Design and Optimization of Automated Storage and Retrieval Systems: A Review

Zeki Murat Cinar and Qasim Zeeshan

Abstract Automated Storage and Retrieval Systems (AS/RS) are warehouses, specifically designed for material handling in modern manufacturing systems and are extensively utilized as distribution centers, due to the advantages of improved inventory control, cost-effective utilization of time, space and equipment. With the advent of smart manufacturing in the Industry 4.0 era, the significance of adopting automation technology in warehousing becomes increasingly imminent. Techniques and tools are being developed to manage, control, design, and optimize the AS/RS(s). Over the years, many researchers have focused on the design, analysis, and optimization of various AS/RS configurations. This paper aims to present a systematic literature review on the research in Configuration design and Optimization of AS/RS, by classifying the research according to the design objectives, configurations and optimization algorithms used, in order to highlight and expand the awareness on the current best practices, progress, and future research directions.

Keywords Automated storage and retrieval systems · Configuration design · Optimization · Warehouse

Introduction

Material handling systems (MHS) have been of interest to researchers over the past three decades. Material handling constitutes 15–70% of the total manufacturing cost of a product [39]. MHS integrates equipment and other technologies of manufacturing systems. The Automated Storage & Retrieval System (AS/RS) is a typical application of automation technology in modern MHS. AS/RS is specifically designed for the material handling process and is extensively utilized in modern MHS within the

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production, pharmacy, libraries, as well as automotive factories and car parking. AS/RS is a complex system in which equipment and control systems combined together. This complex system offers automatically handles, storage, and retrieval of loads with ideal speed and high accuracy without labor assistance. Although the AS/RS technology initiated in the late 1970s and its development continued over the years [54], however, with the requirement of Flexible Manufacturing Systems (FMS) and the advent of smart manufacturing and Industry 4.0 era, the significance of adopting automation technology in warehousing becomes increasingly imminent. Techniques and tools are being developed to manage, control, design, and optimize the AS/RS. This paper aims to present a systematic review of research in the design and optimization of AS/RS in order to highlight and expand the awareness on the current best practices, progress and future research directions.

AS/RS Configurations

AS/RS play an essential role in warehouses due to transportation of loads, especially for some facilities such as hospital and libraries due to major advantages of AS/RS(s). Typical AS/RS Configurations are shown in Fig. 1 and work as follows: first of all, items to be stored are sequenced and allocated to the special bins, containers, or boxes. The containers with the items inside are taken to the weighting location for confirming the load weights are within limit requirements. In some cases, different parameters of loads, such as dimensions, danger level, and fragile status, should also be checked and tested in a specific station. Those who successfully passed all tests are transported to the Input/Output station. While transportation, testing, and evaluation processes are being processed, the status of loads is regularly and currently received by the central computer. The central computer assigns the decision of the next step of loads, and then the status of loads is saved in its memory. The loads are then moved to corresponding places with the help of the S/R machine. Upon receipt of a request

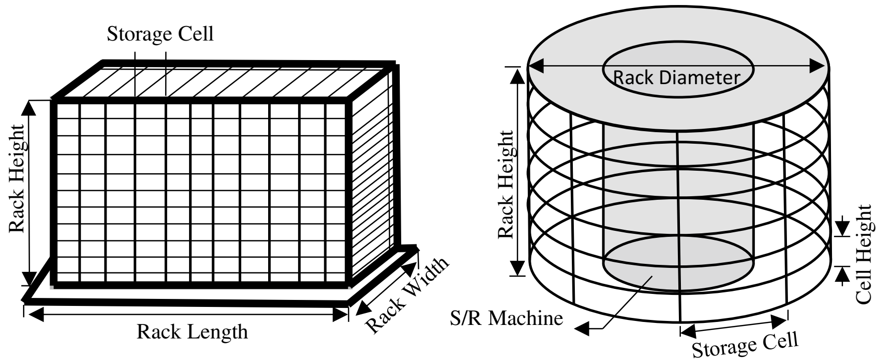

Fig. 1 Typical AS/RS configurations—rectangular and circular

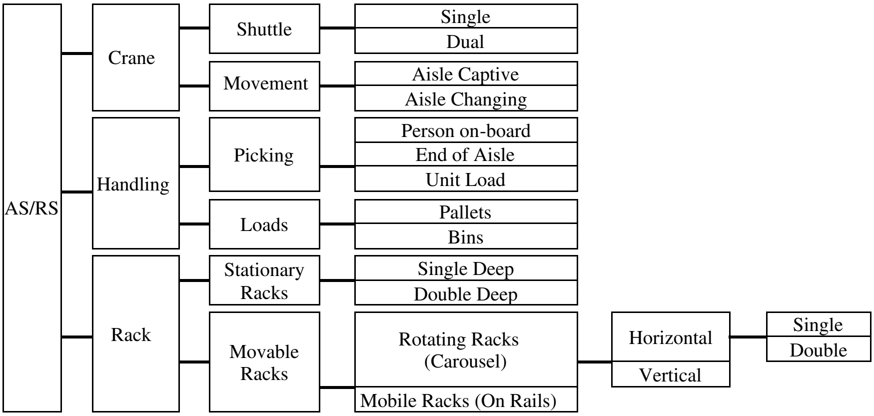

Fig. 2 Classification of AS/RS(s) adapted from Roodbergen and Vis [46]

for an item, the central computer gives a decision about loads, whether where to store or from which storage cell to retrieve and then sends a command to the crane to do the task. The loads are then taken from I/O station by the supporting transportation system to be transported to its final destination.

Classification of AS/RS(s)

Roodbergen et al. [45] categorized AS/RS(s) into three different essential classes according to the bin's arrangement, I/O capacity, and the number of S/R machines utilized in AS/RS. Vasili et al. [53] categorized AS/RS classes as unit load AS/RS, deep line AS/RS, multi-load AS/RS, mini-load AS/RS, the man on board AS/RS, vertical lift storage modules (VLSM), automated item-retrieval systems, multi aisles AS/RS, Carousel Systems, Mobil rack AS/RS (Fig. 2).

Research on AS/RS

A summary of research on AS/RS(s) is presented in this section. Based on SCOPUS data searched by "AS/RS" OR "Automated Storage and Retrieval System," year by year publication in increase trend and expected to have more than 1277 publications in the year of 2020 shown in Fig. 3b. Most of the publications are subjected to engineering (6129 publications) and mathematics (5820 publications), as shown in Fig. 3c. Figure 3d explains that based on the studied literature, most of the publications are from China (418 publications) and followed by Germany (1818 publications). Moreover, the highest publications related to AS/RS searched by affiliation

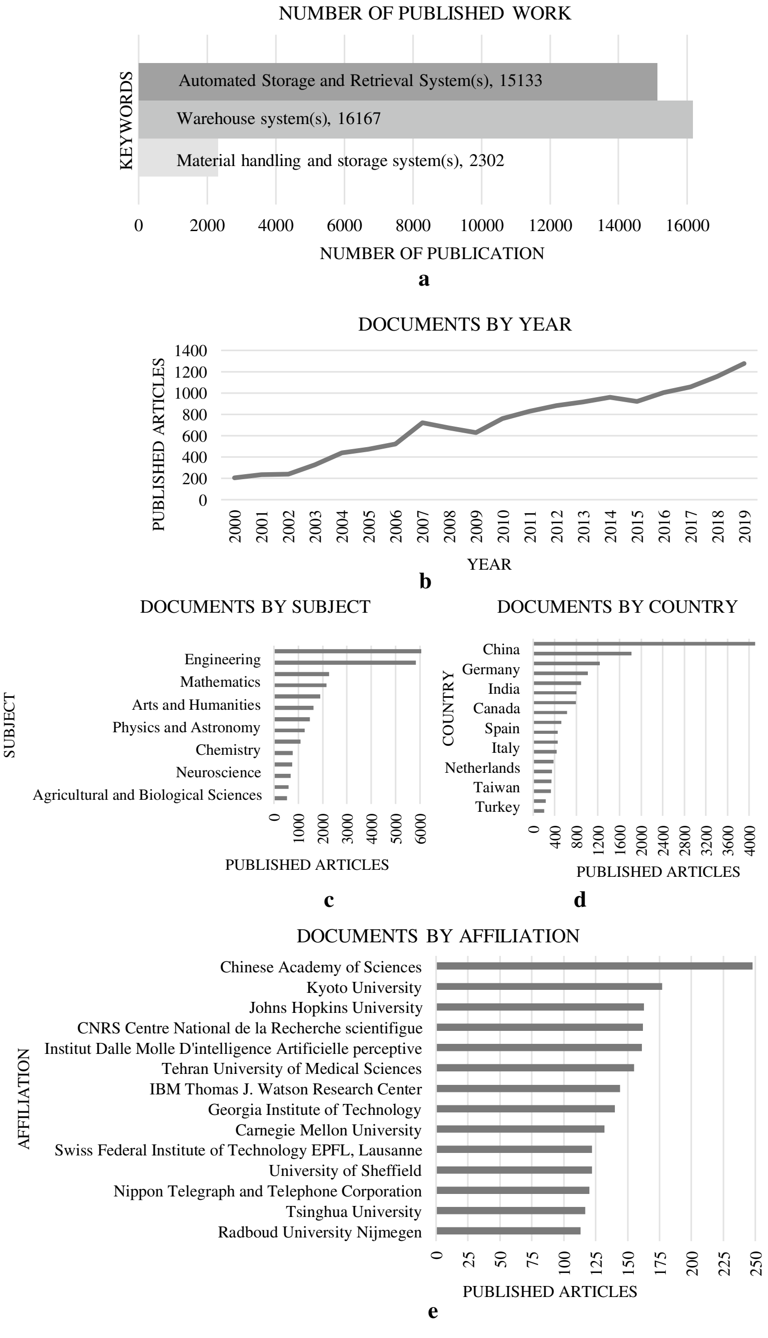

Fig. 3 Statistics from Scopus database (Date: 24.03.2020, keywords: "ASRS" OR "Automated Storage and Retrieval System"). **a** Published documents between 2000 and 2020, **b** Published documents per year, **c** Published documents by subject, **d** Published documents by country, **e** Published documents by affiliation

and presented in Fig. 3e. Also, comprehensive published work between “Automated Storage and Retrieval Systems,” “Warehouse systems,” and “Material Handling and Storage Systems” is presented in Fig. 3a.

Classification of Research

Systematic classification of research according to the design objectives, configurations, and optimization algorithms used in the design and optimization of AS/RS is presented in Tables 1 and 2.

Roodbergen et al. [45] studied that there are significant benefits such as improvement in efficiency and capacity of storage systems, improvement in quality and performance, better inventory security. Also, they studied the disadvantages of AS/RS, such as inflexibility of the system, high capital cost, fixed storage capacity, lack of visibility. Roodbergen and Vis [46] studied operating requirements of an AS/RS listed common subsystems: storage structure, S/R machine, storage modules, I/O station, control systems, and RFID systems. Storage structure is the main structure that accommodates the high weighted loads without significant deflection. The structure must have sufficient strength and rigidity. S/R machine provides transportation. Storage modules used to carry bins including stored products inside. Pallets, baskets, bins, containers, drawers are commonly used in AS/RS as storage modules. The station where the loads are taken in or out of the AS/RS termed as I/O stations. They are mostly accessed by external handling system that brings the loads into the AS/RS or takes out of AS/RS.

Vasili et al. [53] studied AS/RS in terms of specifically focused objectives and requirements, i.e., maximization of storage capacity, throughput, travel time, whereas minimization of the total cost, carbon footprint, maximization of storage density as well as improvement on inventory control and safety. Recently many researchers have focused on the design, analysis, and optimization of various AS/RS configurations [53]. However, there is no author found in the literature focusing on circular AS/RS.

Recently AS/RS are implemented to the automotive factories due to improved safety, inventory control, landscape utilization, cost and efficiency [12, 15, 20, 49].

A general overview of warehouse control and design haven been studied in the past years [3, 15, 48, 51]. The clarification of the current developments of the AS/RS design and design issues are presented by [46]. Sarker and Babu [49] studied the design aspects of an AS/RS and travel time model of the rectangular type AS/RS. In his research, Throughput capacity is explained as the inverse of the mean transaction time that is the expected travel time required for storage or retrieval process and P/D time. Therefore, the travel time of an AS/RS usually related to the S/R machine features as well as AS/RS rack configuration. Moreover, Sarker and Babu [49] made a list of top interesting design problems, as shown: (1) Assignment of the products to the storage locations in the storage structure. (2) Configurations of the storage structure (Ratio of length to height), (3) Operating policies for order storage, and

Table 1 Recent developments in the design and optimization of AS/RS (years between 1976 and 2012)

Category	Author	Hausman et al. (1976)	Graves et al. (1977)	Bozer and White (1984)	Ashayeri, J. et all. (1985)	Sarker, B. R. et al. (1995)	Van den Bergh, J. C. (2000)	Malmborg, C.J (2003)	Rene de Koster et all. (2006)	De Koster, R et all. (2007)	Roodbergen, K. J. et al. (2008)	Vasili, M. R. et all. (2008)	Roodbergen, K. J. et al. (2009)	Gagliardi, J.P. et al. (2010)	Felix T.S. et all.(2010)	Klaus Moellera et all. (2011)	Vasili, M. R. et all. (2012)	Khalid H. et all.(2012)	Haneyah, S. W. A. et al.(2012)	Dou, C. (2012)	Lerher, T. et all. (2012)
Objectives	Review Paper	•				•			•		•			•							
	Travel time					•	•		•	•	•	•	•		•	•		•			•
	Cost minimization				•			•	•	•					•		•			•	
	Comparison between models					•						•	•						•		•
	System Configuration				•		•	•			•	•	•		•		•			•	
	Requests sequencing		•						•	•	•		•					•			
	Storage Capacity / Assingment	•	•	•			•		•			•	•		•		•		•	•	•
	Performance optimization																				
	CO2							•													•
Modelling assumptions – Configurations	Flow-rack AS/RS																				
	Mobil racks																				
	Unit-Load AS/RS	•	•	•	•	•		•	•		•	•	•				•	•			
	Order picking system								•	•									•		
	All locations have same dimentions	•	•	•	•	•					•		•					•		•	
	Multi-load AS/RS				•	•	•				•		•							•	
	Single crane, Single Aisle	•	•	•		•		•	•			•					•	•			
	Symetrical Distances	•	•	•	•	•		•				•					•				
	Each I/O can perform S/R	•	•	•	•				•		•		•				•	•			
	AS/RS (AVS/RS)																				
	Square in time rack	•	•			•															
	Circular AS/RS (C-AS/RS)																				
	Rectangular in time rack			•	•			•	•	•	•	•	•				•			•	•
Modelling assumptions – Crane	Tchebychev time							•													
	Robotic load carrying carts																			•	
	Constant crane acceleration	•	•	•	•		•	•			•		•								•
	Constant pickup and deposit times	•	•	•	•		•	•			•		•					•			•
Modelling assumptions – Products	Constant item turnover	•	•	•			•		•		•	•	•				•	•		•	
	Various types					•			•	•										•	
	Items ordered EOQ model	•		•	•			•	•								•			•	
Modelling assumptions – Storage	Very narrow storage (VNA)																				
	Random storage assignment			•	•	•	•		•	•	•		•				•	•			
	Constant number of pallets	•	•	•	•	•	•		•								•			•	
	%100 Rack utilization	•	•	•	•			•			•		•					•			•
Optimization and Methodology – Analytical	Mathematical modelling	•	•	•	•			•										•			
	Statistical-Based																				
	Genetic algorithm															•			•		
	Dynamic sequencing						•														
	Eye ball technique																				
	Dwell-Point location										•		•								
	Bi-Level Optimization model																				
	Informed search algorithm																			•	
Optimization and Methodology – Simulation	Pareto curve and UL mass dist.																				
	AMPL/CPLEX																	•			
	AutoMod																				
	AMCLOS																				
	ARENA														•						
Application	Baggage handling																		•		
	Automated parking																			•	
	Industrial warehousing system	•	•	•	•	•	•	•	•		•		•		•	•	•	•			

Table 2 Recent developments in the design and optimization of AS/RS (years between 2013 and 2020)

Author	Category	Subcategory	Lerher, T. et all. (2013)	Guezzen, A. H. (2013)	Lisa M.Thomas et all. (2013)	Zollinger, H. (2014)	Lerher, T. et all. (2014)	Lerher, T. et all. (2015)	B.Y.Ekren rf.(2015)	Ghomri, L. et all. (2015)	Lerher, T (2016)	Bortolini, M. at all. (2016)	Cinar, D. et all. (2016)	Yue, L. et al. (2017)	Zrnić, N. et al. (2017)	Cinar, Z.M. (2017)	Xu, X. et al. (2018)	Oki, N. et al. (2019)	Xu, X. et al. (2019)	Tostani, H. H. et al. (2020)	Ekren, B. Y. (2020)
Review Paper																					
Travel time	Objectives		•	•			•	•	•	•	•	•	•	•	•	•	•		•		
Cost minimization	Objectives		•				•					•			•	•				•	
Comparison between models	Objectives					•										•					
System Configuration	Objectives				•	•				•				•						•	
Requests sequencing	Objectives					•															
Storage Capacity / Assingment	Objectives		•	•	•		•	•			•	•	•			•	•	•			
Performance optimization	Objectives																				•
CO2	Objectives				•			•	•			•			•	•				•	
Flow-rack AS/RS	Modelling assumptions	Configurations								•											
Mobil racks	Modelling assumptions	Configurations		•																	
Unit-Load AS/RS	Modelling assumptions	Configurations	•			•			•		•	•							•		
Order picking system	Modelling assumptions	Configurations	•			•			•			•		•							
All locations have same dimentions	Modelling assumptions	Configurations	•			•	•	•	•	•	•	•	•								
Multi-load AS/RS	Modelling assumptions	Configurations															•				
Single crane, Single Aisle	Modelling assumptions	Configurations								•	•	•				•		•	•		
Symetrical Distances	Modelling assumptions	Configurations				•						•				•					
Each I/O can perform S/R	Modelling assumptions	Configurations					•	•	•	•			•								
AS/RS (AVS/RS)	Modelling assumptions	Configurations																			•
Square in time rack	Modelling assumptions	Configurations																			
Circular AS/RS (C-AS/RS)	Modelling assumptions	Configurations														•					
Rectangular in time rack	Modelling assumptions	Configurations	•	•		•	•	•	•	•	•	•	•	•	•		•	•	•		•
Tchebychev time	Modelling assumptions	Crane					•	•				•		•	•	•	•		•		
Robotic load carrying carts	Modelling assumptions	Crane				•					•					•					
Constant crane acceleration	Modelling assumptions	Crane	•			•						•									
Constant pickup and deposit times	Modelling assumptions	Crane	•				•	•	•	•		•	•								
Constant item turnover	Modelling assumptions	Products	•	•		•			•	•	•	•									
Various types	Modelling assumptions	Products												•					•	•	
Items ordered EOQ model	Modelling assumptions	Products	•							•		•									
Very narrow storage (VNA)	Modelling assumptions	Storage				•															
Random storage assignment	Modelling assumptions	Storage		•			•	•	•	•	•		•		•				•		
Constant number of pallets	Modelling assumptions	Storage		•					•		•		•								
%100 Rack utilization	Modelling assumptions	Storage		•			•	•	•	•								•			
Mathematical modelling	Optimization and Methodology	Analytical		•						•		•		•		•					
Statistical-Based	Optimization and Methodology	Analytical			•						•										•
Genetic algorithm	Optimization and Methodology	Analytical	•				•						•		•	•					
Dynamic sequencing	Optimization and Methodology	Analytical																			
Eye ball technique	Optimization and Methodology	Analytical							•												
Dwell-Point location	Optimization and Methodology	Analytical															•				
Bi-Level Optimization model	Optimization and Methodology	Analytical																		•	
Informed search algorithm	Optimization and Methodology	Analytical																			
Pareto curve and UL mass dist.	Optimization and Methodology	Simulation										•									
AMPL/CPLEX	Optimization and Methodology	Simulation																			
AutoMod	Optimization and Methodology	Simulation	•																		
AMCLOS	Optimization and Methodology	Simulation																			
ARENA	Optimization and Methodology	Simulation		•					•	•											
Baggage handling	Application																				
Automated parking	Application															•					
Industrial warehousing system	Application		•	•	•	•			•	•	•	•	•	•				•			•

retrieval. According to [9, 46] studied, the following five lists are the most recurrent assignment strategies for AS/RS warehouses.

1. Dedicated storage requires items to set a fixed storage location. It is also required to assure storage capacity for each product and for any time in the design phase by considering product features such as weight and shape [10].
2. Full-turnover based technique considers turnover frequencies to store the product. Products close to P&D point counted as quick-moving operation whereas, products far from P&D counted as slow-moving operation. Turnover frequency is evaluated through the cube per order index (COI) [26, 27].
3. Closest open location Technique requires product storage to empty locations, which are close to the P&D point. Therefore, storage can be distinguished by all locations close to R&D point, and empty locations are far from R&D points [47].
4. A class-based storage technique is utilized to overcome the disadvantages, and it splits the AS/RS locations into different classes. Based on the product's turnover frequencies this technique assigns products into classes [25].

Commonly literature focuses on average travel distance and time for S/R products [7, 18, 21, 23, 28, 31, 32, 53, 58]. In this context, AS/RS(s) differ from traditional handling tools such as a forklift. These devices/tools perform disjoint horizontal as well as vertical movements. However, AS/RS(s) perform concurrent movements in the two directions [2]. For standard storage locations, the required time for S/R to complete loading is maximum between the horizontal and vertical time intervals. Regarding the highlighted difference above the text, travel time is considered as the KPI metric for AS/RS [40]. Published articles that focus on minimization of travel time are presented as following. Bozer [8] developed for the first time a model to define the travel time of an AS/RS [29] proposed a strategy to minimize travel time for storage assignment. Both authors ignored crane acceleration/deceleration to simplify their models. Nevertheless, several articles presented travel time models, considering crane acceleration/deceleration [30]. Additionally, the dwell point is studied to minimize the travel time of AS/RS by Van den Berg [52]. Multiple goals are also focused on travel time. For instance, the operation cost of AS/RS and space requirement is selected as objective by [57]. Some researchers are studied minimization of energy consumption of AS/RS as well as minimization of travel time as multi-objective study such as [16, 30, 52].

Most of the published papers are about manufacturing environments, and a few papers are highlighted the AS/RS configuration designs as follows; Park and Webster [43] proposed an approach that synchronously picks the storage size and shape of storage of AS/RS. Summarily, almost all simulation models are addressed to physical design features, and only a few AS/RS(s) and their configurations are evaluated in combination with constant input values. Sarker and Babu [49] studied specific parameters of the physical design of an AS/RS and also defined that size of the storage bins, baskets or boxes is important to determine storage cell dimensions as well as expected travel time to a specific location. The shape factor is another parameter that deals with the AS/RS length and height. It is also used to determine the AS/RS structure as the square in time or rectangle in time. The shape factor is known as the time spent to reach an extreme location in the storage structure. The depth of the rack is another parameter for physical design and can be a single or double deep rack. The last parameter is the capacity and the no of S/R machines utilized in the system. As the number of S/R machine increases, faster product storage and retrieval process can be done. However, for the system performance, the no of S/R machines utilized in the system should be selected based on on-demand requirements. Lerher and Šraml [35] focused on the energy efficiency model for mini-load automated storage and retrieval systems. Crane velocities, accelerations, number of rows, and number of columns with the required number of cranes are set as design variables. In the paper, CO_2 consumption of the system is evaluated.

Bartlett and Strei [5] studied cost analysis of warehouse facility establishment at Ford. California. Lerher et al. [36] studied the total cost of an AS/RS and conducted Pareto optimization design to find optimal investment cost with respect to optimal travel time and reliability. Zrnić et al. [58] studied a multi-objective optimization model for minimizing cost, travel time, and energy consumption in an AS/RS.

Barbato et al. [4] identified significant factors affecting the performance of the shuttle-based storage and retrieval system (SBS/RS) by conducting an experimental study. Their research includes Tukey's test that is used to identify design factors, and then ARENA software is utilized for modeling. Consequently, the results of the proposed model are obtained by using Minitab software. Barbato et al. [4] research resulted that:

1. For travel time: SBS/RS design should have a high value of velocities for lifts and shuttles. Also, the number of bays should be less in the system.
2. For energy consumption: lifts and shuttle velocities should be high, whereas the number of tiers and acceleration/deceleration of lift should be low.

Bertolini et al. [6] proposed a meta-heuristic algorithm based on simulated annealing in which retrieval operation performance-optimized. In their proposed algorithm, a job list is created based upon customer demand, and retrieving performance according to missions per hour is evaluated to optimize the performance of retrieving operation. In order to validate this algorithm, the existing warehouse is utilized to test and then compared it with the current performance of the existing warehouse [6].

Ma and Wang [37] studied a single and dual command cycle time model for the Shuttle Based Storage and Retrieval System (SBS/RS) by considering the motion characteristics of the system. Different design configurations with four different velocity options are evaluated by the author. Summarily, it concluded that the dual command cycle time of SBS/RS decreased by up to 28.3%, and relatively throughput capacity is increased by up to 1.3% [37].

Rajković et al. [44] presented a new optimization model that contains three objectives; (1) minimization of investment expenses, (2) minimization of cycle time and (3) minimization of CO_2 consumption of the AS/RS(s). Also, author-defined constraints as; (1) capacity must be bigger than the required capacity, (2) throughput capacity must be higher than the minimum required throughput capacity, (3) warehouse capacity must not exceed the 20% of required capacity, and (4) number of storage and retrieval machines must be lower or equal to the number of hallways. Based on these objectives and constraints author applied NSGA II in order to optimize decision variables and model resulted that the best configuration has 25.68 acres of forest per year, cycle time is 26.32 s, and investment cost is 7.01 EUR/TUL.

Ekren [18] carried out a multi-objective optimization solution procedure for the design of Autonomous Vehicle-based Storage and Retrieval System (AVS/RS) by considering the minimization of average cycle time and average energy consumption. ARENA software is utilized by the author to perform simulation and simulation results presented as following;

1. Cycle time is affected by the footprint shape of the system. Also, the number of tiers has a direct impact on electricity consumption.
2. For the optimal solution, the number of tiers should be decreased, whereas the number of aisles increased.

Discussion and Conclusion

This paper presents a systematic literature review on the research in configuration design and optimization of AS/RS, by classifying the research according to the design objectives, configurations and optimization algorithms used, in order to highlight and expand the awareness on the current best practices, progress, and future research directions.

Based on the literature review, it is concluded that most of the researchers [1, 8, 11, 17, 18, 33, 34, 38, 42, 50, 53, 55–58] focused on rectangular AS/RS and some researchers such as [22, 25, 49] focused on square AS/RS. It is observed that over the years, many researchers have focused on the design, analysis, and optimization of various AS/RS configurations, as shown in Tables 1 and 2; however, less research is focused on the Circular AS/RS Configurations. Cinar [12] applied Genetic Algorithms (GAs) for the configuration design and optimization of Circular AS/RS with the objective to optimize the throughput, cost, and carbon footprint.

Common objectives from the studied articles found as; travel time optimization, total cost optimization, carbon footprint optimization. Also, critical parameters for the design of AS/RS are defined as crane, storage configuration, product types, and crane features [11].

Most authors [11, 12, 24, 33, 36, 58] used genetic algorithm to obtain optimal storage systems. Nevertheless, fewer considerations given by authors to the application of other optimization algorithms like Swarm Intelligence, Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO). Moreover, the application of machine learning and deep learning tools needs to be further explored. In addition, an uncertainty-based design approach can also be utilized to achieve more robust configurations.

Computer-based models and simulations are critical to the design, development, and optimization of smart manufacturing systems required for Industry 4.0. [17, 19, 21, 41] carried out simulation-based design in order to obtain optimal storage systems. Cinar et al. [13]. Virtual reality simulation platforms must be further explored for the design and optimization of AS/RS. In the context of the 4th industrial revolution, logistics and storage systems are required automatization and connectivity. However, there are challenges while implementing those technologies. Cinar et al. [13] defined the challenges of Industry 4.0 applications and also listed simulation techniques for smart factories, including logistics and storage systems.

Digital twins (DT) are the key enablers for virtual design and optimization of smart manufacturing systems required for transformation to Industry 4.0. Recently many researchers have contributed to the development of DTs for smart production processes and manufacturing systems. DTs are being applied to manage the performance, effectiveness, and quality of a manufacturer's fixed assets, such as manufacturing plants. DTs are also applied to shop-floor control, assembly production lines, and flexible manufacturing systems to optimize robustness, efficiency, autonomous failure detection, and production flow control [14]. Digital twin technology must be utilized for the design of AS/RS(s).

Rajković et al. [44] recommended that their presented model can be modified to optimize AS/RS with double deep SR machine by adding more variables and constraints. Ma and Wang [37] suggested having more than two I/O points and different assignment policies such as class-based storage policy and turnover based policy in order to understand the impact of I/O separation. Bertolini et al. [6] proposed an algorithm based on simulated annealing procedure to perform optimization for a more complex AS/RS where the storage compartments are double depth or two cranes share the same railway as a future study and also suggested that a new algorithm should be created and optimization can be performed for scheduling.

The scope of the study is not to include all the available articles about the theme, but to analyze a significant sample to give understandings about the recent best practices on design and optimization of AS/RS, assisting researchers and practitioners for further studies.

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