis granted the author the opportunity to study a relevant subject for Industrial Engineering and acquire important knowledge and skills, no matter the professional career to be pursued. Firstly, novel storage and retrieval systems, which are increasingly important for warehouse activities, were studied in detail. Secondly, the multiple modeling approaches adopted to study these systems were extensively investigated. Lastly, the personal objective to learn in practice how to develop a robust systematic literature review was successfully accomplished.

References

AKPUNAR, A.; EKREN, B. Y.; LERHER, T. Energy efficient design of autonomous vehicle based storage and retrieval system. *Journal of Applied Engineering Science*, v. 15, n. 1, 2017.

AUTOMHA. *Our industrial handling systems*. 2021. Accessed: 2022-10-15. Available at: <automha.com/products-industrial-handling-system/>.

AUTOSTORE. *Warehouse Automation - Products and Systems*. 2021. Accessed: 2022-10-10. Available at: < www.autostoresystem.com/system>.

AVI-ITZHAK, B.; HEYMAN, D. P. Approximate queuing models for multiprogramming computer systems. *Operations Research*, INFORMS, v. 21, n. 6, p. 1212–1230, 1973.

AZADEH, K.; KOSTER, R. D.; ROY, D. Robotized and automated warehouse systems: Review and recent developments. *Transportation Science*, INFORMS, v. 53, n. 4, p. 917–945, 2019.

AZADEH, K.; ROY, D.; KOSTER, R. D. Design, modeling, and analysis of vertical robotic storage and retrieval systems. *Transportation Science*, INFORMS, v. 53, n. 5, p. 1213–1234, 2019.

BAHURDIN, M. M. et al. Comparison of carrier parking location in shuttle-based storage and retrieval system to determine optimal retrieval transaction performance. *International Journal of Advanced Technology and Engineering Exploration*, Accent Social and Welfare Society, v. 8, n. 77, p. 520, 2021.

BATTARRA, I. et al. Hybrid model for the design of a deep-lane multisatellite AVS/RS. *The International Journal of Advanced Manufacturing Technology*, Springer, p. 1–27, 2022.

BOROVINŠEK, M. et al. Multi-objective optimisation model of shuttle-based storage and retrieval system. *Transport*, Taylor & Francis, v. 32, n. 2, p. 120–137, 2017.

BRERETON, P. et al. Lessons from applying the systematic literature review process within the software engineering domain. *Journal of Systems and Software*, Elsevier, v. 80, n. 4, p. 571–583, 2007.

BUITENHEK, R.; HOUTUM, G.-J. van; ZIJM, H. AMVA-based solution procedures for open queueing networks with population constraints. *Annals of Operations Research*, Springer, v. 93, n. 1, p. 15–40, 2000.

CAI, X.; HERAGU, S. S.; LIU, Y. Modeling and evaluating the AVS/RS with tier-to-tier vehicles using a semi-open queueing network. *IIE Transactions*, Taylor & Francis, v. 46, n. 9, p. 905–927, 2014.

CARLO, H. J.; VIS, I. F. Sequencing dynamic storage systems with multiple lifts and shuttles. *International Journal of Production Economics*, Elsevier, v. 140, n. 2, p. 844–853, 2012.

CHEN, X.; YANG, P.; SHAO, Z. Simulation-based time-efficient and energy-efficient performance analysis of an overhead robotic compact storage and retrieval system. *Simulation Modelling Practice and Theory*, Elsevier, v. 119, p. 102560, 2022.

CONFORTI, M. et al. *Integer programming*. [S.l.]: Springer, 2014. v. 271.

DALLERY, Y. Approximate analysis of general open queuing networks with restricted capacity. *Performance evaluation*, Elsevier, v. 11, n. 3, p. 209–222, 1990.

DENG, L. et al. Modeling and performance analysis of shuttle-based compact storage systems under parallel processing policy. *PloS One*, Public Library of Science San Francisco, CA USA, v. 16, n. 11, p. e0259773, 2021.

DONG, W.; JIN, M. Travel time models for tier-to-tier SBS/RS with different storage assignment policies and shuttle dispatching rules. *Transportation Research Part E: Logistics and Transportation Review*, Elsevier, v. 155, p. 102485, 2021.

D'ANTONIO, G.; CHIABERT, P. Analytical models for cycle time and throughput evaluation of multi-shuttle deep-lane AVS/RS. *The International Journal of Advanced Manufacturing Technology*, Springer, v. 104, n. 5, p. 1919–1936, 2019.

D'ANTONIO, G. et al. Analytical models for the evaluation of deep-lane autonomous vehicle storage and retrieval system performance. *The International Journal of Advanced Manufacturing Technology*, Springer, v. 94, n. 5, p. 1811–1824, 2018.

EDER, M. An analytical approach for a performance calculation of shuttle-based storage and retrieval systems. *Production & Manufacturing Research*, Taylor & Francis, v. 7, n. 1, p. 255–270, 2019.

EDER, M. Analytical model to estimate the performance of shuttle-based storage and retrieval systems with class-based storage policy. *The International Journal of Advanced Manufacturing Technology*, Springer, v. 107, n. 5, p. 2091–2106, 2020a.

EDER, M. An approach for a performance calculation of shuttle-based storage and retrieval systems with multiple-deep storage. *The International Journal of Advanced Manufacturing Technology*, Springer, v. 107, n. 1, p. 859–873, 2020b.

EDER, M. An approach for performance evaluation of SBS/RS with shuttle vehicles serving multiple tiers of multiple-deep storage rack. *The International Journal of Advanced Manufacturing Technology*, Springer, v. 110, n. 11, p. 3241–3256, 2020c.

EDER, M. An analytical approach for a performance calculation of shuttle-based storage and retrieval systems with multiple-deep and class-based storage. *Production & Manufacturing Research*, Taylor & Francis, v. 10, n. 1, p. 321–336, 2022.

EDER, M.; KARTNIG, G. Throughput analysis of s/r shuttle systems and ideal geometry for high performance. *FME Transactions*, v. 44, n. 2, p. 174–179, 2016.

EDER, M.; KARTNIG, G. Calculation method to determine the throughput and the energy consumption of s/r shuttle systems. *FME Transactions*, v. 46, n. 3, p. 424–428, 2018.

EKREN, B. Y. Performance evaluation of AVS/RS under various design scenarios: a case study. *The International Journal of Advanced Manufacturing Technology*, Springer, v. 55, n. 9, p. 1253–1261, 2011.

EKREN, B. Y. Graph-based solution for performance evaluation of shuttle-based storage and retrieval system. *International Journal of Production Research*, Taylor & Francis, v. 55, n. 21, p. 6516–6526, 2017.

EKREN, B. Y. A simulation-based experimental design for SBS/RS warehouse design by considering energy related performance metrics. *Simulation Modelling Practice and Theory*, Elsevier, v. 98, p. 101991, 2020.

EKREN, B. Y. A multi-objective optimisation study for the design of an AVS/RS warehouse. *International Journal of Production Research*, Taylor & Francis, v. 59, n. 4, p. 1107–1126, 2021.

EKREN, B. Y.; AKPUNAR, A. An open queuing network-based tool for performance estimations in a shuttle-based storage and retrieval system. *Applied Mathematical Modelling*, Elsevier, v. 89, p. 1678–1695, 2021.

EKREN, B. Y. et al. A tool for time, variance and energy related performance estimations in a shuttle-based storage and retrieval system. *Applied Mathematical Modelling*, Elsevier, v. 63, p. 109–127, 2018.

EKREN, B. Y.; ARSLAN, B. A reinforcement learning approach for transaction scheduling in a shuttle-based storage and retrieval system. *International Transactions in Operational Research*, Wiley Online Library, 2022.

EKREN, B. Y.; HERAGU, S. S. Simulation-based regression analysis for the rack configuration of an autonomous vehicle storage and retrieval system. *International Journal of Production Research*, Taylor & Francis, v. 48, n. 21, p. 6257–6274, 2010.

EKREN, B. Y.; HERAGU, S. S. Simulation based performance analysis of an autonomous vehicle storage and retrieval system. *Simulation Modelling Practice and Theory*, Elsevier, v. 19, n. 7, p. 1640–1650, 2011.

EKREN, B. Y.; HERAGU, S. S. Performance comparison of two material handling systems: AVS/RS and cbas/rs. *International Journal of Production Research*, Taylor & Francis, v. 50, n. 15, p. 4061–4074, 2012.

EKREN, B. Y. et al. Simulation based experimental design to identify factors affecting performance of AVS/RS. *Computers & Industrial Engineering*, Elsevier, v. 58, n. 1, p. 175–185, 2010.

EKREN, B. Y. et al. An approximate solution for semi-open queueing network model of an autonomous vehicle storage and retrieval system. *IEEE Transactions on Automation Science and Engineering*, IEEE, v. 10, n. 1, p. 205–215, 2012.

EKREN, B. Y. et al. Matrix-geometric solution for semi-open queuing network model of autonomous vehicle storage and retrieval system. *Computers & Industrial Engineering*, Elsevier, v. 68, p. 78–86, 2014.

EPP, M.; WIEDEMANN, S.; FURMANS, K. A discrete-time queueing network approach to performance evaluation of autonomous vehicle storage and retrieval systems. *International Journal of Production Research*, Taylor & Francis, v. 55, n. 4, p. 960–978, 2017.

EXOTEC. *Robots*. 2022. Accessed: 2022-10-20. Available at: <https://www.exotec.com/system/robots/>.

FRAUNHOFER IML. *Rackracer – Versatile and flexible rack feeder for container racks*. 2014. Accessed: 2022-10-15. Available at: <https://www.iml.fraunhofer.de/content/dam/iml/en/documents/OE140/Produktblatt_RACKRACER_EN_2014.pdf>.

FUKUNARI, M.; MALMBORG, C. J. An efficient cycle time model for autonomous vehicle storage and retrieval systems. *International Journal of Production Research*, Taylor & Francis, v. 46, n. 12, p. 3167–3184, 2008.

FUKUNARI, M.; MALMBORG, C. J. A network queuing approach for evaluation of performance measures in autonomous vehicle storage and retrieval systems. *European Journal of Operational Research*, Elsevier, v. 193, n. 1, p. 152–167, 2009.

GUERRAZZI, E. et al. Energy evaluation of deep-lane autonomous vehicle storage and retrieval system. *Sustainability*, MDPI, v. 11, n. 14, p. 3817, 2019.

HA, Y.; CHAE, J. Free balancing for a shuttle-based storage and retrieval system. *Simulation Modelling Practice and Theory*, Elsevier, v. 82, p. 12–31, 2018.

HA, Y.; CHAE, J. A decision model to determine the number of shuttles in a tier-to-tier SBS/RS. *International Journal of Production Research*, Taylor & Francis, v. 57, n. 4, p. 963–984, 2019.

HANEEM, F. et al. Descriptive analysis and text analysis in systematic literature review: a review of master data management. In: IEEE. *2017 International Conference on Research and Innovation in Information Systems (ICRIIS)*. [S.l.], 2017. p. 1–6.

HE, S.; LUO, J. Deadlock control of autonomous vehicle storage and retrieval systems via coloured timed petri nets and digraph tools. *International Journal of Production Research*, Taylor & Francis, v. 47, n. 12, p. 3253–3263, 2009.

HERAGU, S. S. et al. Analytical models for analysis of automated warehouse material handling systems. *International Journal of Production Research*, Taylor & Francis, v. 49, n. 22, p. 6833–6861, 2011.

HERAGU, S. S.; SRINIVASAN, M. Analysis of manufacturing systems via single-class, semi-open queuing networks. *International Journal of Production Research*, Taylor & Francis, v. 49, n. 2, p. 295–319, 2011.

JERMAN, B. et al. Simulation-based performance analysis for a novel AVS/RS technology with movable lifts. *Applied Sciences*, MDPI, v. 11, n. 5, p. 2283, 2021.

KANG, C. An order picking algorithm for vertically stacked and top-retrieval storage systems. *ICIC Express Letters*, ICIC International, v. 15, n. 9, p. 991–997, 2021.

KO, D.; HAN, J. A rollout heuristic algorithm for order sequencing in robotic compact storage and retrieval systems. *Expert Systems with Applications*, Elsevier, v. 203, p. 117396, 2022.

KRIEHN, T. et al. Impact of class-based storage, sequencing of retrieval requests and warehouse reorganisation on throughput of shuttle-based storage and retrieval systems. *FME Transactions*, v. 46, n. 3, p. 320–329, 2018.

KÜÇÜKYAŞAR, M.; EKREN, B. Y.; LERHER, T. Cost and performance comparison for tier-captive and tier-to-tier SBS/RS warehouse configurations. *International transactions in operational research*, Wiley Online Library, v. 28, n. 4, p. 1847–1863, 2021.

KUMAR, A.; ROY, D.; TIWARI, M. Optimal partitioning of vertical zones in vehicle-based warehouse systems. *International Journal of Production Research*, Taylor & Francis, v. 52, n. 5, p. 1285–1305, 2014.

KUMAWAT, G. L.; ROY, D. A new solution approach for multi-stage semi-open queuing networks: An application in shuttle-based compact storage systems. *Computers & Operations Research*, Elsevier, v. 125, p. 105086, 2021.

KUO, P.-H.; KRISHNAMURTHY, A.; MALMBORG, C. J. Design models for unit load storage and retrieval systems using autonomous vehicle technology and resource conserving storage and dwell point policies. *Applied Mathematical Modelling*, Elsevier, v. 31, n. 10, p. 2332–2346, 2007.

KUO, P.-H.; KRISHNAMURTHY, A.; MALMBORG, C. J. Performance modelling of autonomous vehicle storage and retrieval systems using class-based storage policies. *International Journal of Computer Applications in Technology*, Inderscience Publishers, v. 31, n. 3-4, p. 238–248, 2008.

LEI, B. et al. Optimization of storage location assignment in tier-to-tier shuttle-based storage and retrieval systems based on mixed storage. *Mathematical Problems in Engineering*, Hindawi, v. 2020, 2020.

LERHER, T. Multi-tier shuttle-based storage and retrieval systems. *FME Transactions*, v. 44, n. 3, p. 285–290, 2016a.

LERHER, T. Travel time model for double-deep shuttle-based storage and retrieval systems. *International Journal of Production Research*, Taylor & Francis, v. 54, n. 9, p. 2519–2540, 2016b.

LERHER, T. Aisle changing shuttle carriers in autonomous vehicle storage and retrieval systems. *International journal of production research*, Taylor & Francis, v. 56, n. 11, p. 3859–3879, 2018.

LERHER, T. et al. Parametric study of throughput performance in SBS/RS based on simulation. *International Journal of Simulation Modelling*, v. 16, n. 1, p. 96–107, 2017.

LERHER, T. et al. Travel time model for shuttle-based storage and retrieval systems. The *International Journal of Advanced Manufacturing Technology*, Springer, v. 78, n. 9, p. 1705–1725, 2015.

LERHER, T. et al. Method for evaluating the throughput performance of shuttle based storage and retrieval systems. *Tehnicki vjesnik/Technical Gazette*, v. 23, n. 3, 2016.

LERHER, T. et al. Simulation analysis of shuttle based storage and retrieval systems. *International journal of simulation modelling*, v. 14, n. 1, p. 48–59, 2015.

LEVY, Y.; ELLIS, T. J. A systems approach to conduct an effective literature review in support of information systems research. *Informing Science*, v. 9, 2006.

LI, H. et al. A joint optimisation of multi-item order batching and retrieving problem for low-carbon shuttle-based storage and retrieval system. *Cleaner Logistics and Supply Chain*, Elsevier, v. 4, p. 100042, 2022.

LIN, Y. et al. A model and a task scheduling method for double-deep tier-captive SBS/RS with alternative elevator-patterns. *IEEE Access*, IEEE, v. 9, p. 146378–146391, 2021.

LIU, Z. et al. Energy consumption model for shuttle-based storage and retrieval systems. *Journal of Cleaner Production*, Elsevier, v. 282, p. 124480, 2021.

MALMBORG, C. J. Conceptualizing tools for autonomous vehicle storage and retrieval systems. *International Journal of Production Research*, Taylor & Francis, v. 40, n. 8, p. 1807–1822, 2002.

MALMBORG, C. J. Interleaving dynamics in autonomous vehicle storage and retrieval systems. *International Journal of Production Research*, Taylor & Francis, v. 41, n. 5, p. 1057–1069, 2003.

MANZINI, R. et al. Travel time models for deep-lane unit-load autonomous vehicle storage and retrieval system (AVS/RS). *International Journal of Production Research*, Taylor & Francis, v. 54, n. 14, p. 4286–4304, 2016.

MARCHET, G. et al. Analytical model to estimate performances of autonomous vehicle storage and retrieval systems for product totes. *International Journal of Production Research*, Taylor & Francis, v. 50, n. 24, p. 7134–7148, 2012.

MARCHET, G. et al. Development of a framework for the design of autonomous vehicle storage and retrieval systems. *International Journal of Production Research*, Taylor & Francis, v. 51, n. 14, p. 4365–4387, 2013.

MAROLT, J.; ˇSINKO, S.; LERHER, T. Model of a multiple-deep automated vehicles storage and retrieval system following the combination of depth-first storage and depth-first relocation strategies. *International Journal of Production Research*, Taylor & Francis, p. 1–18, 2022.

MORETTI, E. et al. A performance model for mobile robot-based part feeding systems to supermarkets. *Flexible Services and Manufacturing Journal*, Springer, v. 34, n. 3, p. 580–613, 2022.

MWPVL INTERNATIONAL INC. *Dematic Multishuttle 2: An In-depth and Independent Review from a Supply Chain Consultant*. 2013. Accessed: 2022-10-12. Available at: <https://mwpvl.com/NA_WP-1022_Multishuttle-2.pdf>.

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*, Elsevier, v. 67, p. 100–116, 2016.

OKOLI, C.; SCHABRAM, K. A guide to conducting a systematic literature review of information systems research. 2010.

OPEX CORPORATION. *Product: Perfect Pick*. 2022. Accessed: 2022-10-16. Available at: <https://www.warehouseautomation.com/asrs/perfect-pick/>.

PETTICREW, M.; ROBERTS, H. *Systematic reviews in the social sciences: A practical guide*. [S.l.]: John Wiley & Sons, 2008.

ROY, D. Semi-open queuing networks: a review of stochastic models, solution methods and new research areas. *International Journal of Production Research*, Taylor & Francis, v. 54, n. 6, p. 1735–1752, 2016.

ROY, D. et al. Queuing models to analyze dwell-point and cross-aisle location in autonomous vehicle-based warehouse systems. *European Journal of Operational Research*, Elsevier, v. 242, n. 1, p. 72–87, 2015.

ROY, D. et al. Stochastic models for unit-load operations in warehouse systems with autonomous vehicles. *Annals of Operations Research*, Springer, v. 231, n. 1, p. 129–155, 2015.

ROY, D. et al. Performance analysis and design trade-offs in warehouses with autonomous vehicle technology. *IIE Transactions*, Taylor & Francis, v. 44, n. 12, p. 1045–1060, 2012.

ROY, D. et al. Blocking effects in warehouse systems with autonomous vehicles. *IEEE Transactions on Automation Science and Engineering*, IEEE, v. 11, n. 2, p. 439–451, 2013.

ROY, D. et al. A simulation framework for studying blocking effects in warehouse systems with autonomous vehicles. *European Journal of Industrial Engineering*, Inderscience Publishers (IEL), v. 10, n. 1, p. 51–80, 2016.

ROY, D. et al. A multi-tier linking approach to analyze performance of autonomous vehicle-based storage and retrieval systems. *Computers & Operations Research*, Elsevier, v. 83, p. 173–188, 2017.

SAVOYE. *Automated storage: maximum performance in minimum volume*. 2022. Accessed: 2022-10-05. Available at: <https://www.savoye.com/en/solutions/automated-storage/>.

SCHOTTEN, M. et al. A brief history of scopus: The world’s largest abstract and citation database of scientific literature. In: *Research analytics*. [S.l.]: Auerbach Publications, 2017. p. 31–58.

SURI, H.; CLARKE, D. Advancements in research synthesis methods: From a methodologically inclusive perspective. *Review of Educational Research*, Sage Publications Sage CA: Los Angeles, CA, v. 79, n. 1, p. 395–430, 2009.

TAPPIA, E. et al. Incorporating the environmental dimension in the assessment of automated warehouses. *Production Planning & Control*, Taylor & Francis, v. 26, n. 10, p. 824–838, 2015.

TAPPIA, E. et al. Modeling, analysis, and design insights for shuttle-based compact storage systems. *Transportation Science*, INFORMS, v. 51, n. 1, p. 269–295, 2017.

THOMAS, R.; HOOPER, E. Simulations: An opportunity we are missing. *Journal of Research on Computing in Education*, v. 23, n. 4, p. 497–513, 1991.

TOTAL SOLUTION PROVIDER GROUP. *Brochure*. 2015. Accessed: 2022-10-05. Available at: <http://www.tspg.co.uk/mdps/brochure/>.

WANG, Y. et al. DSS approach for sustainable system design of shuttle-based storage and retrieval systems. *Flexible Services and Manufacturing Journal*, Springer, p. 1–29, 2022.

WEBSTER, J.; WATSON, R. T. Analyzing the past to prepare for the future: Writing a literature review. *MIS quarterly*, JSTOR, p. xiii–xxiii, 2002.

WHITT, W. The queueing network analyzer. *The Bell System Technical Journal*, Nokia Bell Labs, v. 62, n. 9, p. 2779–2815, 1983.

WU, Y. et al. Modelling and design for a shuttle-based storage and retrieval system. *International Journal of Production Research*, Taylor & Francis, v. 58, n. 16, p. 4808–4828, 2020.

XIAO, Y.; WATSON, M. Guidance on conducting a systematic literature review. *Journal of Planning Education and Research*, SAGE Publications Sage CA: Los Angeles, CA, v. 39, n. 1, p. 93–112, 2019.

ZHANG, L. et al. Variance-based approximations of transaction waiting times in autonomous vehicle storage and retrieval systems. *European Journal of Industrial Engineering*, Inderscience Publishers, v. 3, n. 2, p. 146–169, 2009.

ZHAO, N.; LUO, L.; LODEWIJKS, G. Scheduling two lifts on a common rail considering acceleration and deceleration in a shuttle based storage and retrieval system. *Computers & Industrial Engineering*, Elsevier, v. 124, p. 48–57, 2018.

ZHAO, X. et al. Integer programming scheduling model for tier-to-tier shuttle-based storage and retrieval systems. *Processes*, MDPI, v. 7, n. 4, p. 223, 2019.

ZHAO, X. et al. Analysis of the shuttle-based storage and retrieval system. *IEEE Access*, IEEE, v. 8, p. 146154–146165, 2020.

ZOU, B.; KOSTER, R. D.; XU, X. Operating policies in robotic compact storage and retrieval systems. *Transportation Science*, INFORMS, v. 52, n. 4, p. 788–811, 2018.

ZOU, B. et al. Modeling parallel movement of lifts and vehicles in tier-captive vehicle-based warehousing systems. *European Journal of Operational Research*, Elsevier, v. 254, n. 1, p. 51–67, 2016.

Annex 1

In this annex, the documentation of the selection of papers developed is presented to provide a record of the steps followed in the literature review methodology. As Okoli and Schabram (2010) argue, this documentation is important to establish reliability among researchers and to allow them to reproduce and validate the steps followed by the author.

For this purpose, Tables 11, 12, 13 and 14 bring all the articles found for each search cluster in Scopus database, using the query strings depicted in Table 1, showing whether each article was included or excluded and, in the latter case, the criterion of exclusion following the methodology described in Chapter 2. Therefore, some papers were excluded due to: ***(i)*** not being published in journals; ***(ii)*** not being published in English; ***(iii)*** the system studied; ***(iv)*** the research design; and ***(v)*** full text not found. Besides the papers found in Scopus database, papers found through backward and forward search are also documented.

Table 11 shows the documentation of papers found for the search cluster on the AVS/RS and SBS/RS. In total, 120 papers are presented, of which 117 were found through electronic database and 3 were obtained through backward and forward search. At least one of these papers was excluded for each criterion of exclusion above.

Table 12 presents the documentation of papers found for the search cluster on the SBCSS. In total, 12 papers are presented, of which 11 were found through electronic database and only one was obtained through forward search. No paper on this search cluster was excluded.

Table 13 shows the documentation of papers found for the search cluster on the VRS/RS. 3 papers are presented, all of them found through electronic database. One paper was excluded since it was not published in a journal.

Table 14 presents the documentation of papers found for the search cluster on the RCS/RS. Four papers are presented, of which three were found through electronic database and one was obtained through forward search. No paper on this search cluster was excluded.

Table 11 – Documentation of papers of the search cluster on the AVS/RS and the SBS/RS.

Authors	Year	Document Title	Status	Notes
Akpunar, A., Ekren, B.Y., Lerher, T.	2017	Energy efficient design of autonomous vehicle based storage and retrieval system	Included	Electronic Database
Alam, F., Bin Hasan, K.S., Varshney, A.	2020	Low-cost autonomous vehicle for inventory movement in warehouses	Excluded	Not Published in Journal
Arslan, B., Ekren, B.Y.	2021	Smart transaction picking in tier-to-tier SBS/RS by deep Q-learning	Excluded	Not Published in Journal
Bahurdin, M.M., Zailani, H., Othman, J., Dir, T.M.A.T.	2021	Comparison of carrier parking location in shuttle-based storage and retrieval system to determine optimal retrieval transaction performance	Included	Electronic Database
Battarra, I., Accorsi, R., Manzini, R., Rubini, S.	2022	Hybrid model for the design of a deep-lane multisatellite AVS/RS	Excluded	Type of system
Bauters, K., De Cock, K., Hollevoet, J., Dobbelaere, G., Van Landeghem, H.	2016	A simulation model to compare autonomous vehicle based warehouses with traditional AS/RS systems	Excluded	Not Published in Journal
Bhattathiri, S.S., Li, M.P., Kuhl, M.E.	2021	A traffic avoidance path planning method for autonomous vehicles in a warehouse environment	Excluded	Not Published in Journal
Borovinšek, M., Ekren, B.Y., Burinskienė, A., Lerher, T.	2017	Multi-objective optimisation model of shuttle-based storage and retrieval system	Included	Electronic Database
Bruno, G., D'Antonio, G.	2018	Flexible reconfiguration of AVS/RS operations for improved integration with manufacturing processes	Excluded	Not Published in Journal
Cai, X., Heragu, S.S., Liu, Y.	2014	Modeling and evaluating the AVS/RS with tier-to-tier vehicles using a semi-open queueing network	Included	Electronic Database
Carlo, H.J., Vis, I.F.A.	2012	Sequencing dynamic storage systems with multiple lifts and shuttles	Included	Backward and Forward Search
D'Antonio, G., Bruno, G., Traini, E., Lombardi, F.	2019	An analytical model to estimate AVS/RS energy consumption	Excluded	Not Published in Journal
D'Antonio, G., Chiabert, P.	2019	Analytical models for cycle time and throughput evaluation of multi-shuttle deep-lane AVS/RS	Excluded	Type of system
D'Antonio, G., Maddis, M.D., Bedolla, J.S., Chiabert, P., Lombardi, F.	2018	Analytical models for the evaluation of deep-lane autonomous vehicle storage and retrieval system performance	Excluded	Type of system
Dong, W., Jin, M.	2021	Travel time models for tier-to-tier SBS/RS with different storage assignment policies and shuttle dispatching rules	Included	Electronic Database
Doran, M.V., Henderson, A., Maynard, J.	2018	The warehouse problem: Use of a simulation and scale model to evaluate intelligent control of an autonomous vehicle in a factory	Excluded	Not Published in Journal

Table 11 – Documentation of papers of the search cluster on the AVS/RS and the SBS/RS (continuation).

Authors	**Year**	**Document Title**	**Status**	**Notes**
Eder, M.	2019	An analytical approach for a performance calculation of shuttle-based storage and retrieval systems	Included	Electronic Database
Eder, M.	2020	An approach for a performance calculation of shuttle-based storage and retrieval systems with multiple-deep storage	Excluded	Type of system
Eder, M.	2020	An approach for performance evaluation of SBS/RS with shuttle vehicles serving multiple tiers of multiple-deep storage rack	Excluded	Type of system
Eder, M.	2020	Analytical model to estimate the performance of shuttle-based storage and retrieval systems with class-based storage policy	Included	Electronic Database
Eder, M.	2022	An analytical approach for a performance calculation of shuttle-based storage and retrieval systems with multiple-deep and class-based storage	Excluded	Type of system
Eder, M., Kartnig, G.	2016	Throughput analysis of S/R shuttle systems and ideal geometry for high performance	Included	Electronic Database
Eder, M., Kartnig, G.	2018	Calculation method to determine the throughput and the energy consumption of S/R shuttle systems	Included	Electronic Database
Ekren, B.Y.	2011	Performance evaluation of AVS/RS under various design scenarios a case study	Included	Electronic Database
Ekren, B.Y.	2017	Graph-based solution for performance evaluation of shuttle-based storage and retrieval system	Included	Electronic Database
Ekren, B.Y.	2020	A simulation-based experimental design for SBS/RS warehouse design by considering energy related performance metrics	Included	Electronic Database
Ekren, B.Y.	2021	A multi-objective optimisation study for the design of an AVS/RS warehouse	Included	Electronic Database
Ekren, B.Y., Akpunar, A.	2021	An open queuing network-based tool for performance estimations in a shuttle-based storage and retrieval system	Included	Electronic Database
Ekren, B.Y., Akpunar, A., Sari, Z., Lerher, T.	2018	A tool for time, variance and energy related performance estimations in a shuttle-based storage and retrieval system	Included	Electronic Database
Ekren, B.Y., Arslan, B.	2022	A reinforcement learning approach for transaction scheduling in a shuttle-based storage and retrieval system	Included	Electronic Database
Ekren, B.Y., Heragu, S.S.	2009	Simulation based regression analysis for rack configuration of autonomous vehicle storage and retrieval system	Excluded	Not Published in Journal
Ekren, B.Y., Heragu, S.S.	2010	Simulation-based regression analysis for the rack configuration of an autonomous vehicle storage and retrieval system	Included	Electronic Database
Ekren, B.Y., Heragu, S.S.	2011	Simulation based performance analysis of an autonomous vehicle storage and retrieval system	Included	Electronic Database

Table 11 – Documentation of papers of the search cluster on the AVS/RS and the SBS/RS (continuation).

Authors	Year	Document Title	Status	Notes
Ekren, B.Y., Heragu, S.S.	2011	Simulation based performance comparison of AVS/RS and AS/RS	Excluded	Not Published in Journal
Ekren, B.Y., Heragu, S.S.	2012	A new technology for unit-load automated storage system: Autonomous vehicle storage and retrieval system	Excluded	Not Published in Journal
Ekren, B.Y., Heragu, S.S.	2012	Performance comparison of two material handling systems: AVS/RS and CBAS/RS	Included	Electronic Database
Ekren, B.Y., Heragu, S.S., Krishnamurthy, A., Malmborg, C.J.	2010	Simulation based experimental design to identify factors affecting performance of AVS/RS	Included	Electronic Database
Ekren, B.Y., Heragu, S.S., Krishnamurthy, A., Malmborg, C.J.	2013	An approximate solution for semi-open queueing network model of an autonomous vehicle storage and retrieval system	Included	Electronic Database
Ekren, B.Y., Heragu, S.S., Krishnamurthy, A., Malmborg, C.J.	2014	Matrix-geometric solution for semi-open queuing network model of autonomous vehicle storage and retrieval system	Included	Electronic Database
Ekren, B.Y., Sari, Z., Lerher, T.	2015	Warehouse design under class-based storage policy of shuttle-based storage and retrieval system	Excluded	Not Published in Journal
Epp, M., Wiedemann, S., Furmans, K.	2017	A discrete-time queueing network approach to performance evaluation of autonomous vehicle storage and retrieval systems	Included	Electronic Database
Fang, Y.-J., Tang, M.	2015	Three-dimensional routing optimization for AVS/RS's composite operation	Excluded	Not in English
Fukunari, M., Bennett, K.P., Malmborg, C.J.	2004	Decision-tree learning in dwell point policies in autonomous vehicle storage and retrieval systems (AVSRS)	Excluded	Not Published in Journal
Fukunari, M., Malmborg, C.J.	2004	Analytical design tools for autonomous vehicle unit load storage and retrieval systems	Excluded	Not Published in Journal
Fukunari, M., Malmborg, C.J.	2008	An efficient cycle time model for autonomous vehicle storage and retrieval systems	Included	Electronic Database
Fukunari, M., Malmborg, C.J.	2009	A network queuing approach for evaluation of performance measures in autonomous vehicle storage and retrieval systems	Included	Electronic Database
Guerrazzi, E., Mininno, V., Aloini, D., Dulmin, R., Scarpelli, C., Sabatini, M.	2019	Energy evaluation of deep-lane autonomous vehicle storage and retrieval system	Excluded	Type of system
Ha, Y., Chae, J.	2019	A decision model to determine the number of shuttles in a tier-to-tier SBS/RS	Included	Electronic Database
Ha, Y., Chae, J.	2018	Free balancing for a shuttle-based storage and retrieval system	Included	Electronic Database
He, S.J., Luo, J.	2009	Deadlock control of autonomous vehicle storage and retrieval systems via coloured timed Petri nets and digraph tools	Included	Electronic Database

Table 11 – Documentation of papers of the search cluster on the AVS/RS and the SBS/RS (continuation).

Authors	Year	Document Title	Status	Notes
Heragu, S.S., Cai, X., Krishnamurthy, A., Malmborg, C.J.	2011	Analytical models for analysis of automated warehouse material handling systems	Included	Backward and Forward Search
Heragu, S.S., Cai, X., Krishnamurthy, A., Malmborg, C.J.	2009	Analysis of autonomous vehicle storage and retrieval system by open queueing network	Excluded	Not Published in Journal
Heragu, S.S., Xiao, C., Krishnamurthy, A., Malmborg, C.J.	2008	Analytical model for autonomous vehicle storage and retrieval systems	Excluded	Not Published in Journal
Jerman, B., Ekren, B.Y., Küçükyaşar, M., Lerher, T.	2021	Simulation-based performance analysis for a novel avs/rs technology with movable lifts	Included	Electronic Database
Kaczmarek, S., Goldenstein, J., Ten Hompel, M.	2014	Performance analysis of autonomous vehicle storage and retrieval systems depending on storage management policies	Excluded	Not Published in Journal
Kosanić, N.Ž., Milojević, G.Z., Zrnić, N.D.	2018	A survey of literature on shuttle based storage and retrieval systems	Excluded	Research Design
Kriehn, T., Schloz, F., Wehking, K.-H., Fittinghoff, M.	2018	Impact of class-based storage, sequencing of retrieval requests and warehouse reorganisation on throughput of shuttle-based storage and retrieval systems	Included	Electronic Database
Krishnamurthy, A., Li, Z., Malmborg, C.J., Heragu, S.S.	2008	Lift queue dynamics in autonomous vehicle automated storage and retrieval systems	Excluded	Not Published in Journal
Küçükyasar, M., Y. Ekren, B., Lerher, T.	2021	Cost and performance comparison for tier-captive and tier-to-tier SBS/RS warehouse configurations	Included	Electronic Database
Kumar, A., Roy, D., Tiwari, M.K.	2014	Optimal partitioning of vertical zones in vehicle-based warehouse systems	Included	Electronic Database
Kuo, P.-H., Krishnamurthy, A., Malmborg, C.J.	2007	Design models for unit load storage and retrieval systems	Included	Electronic Database
Kuo, P.-H., Krishnamurthy, A., Malmborg, C.J.	2008	Performance modelling of autonomous vehicle storage and retrieval systems using class-based storage policies	Included	Electronic Database
Lei, B., Hu, F., Jiang, Z., Mu, H.	2020	Optimization of storage location assignment in tier-to-tier shuttle-based storage and retrieval systems based on mixed storage	Included	Electronic Database
Lerher, T.	2016	Multi-tier shuttle-based storage and retrieval systems	Included	Electronic Database
Lerher, T.	2016	Travel time model for double-deep shuttle-based storage and retrieval systems	Included	Electronic Database
Lerher, T.	2017	Design of experiments for identifying the throughput performance of shuttle-based storage and retrieval systems	Excluded	Not Published in Journal

Table 11 – Documentation of papers of the search cluster on the AVS/RS and the SBS/RS (continuation).

Authors	Year	Document Title	Status	Notes
Lerher, T.	2018	Aisle changing shuttle carriers in autonomous vehicle storage and retrieval systems	Included	Electronic Database
Lerher, T., Borovinšek, M., Ficko, M., Palcic, I.	2017	Parametric study of throughput performance in SBS/RS based on simulation	Included	Electronic Database
Lerher, T., Ekren, B.Y., Dukic, G., Rosi, B.	2015	Travel time model for shuttle-based storage and retrieval systems	Included	Electronic Database
Lerher, T., Ekren, B.Y., Sari, Z., Rosi, B.	2015	Simulation analysis of shuttle based storage and retrieval systems	Included	Electronic Database
Lerher, T., Ekren, B.Y., Sari, Z., Rosi, B.	2016	Method for evaluating the throughput performance of shuttle based storage and retrieval systems	Included	Electronic Database
Lerher, T., Potrč, I., Rosi, B.	2014	A model for throughput and energy related performance calculations of SBS/RS	Excluded	Not Published in Journal
Lerher, T., Rosi, B., Potr, I., Jerman, B., Kramberger, T.	2018	Performance analysis of shuttle-based storage and retrieval systems versus mini-load AS/RS	Excluded	Not Published in Journal
Li, D., Smith, J.S., Li, Y.	2019	Coordinated control of multi-zone AVS/RS, conveyors and pick-up operations in warehouse system	Excluded	Not Published in Journal
Li, H., Lyu, J., Zhen, L., Zhuge, D.	2022	A joint optimisation of multi-item order batching and retrieving problem for low-carbon shuttle-based storage and retrieval system	Included	Electronic Database
Lin, Y., Wang, Y., Zhu, J., Wang, L.	2021	A model and a task scheduling method for double-deep tier-captive SBS/RS with alternative elevator-patterns	Included	Electronic Database
Liu, G., Wang, Y., Huang, K., Man, R., Wu, Y.	2022	Adaptability of task scheduling algorithm for shuttle-based storage and retrieval system	Excluded	Not in English
Liu, Z., Wang, Y., Jin, M., Wu, H., Dong, W.	2021	Energy consumption model for shuttle-based storage and retrieval systems	Included	Electronic Database
Ma, W., Hu, J., Wang, Y., Wu, Y.	2022	Simulation-based regression analysis for the replenishment strategy of the crane & shuttle-based storage and retrieval system	Excluded	Type of system
Ma, W., Yang, D., Wu, Y., Wu, Y.	2022	Order dividing optimisation in crane & shuttle-based storage and retrieval system	Excluded	Full text not found
Ma, Y., Wang, J.	2019	Travel time analysis for shuttle-based storage and retrieval system with middle input/output location	Excluded	Not Published in Journal
Malmborg, C.J.	2002	Conceptualizing tools for autonomous vehicle storage and retrieval systems	Included	Electronic Database
Malmborg, C.J.	2003	Interleaving dynamics in autonomous vehicle storage and retrieval systems	Included	Electronic Database

Table 11 – Documentation of papers of the search cluster on the AVS/RS and the SBS/RS (continuation).

Authors	Year	Document Title	Status	Notes
Manzini, R., Accorsi, R., Baruffaldi, G., Cennerazzo, T., Gamberi, M.	2016	Travel time models for deep-lane unit-load autonomous vehicle storage and retrieval system (AVS/RS)	Excluded	Type of System
Marchet, G., Melacini, M., Perotti, S., Tappia, E.	2012	Analytical model to estimate performances of autonomous vehicle storage and retrieval systems for product totes	Included	Electronic Database
Marchet, G., Melacini, M., Perotti, S., Tappia, E.	2013	Development of a framework for the design of autonomous vehicle storage and retrieval systems	Included	Electronic Database
Meng, T., Liu, X.-F.	2015	The AVS/RS modeling and path planning	Excluded	Full text not found
Ning, Z., Lei, L., Saipeng, Z., Lodewijks, G.	2016	An efficient simulation model for rack design in multi-elevator shuttle-based storage and retrieval system	Included	Electronic Database
Ozaki, M., Higashi, T., Ogata, T., Hara, T., Rubrico, J.I.U., Ota, J.	2016	Design of AVS/RS under group constraint	Excluded	Full text not found
Rhazzaf, M., Masrour, T.	2021	Smart autonomous vehicles in high dimensional warehouses using deep reinforcement learning approach	Excluded	Type of system
Roy, D., Krishnamurthy, A.	2011	Improving throughput capacity in multi-tier warehouses with autonomous vehicles	Excluded	Not Published in Journal
Roy, D., Krishnamurthy, A., Heragu, S.S., Malmborg, C.J.	2009	Impact of zones on throughput and cycle times in warehouses with autonomous vehicles	Excluded	Not Published in Journal
Roy, D., Krishnamurthy, A., Heragu, S.S., Malmborg, C.J.	2010	Vehicle interference effects in warehousing systems with autonomous vehicles	Excluded	Not Published in Journal
Roy, D., Krishnamurthy, A., Heragu, S.S., Malmborg, C.J.	2012	Performance analysis and design trade-offs in warehouses with autonomous vehicle technology	Included	Electronic Database
Roy, D., Krishnamurthy, A., Heragu, S.S., Malmborg, C.J.	2014	Blocking effects in warehouse systems with autonomous vehicles	Included	Electronic Database
Roy, D., Krishnamurthy, A., Heragu, S.S., Malmborg, C.J.	2015	Queuing models to analyze dwell-point and cross-aisle location in autonomous vehicle-based warehouse systems	Included	Electronic Database
Roy, D., Krishnamurthy, A., Heragu, S.S., Malmborg, C.J.	2015	Stochastic models for unit-load operations in warehouse systems with autonomous vehicles	Included	Electronic Database
Roy, D., Krishnamurthy, A., Heragu, S.S., Malmborg, C.J.	2016	A simulation framework for studying blocking effects in warehouse systems with autonomous vehicles	Included	Electronic Database
Roy, D., Krishnamurthy, A., Heragu, S.S., Malmborg, C.J.	2017	A multi-tier linking approach to analyze performance of autonomous vehicle-based storage and retrieval systems	Included	Electronic Database
Schloz, F., Kriehn, T., Schulz, R., Fittinghoff, M.	2019	Development of an AI-based sequencing policy for autonomous vehicle storage and retrieval systems	Excluded	Not in English

Table 11 – Documentation of papers of the search cluster on the AVS/RS and the SBS/RS (continuation).

Authors	Year	Document Title	Status	Notes
Schloz, F., Kriehn, T., Wehking, K.-H., Fittinghoff, M.	2017	Development of situation-based storage strategies for autonomous vehicle storage and retrieval systems	Excluded	Full text not found
Sui, Z., Duan, L., Hou, T., Zhang, T.	2019	Modeling and Scheduling of tier-to-tier shuttle-based storage and retrieval systems	Excluded	Not Published in Journal
Tappia, E., Marchet, G., Melacini, M., Perotti, S.	2015	Incorporating the environmental dimension in the assessment of automated warehouses	Included	Backward and Forward Search
Turhanlar, E.E., Ekren, B.Y., Lerher, T.	2021	Aisle-to-aisle design for SBS/RS under smart deadlock control policies	Excluded	Not Published in Journal
Wang, H., Ji, S., Su, G.	2020	Research on autonomous vehicle storage and retrieval system cargo location optimization in e-commerce automated warehouse	Excluded	Not Published in Journal
Wang, S., Zhang, J.	2021	Routing Optimization of Compound Operations in Shuttle-Based Storage and Retrieval Systems	Excluded	Not in English
Wang, Y., Qin, J., Mou, S., Huang, K., Zhao, X.	2022	DSS approach for sustainable system design of shuttle-based storage and retrieval systems	Included	Electronic Database
Wu, C.-Q., He, S.-J., Luo, J.	2008	Cycle-deadlock control of RGVs in autonomous vehicle storage and retrieval systems	Excluded	Not in English
Wu, Y., Zhou, C., Ma, W., Kong, X.T.R.	2020	Modelling and design for a shuttle-based storage and retrieval system	Included	Electronic Database
Wurman, P.R., D'Andrea, R., Mountz, M.	2007	Coordinating hundreds of cooperative, autonomous vehicles in warehouses	Excluded	Not Published in Journal
Wurman, P.R., D'Andrea, R., Mountz, M.	2008	Coordinating hundreds of cooperative, autonomous vehicles in warehouses	Excluded	Type of system
Zhan, N., Luo, L., Zhang, S., Zhao, Z.	2016	Tier captive AVS/RS system retrieval performance analysis based on orthogonal simulation experiment	Excluded	Not in English
Zhang, L., Krishnamurthy, A., Malmborg, C.J., Heragu, S.S.	2009	Variance-based approximations of transaction waiting times in autonomous vehicle storage and retrieval systems	Included	Electronic Database
Zhang, L., Krishnamurthy, A., Malmborg, C.J., Heragu, S.S.	2011	Performance modelling of autonomous vehicle storage and retrieval systems with generally distributed service times	Excluded	Full text not found
Zhang, L., Malmborg, C.J., Krishnamurthy, A.	2007	Service time variance modeling in autonomous vehicle storage and retrieval system cycle time estimation	Excluded	Not Published in Journal
Zhao, N., Luo, L., Lodewijks, G.	2018	Scheduling two lifts on a common rail considering acceleration and deceleration in a shuttle based storage and retrieval system	Included	Electronic Database

Table 11 – Documentation of papers of the search cluster on the AVS/RS and the SBS/RS (continuation).

Authors	Year	Document Title	Status	Notes
Zhao, X., Wang, Y., Wang, Y., Huang, K.	2019	Integer programming scheduling model for tier-to-tier shuttle-based storage and retrieval systems	Included	Electronic Database
Zhao, X., Zhang, R., Zhang, N., Wang, Y., Jin, M., Mou, S.	2020	Analysis of the Shuttle-Based Storage and Retrieval System	Included	Electronic Database
Zou, B., Xu, X., Gong, Y., De Koster, R.	2016	Modeling parallel movement of lifts and vehicles in tier-captive vehicle-based warehousing systems	Included	Electronic Database
Zou, X., Wu, Y., Xia, D., Zhang, R.	2019	Dynamic optimization of goods location in AVS/RS for B2C ecommerce order	Excluded	Not in English

Source: The author.

Table 12 – Documentation of papers of the search cluster on the SBCSS.

Authors	Year	Document Title	Status	Notes
Battarra, I., Accorsi, R., Manzini, R., Rubini, S.	2022	Hybrid model for the design of a deep-lane multisatellite AVS/RS	Included	Electronic Database
D'Antonio, G., Chiabert, P.	2019	Analytical models for cycle time and throughput evaluation of multi-shuttle deep-lane AVS/RS	Included	Electronic Database
D'Antonio, G., Maddis, M.D., Bedolla, J.S., Chiabert, P., Lombardi, F.	2018	Analytical models for the evaluation of deep-lane autonomous vehicle storage and retrieval system performance	Included	Electronic Database
Deng, L., Chen, L., Zhao, J., Wang, R.	2021	Modeling and performance analysis of shuttle-based compact storage systems under parallel processing policy	Included	Electronic Database
Eder, M.	2020	An approach for a performance calculation of shuttle-based storage and retrieval systems with multiple-deep storage	Included	Electronic Database
Eder, M.	2020	An approach for performance evaluation of SBS/RS with shuttle vehicles serving multiple tiers of multiple-deep storage rack	Included	Electronic Database
Eder, M.	2022	An analytical approach for a performance calculation of shuttle-based storage and retrieval systems with multiple-deep and class-based storage	Included	Electronic Database
Guerrazzi, E., Mininno, V., Aloini, D., Dulmin, R., Scarpelli, C., Sabatini, M.	2019	Energy evaluation of deep-lane autonomous vehicle storage and retrieval system	Included	Electronic Database
Kumawat, G.L., Roy, D.	2021	A new solution approach for multi-stage semi-open queuing networks: An application in shuttle-based compact storage systems	Included	Electronic Database
Manzini, R., Accorsi, R., Baruffaldi, G., Cennerazzo, T., Gamberi, M.	2016	Travel time models for deep-lane unit-load autonomous vehicle storage and retrieval system (AVS/RS)	Included	Electronic Database

Table 12 – Documentation of papers of the search cluster on the SBCSS (continuation).

Authors	Year	Document Title	Status	Notes
Marolt, J., Šinko, S., Lerher, T.	2022	Model of a multiple-deep automated vehicles storage and retrieval system following the combination of depth-first storage and depth-first relocation strategies	Included	Forward Search
Tappia, E., Roy, D., De Koster, R., Melacini, M.	2017	Modeling, analysis, and design insights for shuttle-based compact storage systems	Included	Electronic Database

Source: The author.

Table 13 – Documentation of papers of the search cluster on the VRS/RS.

Authors	Year	Document Title	Status	Notes
Azadeh, K., Roy, D., De Koster, R.	2019	Design, modeling, and analysis of vertical robotic storage and retrieval systems	Included	Electronic Database
Moretti, E., Tappia, E., Mauri, M., Melacini, M.	2022	A performance model for mobile robot-based part feeding systems to supermarkets	Included	Forward Search
Tappia, E., Moretti, E., Melacini, M.	2020	A simulation analysis of part feeding to assembly stations with vertical robotic storage and retrieval systems	Excluded	Not Published on Journal

Source: The author.

Table 14 – Documentation of papers of the search cluster on the RCS/RS.

Authors	Year	Document Title	Status	Notes
Chen, X., Yang, P., Shao, Z.	2022	Simulation-based time-efficient and energy-efficient performance analysis of an overhead robotic compact storage and retrieval system	Included	Electronic Database
Kang, C.	2021	An order picking algorithm for vertically stacked and top-retrieval storage systems	Included	Forward Search
Ko, D., Han, J.	2022	A rollout heuristic algorithm for order sequencing in robotic compact storage and retrieval systems	Included	Electronic Database
Zou, B., De Koster, R., Xu, X.	2018	Operating policies in robotic compact storage and retrieval systems	Included	Electronic Database

Source: The author.