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Review of Relevant Literature on Modelling and Simulation Approaches for AS/RSs

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Abstract: Automated Storage and Retrieval Systems support warehouse processes to improve production and logistics efficiency, reducing operating times and costs. In recent years, much attention has been paid on evaluating the performance of these systems using different simulation and modelling approaches. However, the current body of literature is quite fragmented and there is the need for a holistic overview of published scientific literature. To this end, this work presents a literature review in order to adequately identify relevant scientific trends and, consequently, the main research gaps in dealing with the systems under study. From the analysis of the obtained corpus of papers it can be observed that Shuttle Based Storage and Retrieval Systems are the most studied solutions, the most adopted approach is Discrete Event Simulation and operational impacts are the most frequently considered. By focusing on the research gaps, it can be highlighted that the validation process of the chosen methodology is often overlooked and the economic and ergonomic impacts are barely addressed.

Keywords: Automated Storage and Retrieval System, Automated Warehouse, Literature Review, Modelling, Simulation

1. INTRODUCTION

Supply chains have come under increasing pressure from recent global developments. In this context, warehouses are called to play an important role in increasing the effectiveness and efficiency of logistics processes (Kumar et al., 2021). In particular, the last decades have seen rapid advances in the field of Automated Storage and Retrieval Systems (AS/RSs). In general terms, AS/RSs can be defined as computer-controlled systems that automatically and autonomously store and retrieve goods from storage locations by means of mechanical devices. Over the years, this definition has been applied to a wide variety of system implementations as a result of theoretical and practical developments (Gagliardi et al., 2012).

In the academic literature, there is an extensive field of research dedicated to the study of these systems. The first contributions can be found as early as the 1970s with the development of the first travel models for single-aisle stacker cranes (Graves et al., 1977). In more recent years, the study of AS/RSs have taken advantage of modern approaches based on simulation and modelling techniques. Simulation provides a way to generate accurate performance measures for a given system configuration and it has proven to be an effective decision support tool in warehouse operations (Epp et al., 2017). However, different simulation techniques can be used, different system configurations can be analysed, and different aspects of an automated warehouse can be investigated.

Therefore, a structured study aimed at identifying the most commonly used simulation methodologies and their relevant impacts could be useful to identify recent research trends and to highlight critical research gaps. In this context, some studies can be found that focus on evaluating the state of the art of automated warehouses. For example, the study of Kumar et al. (2021) focuses the attention on the general concept of warehouse over the years, while the work of Gagliardi et al. (2012) concentrates more on automated ones. Therefore, there is a need to provide an updated and structured review of the literature focusing on simulation and modelling approaches used to study AS/RSs. In order to bridge this research gap, this paper proposes a Literature Review (LR) that aims to investigate the use of different simulation and modelling methods to study automated warehouses. Moreover, this research has also the objective to study the main automated systems analysed by academics and to assess the relevant impacts at different levels, such as operational and economic, resulting from the adoption of these techniques. To this end, a corpus of 61 articles collected from the Scopus database over a ten-year period (from 2012 to 2021) was analysed.

The reminder of the paper is structured as follows. First, previous similar works are illustrated. Then, the methodology used to build the corpus is described. After that, the obtained corpus is presented and the main research trends and gaps are highlighted based on the analysis of the papers. Finally, implications and conclusions are given.

2. SIMILAR RESEARCH

Taking into account traditional warehouses, Ali and Phan (2022) proposed a Systematic Literature Review (SLR) that focused on investigating of the adoption of Industry 4.0 technologies in warehouse processes and how warehouse operators deal with modern trends in their tasks. The issue of sustainability in warehouse operations was

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instead addressed by the study of Bertolini et al. (2019). There are also literature reviews regarding automated warehouses. An analysis of the different static and dynamic models used to evaluate the performance of AS/RS was presented by Gagliardi et al. (2012). Recently, particular attention has also been paid to the use of Key Performance Indicators (KPIs) to evaluate an AS/RS (Faveto et al., 2021). Focusing on research in order picking solutions, Vijayakumar and Sgarbossa (2021) proposed a literature review investigating the adoption of innovative solutions in order picking processes and their integration with automated systems. Finally, a SLR on flexible automation in warehouse processes was presented by Custodio and Machado (2020), also focusing on how simulation can facilitate the warehouse design process and improve system performance.

As emerged from this analysis of previous works, one of the most recognisable objectives of research studies focusing on AS/RS, is to improve the system performance at different levels depending on design choices. Simulation has received a great deal of attention in the scientific community as it has been shown to be useful in anticipating problems that may occur in the warehousing processes (Buckova et al., 2017). In addition, many system configurations are analysed in the literature, such as AS/RS, Shuttle-Based Systems and Vertical Automated Warehouses. Furthermore, different modelling and simulation approaches are used to study AS/RSs (*e.g* Discrete Event Simulation and Queuing Modelling).

Therefore, the literature on this research area is quite fragmented and there is the need for a structured examination of the academic contributions in order to capture the most important recent trends and to highlight the relevant research gaps that could be bridged in the near future.

3. METHODOLOGY

This paper aims to investigate the state of the art about simulation and modelling techniques used to study and analyse AS/RSs. The Scopus database was chosen to conduct the analysis, as it is recognised by the majority of academics as one of the most complete scientific and technical peer-reviewed literature databases (Vila et al., 2020). A list of keywords to be used to execute in the Scopus searches was established. In particular, two levels of keywords were considered. The first made it possible to frame the systems under analysis, and therefore keywords such as *AS/RS, Automated warehouse,* and *Automated storage and retrieval system* were selected. In fact, these keywords are able to clearly identify the systems at issue, together with the system configuration. The second one was used to define the modelling and simulation approaches, and for this reason the keywords *Simulation, Model, Simulation modelling,* and *Simulation based* were chosen. All the keywords listed above were considered in both British and American English.

Inclusion and exclusion criteria were then established. The time frame of the review was limited to 2012-2021, as the last review focusing on modelling methods for AS/RSs dates back to 2012 (Gagliardi et al., 2012). Furthermore, only peer-reviewed publications and conference proceedings written in English were considered. The Scopus research fields Physics and Astronomy, Neuroscience and Earth were excluded from the analysis in order to better frame the topic. Papers that merely focused on optimisation techniques, *i.e.* researches that only proposed new optimisation, heuristic or scheduling algorithms, were not included. Finally, academic contributions that were not strictly focused on storage systems (*e.g.* Automated Guided Vehicles (AGVs) and robotic fulfilment centres) were discarded.

The total number of articles returned by all the Scopus queries is 842. After reading the articles, excluding the publications outside the scope of the review and removing duplicates, the final number of selected articles is 61.

4. MAIN RESEARCH TRENDS

The corpus of the papers is presented in this section. Due to space constraints, the full list of publications analysed in this study can be obtained by contacting the authors.

4.1 Corpus description

Looking at the time distribution of the papers analysed, the number of publications showed an increasing trend until 2019. Nevertheless, there was a decrease in the number of publications in the last two years considered in the study.

Focusing on the world region where the first author is based, about 59% of the papers were published by European researchers, while about 25% of the contributions were related to Asia. America and Africa were equally represented, with around 8% each. A possible reason for the greater European interest may be that in Europe the issue of space availability is often an important one, and therefore researchers may be more motivated to investigate automated storage solutions that allow better utilisation of floor space and volume.

The corpus analysed consists of a total of 61 papers, of which 46 were papers published in academic journals and the remaining 15 articles were conference proceedings. Considering the academic journals, the majority of the papers was published in the International Journal of Production Research, followed by the International Journal of Advanced Manufacturing Technology, the International Journal of Simulation Modelling, and Simulation Modelling Practice and Theory. The remaining 24 papers were published in 22 different journals, showing a wide granularity of the research topic. Regarding the conferences proceedings, IFAC and the Winter Simulation Conference were the most popular ones. The remaining 6 papers published were presented at 6 different conferences, demonstrating the fragmentation of the research topic.

4.2 Modelling and simulation methodologies

During the construction of the corpus, the papers were classified according to the modelling and simulation technique used to deal with AS/RSs (Figure 1). The analysis showed that Discrete Event Simulation (DES) was the most used approach. In fact, 21 of the papers used this methodology to analyse and evaluate the performance of the automated systems. The widespread use of DES may be due to the fact that warehouse processes are discrete in nature, and therefore a DES approach can be much more

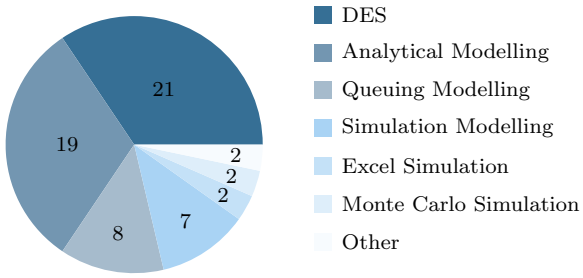

Fig. 1. Modelling and simulation methodologies

effective and adaptable for modelling purposes rather than other ones.

Analytical modelling was the second most used methodology (19 papers). Analytical modelling involves the use of mathematical equations to study and gain insight into the behaviour of complex systems or processes. They are well suited to the analysis of AS/RSs because they are easily reconfigurable, they have a lower computational cost than other approaches, and they allow easy exploration of possible layout configurations (Xu et al., 2018; Liu et al., 2021).

Queuing models were used less than the previous methods. In fact, they were present in 8 papers of the corpus. They can be defined as a mathematical representation of a queuing system that allows to determine the probability distributions of the performance parameters of the systems under study (Epp et al., 2017).

Simulation modelling was the fourth methodology used in the corpus of papers (7 papers). It usually exploits a specific simulation paradigm, but in the 7 papers that fell into this category, it was not explicitly defined. In general, simulation modelling is widely used to solve operational problems, especially in warehouse activities such as storage/retrieval processes and material handling (Ekren, 2020).

Finally, Excel queries, Monte Carlo Simulation and other minor approaches account for a total of 6 papers.

Regarding the validation of the proposed model, for the articles using DES and Simulation Modelling as the main methodology, in 3 cases a mathematical model was built, in 3 papers a case study or real data was used, and in 4 studies the simulation model was compared with similar models in the literature. In 17 articles, the validation was not performed or not explicitly described. On the other hand, of the 27 papers using Analytical and Queuing Modelling, 10 used DES for validation purposes, while 14 exploited Simulation Modelling. The remaining 3 papers validated the proposed models using Monte Carlo Simulation.

Furthermore, AS/RSs can be studied in terms of future solutions and configurations, as simulation or modelling approaches proved to be effective in anticipating the behaviour of the system. These cases can be referred to as *ex-ante* methods, and they were found in 58 scientific papers out of the total corpus. On the contrary, in only 3 papers, the methodology used was *ex-post*, *i.e.* to evaluate a predesigned model or an existing system.

4.3 Automated warehousing systems

The analysis of the corpus showed that one of the most automated warehouse systems studied was the traditional AS/RS (T-AS/RS). In fact, it was present in 16 papers out of the total. In T-AS/RSs, a single unit load (UL), typically a full pallet, is moved between the I/O and the storage or retrieval locations by an automated crane. In single-deep systems, each storage location can hold only one UL, while in multi-deep systems each storage location can hold more than one UL. In most cases, a crane is assigned to a specific aisle (aisle-captive), but sometimes cranes can move from one aisle to another (aisle-to-aisle) (Gagliardi et al., 2015).

The 3D-AS/RS is a special configuration of the T-AS/RS, in which the stacker crane moves in an aisle in front of the rack. The rack consists of coupled conveyors that move products in the depth direction (Xu et al., 2018). This system was only studied in 2 academic papers.

A more recent implementation is the Multiple In-The-Aisle Pick Positions (MIAPP), which was present in 2 papers of the corpus. Pickers manually perform the picking operation from a pallet rack located on both sides of a picking aisle. Another aisle on the opposite side of this rack is entirely dedicated to the stacker crane. The pick locations are on the lowest levels of the storage rack, while the reserve storage locations are on the upper levels. The stacker crane performs a replenishment operation when the last item of a UL is picked (Liu et al., 2021).

The Flow-Rack AS/RS (FR-AS/RS) is the automated counterpart to gravity warehouses (6 articles). ULs are stored in the storage face by means of a storage machine, they slide to the opposite side and they are retrieved from the retrieval face by the means of a retrieval machine. Due to its design, some ULs may be blocked by other ones, and in retrieval operations the blocking ULs must be removed before the desired one can be retrieved (Chen et al., 2016).

Autonomous Vehicle Storage and Retrieval Systems (AVS/RSs) are another warehouse system that has been developed over the last few decades. In AVS/RS, lifts are responsible for vertical movements of ULs, shuttles perform horizontal movements along the aisle of each tier, and satellites travel through the channels of the rack to store and retrieve ULs (Epp et al., 2017). They were analysed in 10 papers.

Shuttle-Based Storage and Retrieval Systems (SBS/RSs) are similar to AVS/RSs, but they are mainly used in mini-load warehouses (Ekren, 2020). SBS/RS was the most studied implementation in the corpus, appearing in 17 publications. Lifting devices allow the vertical transfer of ULs between the different tiers of the storage rack, shuttles provide horizontal movement and store and retrieve ULs using mechanical devices. These systems can be tier-captive, where there is one shuttle for each tier, or tier-to-tier, where the shuttles can be transferred between tiers by the lifting device. As with T-AS/RS, shuttles can be aisle-captive or aisle-to-aisle.

Vertical Lift Modules (VLM) are a completely different system to the one described above. They consist of a storage column in which items are stored in movable trays. A handling mechanism, which can move vertically in the storage column, stores and retrieves these trays, and it also transports the trays to the picking bay, where the

Table 1. Automated storage and retrieval systems

System	Relevant reference	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total
SBS/RS	(Ekren, 2020)				3	1	3	3	2	4	1	17
T-AS/RS	(Gagliardi et al., 2015)	1	3	1	1	2		2	3	2	1	16
AVS/RS	(Epp et al., 2017)	1		1			2	1	4		1	10
Flow-rack AS/RS	(Chen et al., 2016)	1			1		3	1				6
VLM	(Sgarbossa et al., 2019)				1	1			1			3
3D AS/RS	(Xu et al., 2018)							1		1		2
MIAPP-AS/RS	(Liu et al., 2021)			1							1	2
Others	-		1			1		1		2		5
Total		3	4	3	6	5	8	9	10	9	4	61

operator can complete the picking order (Sgarbossa et al., 2019). VLMs were analysed in 3 papers of the corpus.
According to the categorisation defined above, T-AS/RSs and SBS/RSs were the most analysed ones (Table 1). T-AS/RSs were particularly popular in the first years considered in this study. From 2019 onward, they faced a decline in interest from academics, which is probably an indication of the maturity of the technology. SBS/RS started to be studied in 2015, showing that this technology is at the beginning of its development curve. Apart from a drop in 2021, the interest trend was positive. The number of publications on AVS/RS increased slowly until 2019, and then they fell in number.

4.4 Design and Operational aspects

In modelling and simulating the automated warehousing systems, various design and operational aspects were considered by academics. Focusing on the design ones, the number of ULs that the handling machine (HM) can move per travel was taken into account. In most of the papers, the designed system was able to handle a single UL per travel (46 papers). In 2 papers the number of ULs moved per travel was two and in 1 paper more ULs could be moved.
The HM speed, which can be either constant or variable (taking into account acceleration and deceleration), is another crucial design factor. In the corpus, 24 papers assumed a constant speed, while in 32 cases acceleration and deceleration were considered. 5 papers did not specify the speed of the HM.
Another design factor included while studying AS/RSs was the number of deep positions of the storage rack. 34 out of 61 papers studied single deep systems, only 2 focused on double deep, and 18 considered multiple deep storage locations.
In the academic articles analysed, the location and the number of I/O stations was a design aspect taken into account. The majority of the papers considered the I/O to be located at the first tier of the system, or at a corner of the storage rack (35 papers). 3 papers examined I/O points located at higher tiers of the rack, while in only 1 article the I/O was separated in two different stations and located at the opposite ends of an aisle. In 19 papers out of the total, no information was given on this aspect.
Finally, the distinction between aisle-captive and aisle-to-aisle systems, as well as tier-captive and tier-to-tier configurations, are other important design aspects. However, these two elements were not considered when comparing the systems, as not all of them have aisles (*e.g.* VLM) or HMs dedicated to tiers (*e.g.* FR-AS/RS).
Focusing on the operational aspects of AS/RSs, the command type was one of the elements mainly studied. Single command cycles (SC) perform only one storage or retrieval operation, whereas dual command cycles (DC) perform both storage and retrieval activities. Finally, in multiple command cycles (MC), the HM manages more than two ULs sequentially. In the corpus examined, 16 publications assumed SC and 10 articles DC. 20 papers investigated how system performance changes in response to different command types, while only 3 papers focused on MC. 12 papers did not specify the command type of the HM.
Another operational aspect studied is the dwell point policy, described as the position of the S/R machine when it is idle. Three main dwell point policies can be identified, namely Point of Service Completion (POSC), Return I/O (RIO), and Return to Middle Point (RMP). In POSC, the HM remains where it completed its last task, while in RIO, the HM machine moves to the I/O point. Finally, in RMP, the HM travels to the middle position of the rack after finishing the last storage/retrieval operation. Of the 61 papers analysed, only 34 explicitly took into account the dwell point policy. The most commonly considered ones were POSC and RIO (15 and 12 papers respectively), while RMP was used in only 3 publications. 4 articles proposed a comparison between different policies.
By studying operational aspects, researchers also considered inventory policies, defined as the set of rules used to select the best locations for ULs to be stored within the warehouse. Among the 61 papers analysed, the most used policy was the random one (31 papers), which assumes equal probability of selecting a storage location for an incoming UL to be stored. The class-based policy, which divides the items into a number of classes based on different criteria, came second, appearing in 3 papers. The third most considered policy was the dedicated one, in which each storage location is dedicated only to a specific product (2 papers). Additionally, 14 papers compared the performance of the warehouse systems according to different storage policies, while 10 articles did not explicitly define the policy adopted.
The last operational aspect considered is the operations sequencing. The First-Come-First-Served (FCFS) policy is most commonly used. A system using the FCFS technique performs the first operation or manages the first UL requesting a resource. 18 publications described systems using the FCFS. 2 publications looked instead at the Last-Come-First-Served (LCFS) policy, which prioritises the last operation or UL requesting for a resource. 3 papers compared different sequencing strategies, and

other 2 papers used optimisation approaches (*e.g.* shortest path, shortest travel time). 35 papers did not consider the operations sequencing.

4.5 Impacts

Focusing on the impacts described in the discussion section of each paper analysed, it is worth highlighting that the operational ones were the most addressed ones. As a matter of fact, about 90 operational impacts were explained. The number of impacts was higher than the number of papers because more than one impact could be identified in a single paper. In particular, 16 contributions mentioned more than one operational impact. However, in 19 papers, the operational impacts were not described in detail, but only in terms such as "better performance evaluation/estimation" or "improved design". By observing the detailed impacts, 13 papers identified an impact on cycle time and 11 papers focused on throughput evaluation. These issues are crucial when dealing with the performance of warehouses systems.
Only 15 papers addressed economic impacts. 6 out of them discussed aspects related to a better estimation of the energy required to operate the system and 5 mentioned the estimation of costs without specifying whether they were fixed or variable ones. Only 2 papers considered the impact on investment.
Finally, ergonomic impacts were also taken into account. However, even if ergonomic benefits could be obtained by using modelling and simulation approaches, *e.g.* for parts requiring heavy and repetitive lifting (Sgarbossa et al., 2020), impacts related to ergonomics were not mentioned.

4.6 Trends summary

In the field of automated warehouses, among the modelling and simulation techniques used to investigate AS/RSs performance, DES and Analytical Modelling were the most widely used. The DES approach was mainly exploited to study SBS/RSs and T-AS/RSs, while the majority of articles using Analytical Modelling focused on T-AS/RSs and AVS/RSs. This is probably due to the fact that DES has been shown to be an effective method of dealing with the existing complexity associated with these systems.
In terms of system configuration and technology, T-AS/RSs and SBS/RSs were the most analysed ones. T-AS/RSs quite captured the attention among researchers, although a decreasing trend has been observed in the most recent period. On the other hand, SBS/RSs have recently started to be examined, indicating a growing interest in this technology and probably higher benefits compared to traditional T-AS/RSs. Indeed, SBS/RSs have been increasingly adopted in e-commerce warehouses, as they are seen as an effective response to customer expectations for fast and efficient fulfilment.
Finally, looking at the impacts assessed by the papers analysed, the operational ones were the most studied. Particular attention was paid to the overall performance, cycle time and throughput, which have been identified as the most important elements in the evaluation of automated warehouse systems. In terms of economic impacts, attention was mainly focused on the energy issue and, more generally, on cost evaluations. These results demonstrated the growing awareness of the environmental sustainability, which could become a lever for significant cost savings and, in turn, competitive advantage.

5. RESEARCH GAPS

This section proposes a number of research gaps that could be fulfilled by future research are proposed. A first one resides in the fact that the analysis and description of methodologies aimed at validating previously developed simulation models were often overlooked. In fact, almost 78% of the papers that used a simulation-based approach as main methodology did not explicitly describe the validation process aimed at guaranteeing the repeatability of the results and the robustness of the model.
In addition, as regards the methodology used, there is a lack of studies applying Agent Based Modelling (ABM). ABM has been proven to be an effective technique for modelling warehouse systems where the level of complexity is very high (Braglia et al., 2019). Moreover, a relevant number of papers using a simulation approach, either as the main methodology or for validation, lacked a detailed description of the model used. As a consequence, this could prevent other researchers from accurately replicating the proposed methodologies and it might jeopardise the development of advances in the field.
When looking at the impacts, it is worth noting that the literature was mostly focused on underlining the operational ones. On the contrary, the economic effects were less taken into account. In fact, they were missing in 46 papers. This aspect is even more evident when considering the ergonomic effects of dealing with automated warehouses. Ergonomics was not taken into account in the corpus, despite its acknowledged importance in the management of internal warehouse activities. Therefore, additional data on the assessment of ergonomics could support designers to develop more effective and safer workplaces.
Finally, the Digital Twin (DT) approach, although increasingly seen as promising and effective, was scarcely used in the evaluation of automated warehouses. This technology is designed to create a virtual model of a physical system in a digital way, and to extend the capabilities between the physical and digital spaces. Thus, it aims at bridging and connecting the physical and digital worlds in order to improve the digitisation of operational processes (Kritzinger et al., 2018). Therefore, DT is characterised by a two-way interaction between the digital and physical worlds. This could make the physical asset more "intelligent" by actively adjusting its real-time behaviour according to the "recommendations" of the virtual product (Tao et al., 2019). Therefore, this approach might be beneficial in evaluating innovative solutions in automated warehouses.

6. CONCLUSIONS

The aim of this paper is to provide an overview of the relevant scientific literature, focusing on the adoption of the main simulation and modelling approaches for studying automated warehouse solutions. To this end, a literature review analysis was carried out and a sample of 61 papers was obtained. The papers in the corpus were deeply studied, examining the automated warehousing system at issue, as well as the most relevant design and operational

factors of an automated warehouse. In this way, a broad and comprehensive perspective was obtained on the most relevant solutions studied and how they were analysed in terms of the simulation techniques adopted. It was therefore possible to capture the main evidences and to identify research trends and gaps so that they might be bridged by future research studies in the field. The results show that automated warehouses have been largely studied by the academia. In particular, SBS/RSs were the most studied solutions. Looking at the most used methodology, DES was the most chosen one by academics. This approach appeared to be widely used in the evaluation of SBS/RSs. Then, by focusing on the main impacts studied, it is worth noting how the operational ones, with a particular attention paid to the cycle time issue and the overall performances of the systems, were the most evaluated.
Therefore, the proposed analysis will allow to easily identify more suitable solutions that are expected to provide more benefits related to their implementation. In particular, the effect on ergonomics might receive more attention, especially considering the growing interest about the human-machine interaction issue. Similarly, economic impacts could be studied in more detail in the future.
From a more practical perspective, this study might provide the instruments for focusing on the main aspects that should be taken into account in designing and evaluating AS/RS solutions. It could also help practitioners to select the most appropriate AS/RS configuration during the design phase. Future research will be addressed towards the enlargement of the corpus of the papers by completing both backward and forward snowballing, so that to include relevant citations in the study.

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