Metaheuristic Optimization Techniques for control on Automated Storage and Retrieval Systems: A Comprehensive Survey

Bahmid O [1], Kouloughli S [2], Ouis A [3]

[1,3] *Manufacturing Engineering Laboratory of Tlemcen (MELT), Faculty of technology University of Tlemcen, Algeria*

E-mail: omar.bahmid@univ-tlemcen.dz, kouloughli_sihem@yahoo.fr, khdim3@gmail.com

Abstract: Optimizing automated storage and retrieval systems (AS/RS) presents a complex combinatorial challenge within warehouse logistics and supply chain management. Research in this area has primarily focused on two key aspects. system design and control. Utilizing metaheuristic approaches, researchers have made significant strides in enhancing system efficiency and throughput. This paper provides a brief overview of recent research that addresses the control side of AS/RS optimization using various metaheuristic techniques.

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Keywords: AS/RS, Optimization, performance measurement, Metaheuristic.

1 . INTRODUCTION

Automated storage and retrieval systems (AS/RS) have become indispensable components of modern warehouses and supply chain management. These systems enable efficient storage and retrieval of goods by utilizing automated cranes, conveyors, and storage racks, thereby minimizing human intervention and increasing productivity. However, optimizing the performance of AS/RS presents a complex combinatorial challenge due to the intricate interplay of various factors, such as storage policies, retrieval sequences, and resource allocation.

Traditionally, exact optimization methods have been employed to address AS/RS optimization problems in system design and control strategy. However, these methods often struggle to find optimal solutions within reasonable computational times, especially for large-scale instances. Consequently, researchers have turned to metaheuristic approaches, which offer near-optimal solutions by intelligently exploring the search space and exploiting promising regions.

Metaheuristic techniques, such as genetic algorithms, simulated annealing, ant colony optimization, and particle swarm optimization, have gained significant traction in the field of AS/RS optimization. These techniques leverage principles inspired by natural phenomena or physical processes to guide the search towards high-quality solutions (Bessenouci et al., 2012). By balancing exploration and exploitation strategies, metaheuristics can effectively navigate the complex solution landscapes associated with AS/RS optimization problems.

In recent years, a growing body of research has focused on leveraging metaheuristic approaches to optimize various aspects of AS/RS control and operation. These efforts have yielded promising results, demonstrating the potential of metaheuristics to enhance system efficiency, throughput, and overall performance. This paper aims to provide a comprehensive overview of recent research efforts in applying metaheuristic techniques to optimize the control and operation of AS/RS

1.1 AS/RS System

Automated Storage and Retrieval Systems (AS/RS) **figure 1** are computer-controlled systems that automatically store and retrieve items or loads from defined storage locations within a warehouse or distribution center (Sarker & Babu, 1995). The key components of an AS/RS typically include:

Storage racks or shelving to hold the inventory.

Automated storage and retrieval machines (such as cranes, shuttles, or robots) that move along aisles to deposit and retrieve items.

A computer control system that manages the storage and retrieval operations, tracking inventory locations.

Input and output point.

1.2 Classification of AS/RS

Automated Storage and Retrieval Systems (AS/RS) come in a variety of types and styles to meet the diverse needs of different industries and applications. This classification of AS/RS primarily depends on the load characteristics, storage density, throughput requirements, and available space within the facility (Roodbergen & Vis, 2009). We will show among the most common systems:

Unit-Load AS/RS: A unit-load AS/RS is a system that automatically stores and retrieves large unit loads, such as pallets, crates, or containers, in a high-density storage environment.

Sliding-racks AS/RS: Is a system where the storage racks can slide horizontally to create a temporary aisle for the automated

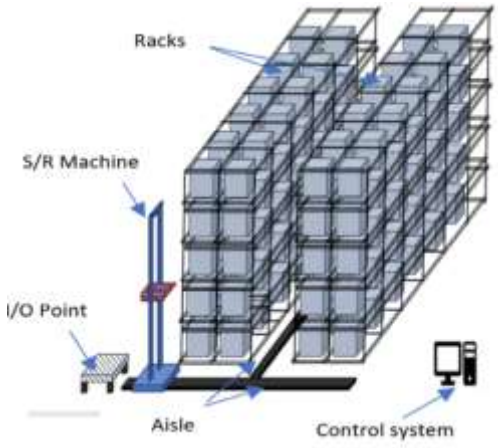

Figure 1. Automated storage and retrieval systems

storage/retrieval machine to access the loads(Chen et al., 2015).

Mini-Load AS/RS: A mini-load AS/RS is a system designed to automatically store and retrieve smaller loads, such as totes or cartons, in a high-density and high-throughput environment (Hameed, 2019).

Double-Deep AS/RS: A double-deep AS/RS is a system where the storage racks are designed to accommodate two loads deep, allowing for higher storage density by doubling the capacity of each storage lane(Hameed, 2019).

Double-ended compact AS/RS: Is a system that has two openings or points of access, allowing storage and retrieval operations to occur simultaneously from both ends, increasing throughput(Q. Yan et al., 2023).

SP-AS/RS: The split-platform automated storage and retrieval system (SP-AS/RS) is a specialized type of AS/RS meant for rapidly handling extremely heavy loads like shipping containers. It utilizes two independently moving platforms - one for storage and one for retrieval - enabling quicker operation cycles compared to traditional AS/RS designs(Vasili et al., 2012).

1.3 Storage policy

Random: Is a storage without any specific organization or predetermined rules(Roodbergen & Vis, 2009).

A dedicated storage policy: Dedicated storage is a policy in AS/RS where specific storage locations are permanently assigned to particular stock-keeping units (SKUs) or product types(Roodbergen & Vis, 2009).

Class-based storage policy: Is a policy where products or SKUs are grouped into classes based on characteristics, and each class is assigned dedicated storage zones(Roodbergen & Vis, 2009).

1.4 *Cycle type*

Single cycle: The storage/retrieval machine performs either a storage or retrieval operation in one movement.

Dual cycle: The storage/retrieval machine performs both storage and retrieval operations in a single movement.

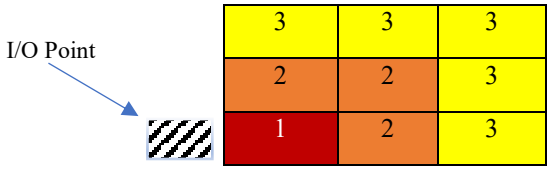

Figure 2: Class-based storage policy

1.5 Control policies

A storage assignment: A storage assignment policy dictates how incoming products are allocated to specific storage locations within the AS/RS to optimize space and efficiency(Roodbergen & Vis, 2009).

A dwell-point policy: When AS/ RS is idle, the stacker crane located at the assigned location, called a dwell point within the storage system*(Regattieri et al., 2013)*.

Sequencing rules: Determining the optimal sequence of storage and retrieval jobs*(Parab & Gore, 2018)*.

2 . LITERATURE REVIEW

(Homayouni et al., 2014) propose a genetic algorithm (GA) with specialized operators for the integrated scheduling of quay cranes, automated guided vehicles, and storage platforms in the split-platform storage/retrieval system (SP-AS/RS). Through parameter tuning experiments, the authors identify an effective tournament selection scheme and appropriate crossover/mutation rates. Their GA outperforms a previous simulated annealing approach, especially for medium- and large-scale instances. The "stay in place" dwell point policy for storage platforms is shown to minimize expected travel times, corroborating theoretical findings.

(Chen et al., 2015) concentrate on the sequencing of storage and retrieval operations within automated systems, specifically analyzing sequencing in AS/RS with a duration-of-stay storage policy for flow-rack systems. They introduce a novel grouping-matching method aimed at minimizing the total travel time of the storage/retrieval machine. Through simulation experiments, they evaluate the effectiveness of this method, which involves two grouping heuristics designed for the grouping step and formulating the matching subproblem as an assignment to be solved. Their proposed grouping-matching method demonstrates enhancements in AS/RS performance, offering promising avenues for optimizing logistics and supply chain management operations.

(Yang et al., 2015) focus on the joint optimization of storage and retrieval operations within multi-shuttle Automated Storage and Retrieval Systems (ASRS). Their study involves the verification of the advantages of the shared storage operational mode through an analytical model. To tackle large-scale optimization problems in ASRS, they developed a

variable neighborhood search (VNS) algorithm. Their method incorporates a three-index formulation for storage location assignment and scheduling. The conclusion drawn from their research highlights the effectiveness of the VNS algorithm for storage location assignment and scheduling, ultimately enhancing travel efficiency within multi-shuttle ASRS systems.

(Ene et al., 2016) introduces a genetic algorithm (GA) methodology aimed at reducing energy consumption in warehouse order picking activities through optimized batching and routing. Unlike previous research, which primarily focused on minimizing travel distance or time, this work considers environmental sustainability by minimizing the energy usage of forklifts. Encoding solutions as chromosomes representing batch storage sequences, the GA employs a fitness function based on horizontal and vertical travel distances. This research underscores the pioneering fusion of environmental considerations into warehouse operational optimization.

(Homayouni & Tang, 2016)contribute to the literature on automated container terminal (ACT) operations by proposing a multi-objective mixed-integer programming (MIP) model and a simulated annealing algorithm (SAA) for integrated scheduling of handling and storage operations. Their study focuses on the utilization of the Split-Platform Automated Storage/Retrieval System (SP-AS/RS) for temporary container storage. The MIP model aims to minimize delays in crane loading/unloading tasks, vehicle travel time, and platform movements within the SP-AS/RS. Complementarily, the SAA is employed to obtain near-optimal solutions within reasonable computational times. Empirical findings demonstrate the efficacy of the integrated scheduling approach, exhibiting an average 58% reduction in the objective function compared to non-integrated scheduling methods.

(Cao et al., 2018) looked into how to schedule orders in warehouses that work automatically for factories. They came up with a new way by mixing two different algorithms, MOEA/D and SFLA. This innovative approach tackles a dual objective problem, seeking to minimize both completion time and tardiness. Their idea works well in breaking down the problem into smaller parts and finding good solutions. Furthermore, the introduction of a nearest-neighbor strategy enhances the efficacy of storage location selection, which makes the whole scheduling process work better.

(Hu et al., 2019) developed an improved genetic algorithm to tackle the co-scheduling problem involving the coordination of stackers and a single rail-guided vehicle (RGV) system during the retrieval process in an automated storage and retrieval system (AS/RS). The authors frame the problem as a mixed-integer linear programming model, aiming to minimize the total retrieval time. Results indicate the efficacy of the proposed algorithm in comparison to the conventional first-come-first-served (FCFS) strategy.

(Yan, X et al., 2020) addressed the scheduling optimization problem for multi-aisle automatic storage/retrieval systems (AS/RS) with multi-carrier storage/retrieval (S/R) machines. They formulated an optimization model that incorporates realistic constraints, such as the sequence of inbound and outbound tasks, and an accurate calculation of the number of aisles traversed. A modified artificial bee colony (MABC) algorithm was proposed to solve this problem, specifically designed for AS/RS scheduling optimization. The MABC algorithm employed redesigned encoding, decoding, and solution updating strategies. A repair mechanism ensured the feasibility of solutions across all tested algorithms. Experimental results demonstrated that the MABC algorithm exhibited superior convergence speed and solution accuracy compared to particle swarm optimization (PSO) and genetic algorithm (GA).

(Yan, X et al., 2021) presents a novel approach for scheduling in multi-aisle automated storage and retrieval systems (AS/RS) using a multi-carrier storage/retrieval (S/R) machine. They introduce a multi-objective optimization model that incorporates sequence constraints for both inbound and outbound tasks. A non-dominated sorting artificial bee colony (NSABC) algorithm is proposed to solve the multi-objective problem of minimizing total completion time and total delay penalty. This innovative approach combines the multi-objective handling framework of NSGA-II with the neighborhood search capabilities of the artificial bee colony (ABC) algorithm. The encoding, decoding, and updating operators are redesigned to suit the specific demands of the problem.

(Geng et al., 2022) focused on refining scheduling strategies for unit load automated storage and retrieval systems (AS/RS). They introduced the dual-end, dual-stacker scheduling model (TDSM) and applied this strategy to it. They also developed a novel enhanced genetic algorithm (NIGA) to optimize stacker paths, along with an improved anti-collision principle to prevent collisions between stackers. Comparative analysis showed that NIGA performed better than alternative genetic algorithms. Furthermore, TDSM exhibited a notable advantage in achieving optimal solutions compared to conventional unit load AS/RS approaches.

(Lu et al., 2022) directed their research towards the integrated scheduling problem in automated storage and retrieval systems (AS/RS) and hybrid flow shops. They formulated a bi-objective model aimed at minimizing both the operation time within AS/RS and the makes pane. In order to address this optimization challenge effectively, they introduced the GAMBO algorithm, which combines a genetic algorithm with migratory bird optimization. The GAMBO algorithm integrates an adaptive adjustment strategy designed to regulate the frequency of employing various neighborhood structures. The comparative analysis validated the superiority of the GA-MBO integrated scheduling optimization approach over other methods.

(Li et al., 2022) focused on optimizing the stacker scheduling sequence in automated storage and retrieval systems (ASRS) using an improved genetic algorithm to enhance efficiency and avoid premature convergence during the scheduling process. Their new algorithm can find the optimal solutions quicker,

needing fewer population individuals and iterations compared to traditional genetic algorithms. To achieve this, they employed a greedy algorithm that minimizes the variance of the distance matrix to improve the quality of the initial population. Additionally, they incorporated a dynamic adaptation of the crossover probability to enhance the population evolution within the genetic algorithm. Furthermore, an adaptive mutation probability mechanism was introduced to improve the local search capability while maintaining population diversity.

(Yan, Q et al., 2023) have introduced an Improved Shuffled Frog Leaping Algorithm (ISFLA) aimed at optimizing stacker-scheduling within the double-ended compact storage system. This algorithm seeks to enhance storage space utilization, improve operational efficiency, and determine the optimal task sequence for stacker-scheduling paths. ISFLA addresses the limitations of slow convergence and local optimization observed in standard SFLA approaches, thereby offering accelerated convergence speeds and higher-quality solutions.

(2022) (Hsu et al., 2022) introduces the Improved Whale Optimization Algorithm (IWOA) for AS/RS crane scheduling, focusing on energy consumption reduction. It outlines the integration of simulation and optimization methods, emphasizing the benefits of using IWOA with Dynamic Programming. Experimental results demonstrate the superior performance of IWOA compared to other heuristics/metaheuristics. The study proposes a framework for efficient AS/RS crane scheduling by closely coupling simulation and optimization techniques.

this recent research studies that investigating in different types of automated storage and retrieval systems (AS/RS). Its covers a diverse range of AS/RS configurations, including unit-load, multi-aisle, flow-rack, multi-shuttle, double-ended compact, SP-AS/RS and double-deep systems.

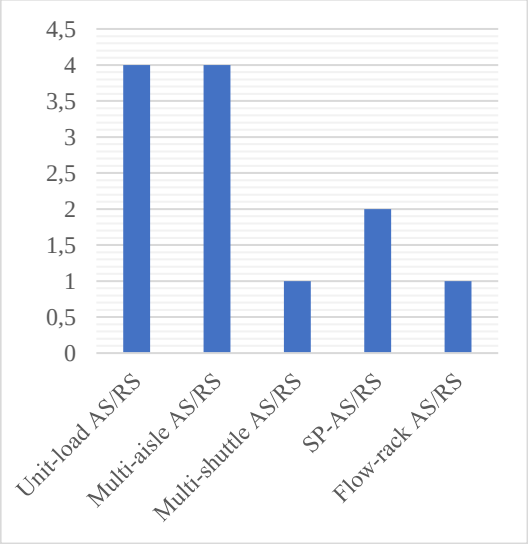

Figure 3: Distribution of AS/RS Research by System Type

Overall, the **table 1** summarizes the key characteristics, assumptions, and focus areas of these research efforts, highlighting the variety of approaches taken to analyze and optimize the performance of automated storage systems in different operational context.

Table 1: Overview of research in optimization control of different type of AS/RS

Literature	**System Type**	**Storage type**	**S/R Equipment**			**I/O Point**
			Type and number	Cycle	Speed	
Homayouni, S., and al (2014)	SP-AS/RS	Random	Four cranes, six vehicles	DC	Constant	Single location
Zhuxi, C., and al (2015)	Flow-rack AS/RS	A dedicated storage policy	Two handling machines,	/	Constant	Single location
Peng, Y., and al (2015)	Multi-shuttle AS/RS	A dedicated storage policy	Shuttles varies among 2, 3 and 4	DC	Constant = 1 m/s	Single location
Ene, S., and al (2016)	Multi-aisle AS/RS	Class-based storage policy	Single Forklift	DC	Horizontal=10 km/h Vertical=057km/h	Single location
Homayouni, S., and Tang, S (2016)	SP-AS/RS	Random	Cranes, vehicles, horizontal platforms, and vertical platforms	SC	Constant	Single location
Zhengcai, C., and al (2018)	Unit-load AS/RS	Random	13 AGV and 4 Forklift	DC	AGV (Hs =1m/s, Vs=0.8m/s) Forklift (V=1m/s)	Single location
HU, P., and al (2019)	Multi-aisle AS/RS	Random	RGV and 8 stackers.	SC	U [6, 10]	A set of I/O point

Yan, X., and al (2020)	Multi-aisle AS/RS	Random	Multi-shuttle S/R machine	DC	Hs= 1.2 m/s Vs= 0.4 m/s	Single location
Yan, X., and al (2021)	Multi-aisle AS/RS	Random	Multi-shuttle S/R machine	DC	Constant	Single location
Geng, S., and al (2021)	Unit-load AS/RS	Random	Two stackers	SC/ DC	Constant	Two I/O stations
Lu, J., and al (2022)	Unit-load AS/RS	Random	3 Crane	DC	Constant (Hs= 3 m/s Vs= 1 m/s)	I/O point for each aisle
Li, H., and al (2022)	Unit-load AS/RS	Random	Stacker	DC	Constant V=0.5 m/s	Single location
Yan, Q., and al (2022)	Double-ended compact AS/RS	Random	Single S/R machine	SC/ DC	Constant (Hs= 2 m/s Vs= 1 m/s)	A set of I/O point located at both ends of the aisle
Hsu, H., and al (2022)	Double-Deep AS/RS	Class-based storage policy	Single S/R machine	SC/ DC	Constant	Single location

The studies summarized in the **table 2** showcase the application of a diverse array of optimization algorithms to tackle various challenges in AS/RS. Genetic algorithms (GAs) are among the most widely employed techniques, as seen in the works of Homayouni et al. (2014), Ene et al. (2016), Hu et al. (2019), Yan et al. (2020), Geng et al. (2021), Lu et al. (2022), and Li et al. (2022). GAs are population-based metaheuristics that mimic natural evolution, making them well-suited for complex optimization problems with large search spaces. However, their performance can be sensitive to parameter settings and representation scheme.

Simulated annealing algorithms (SAA), as employed by Homayouni and Tang (2016), and Variable neighborhood search (VNS), utilized by Yang et al. (2015), involve the systematic exploration of diverse neighborhood structures with the objective of diversifying the search and escaping local optima. Although VNS can be effective for certain problem instances, its performance may be contingent upon the specific neighborhood structures defined and the transition strategies employed. Additionally, Chen, Z., et al. (2015) implemented a grouping-matching heuristic in their study.

In recent years, researchers have increasingly employed hybridization or the integration of multiple optimization techniques to address optimization problems in automated storage and retrieval systems (AS/RS). This approach aims to circumvent the limitations of individual algorithms and synergistically leverage their complementary strengths. The results presented in the following table demonstrate the marked superiority of hybrid optimization techniques over single or traditional techniques.

Overall, each algorithm family offers unique strengths and weaknesses, and the choice of approach may depend on factors such as problem characteristics, computational requirements, and the specific objectives or constraints considered. Hybrid approaches that combine different algorithms or incorporate problem-specific heuristics may also be promising avenues for future research endeavors.

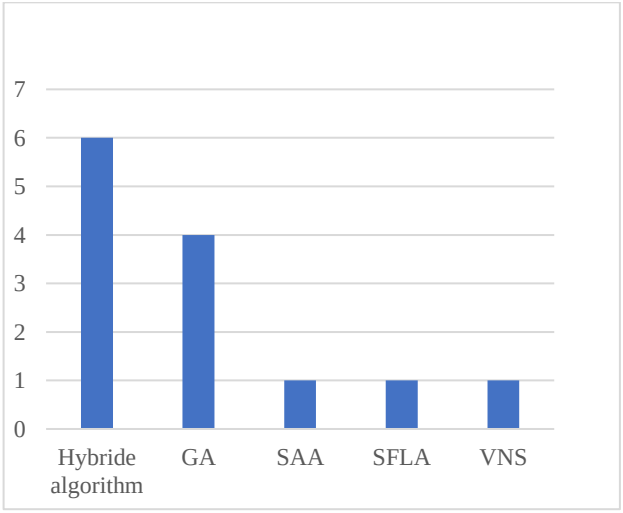

Figure 4: Comparative Analysis of Metaheuristic Technique Usage for AS/RS Control Optimization

Table 2: Summary of Recent Literature on Optimization Algorithms for Automated Storage and Retrieval Systems (AS/RS)

Literature	**Algorithm**	**Task representation**	**Control**			**Performance measures**	**Results**
			Sequencing	**dwell point**	**storage assign**		

Homayouni, S., and al (2014)	GA	Real Numbers	x	x		Total travel time	GA outperformed a simulated annealing algorithm in optimizing integrated scheduling problems.
Chen, Z., and al (2015)	Grouping-matching heuristic	Real number and form	x		x	Computational time	Proposed grouping-matching method enhances AS/RS performance.
Yang, P., and al (2015)	VNS	Location numbers			x	Travel time	VNS algorithm is effective and efficient for large-sized optimization problems
Ene, S., and al (2016)	GA	Number of cranes			x	Total energy consumption	GA can enhance the environmental sustainability of warehouse facilities by decreasing their energy footprint.
Homayouni, S., and Tang, S (2016)	SAA	Real number	x	x		Total travel time of the vehicles, and travel time of the platforms in the SP-AS/RS	The SAA demonstrates its effectiveness by achieving solutions only 3.7% less optimal than those derived from the MIP model.
Zhengcai, C., and al (2018)	mMOEA/D-SFLA	Integer	x		x	Completion time and the maximum tardiness	Comparison with NSGA-II and MOEAD shows algorithm's effectiveness.
HU, P., and al (2019)	GA	Real number	x			Total retrieval time	Reduced Total Recall time by 8.36% compared to FCFS
Yan, X., and al (2020)	MABC	Integer	x			Total operation time	MABC algorithm outperformed PSO and GA in ASRS scheduling optimization.
Yan, X., and al (2021)	NSABC	Real number	x			Total completion time and total delay penalty.	NSABC outperformed EMBBO, NSGA-II, and MOEA/D algorithms.
Geng, S., and al (2021)	NIGA	Integer	x		x	Travel time of stackers	Compared with GA and AGA, NIGA has a faster convergence speed to jump out of the local optimum.
Lu, J., and al (2022)	GA-MBO	Integer		x	x	The operation time.	GA-MBO outperforms IPSO and IGA and GA-PSO
Li, H., and al (2022)	GA	Integer	x			The path length.	Improved algorithm finds optimal solution faster with less population and iterations.
Yan, Q., and al (2022)	SFLA	Integer	x			Total travel time	ISFLA significantly improves solution quality.

3 CONCLUSION

The complexity of optimizing automated storage and retrieval systems (AS/RS) has driven researchers to explore metaheuristic techniques. This paper surveyed recent studies employing various metaheuristics, from genetic algorithms to nature-inspired methods, for enhancing AS/RS control and efficiency. The exploration of hybrid algorithms and the integration of problem-specific heuristics have proved a fruitful direction for future research in optimizing AS/RS operations. Additionally, the consideration of emerging challenges, such as energy efficiency, sustainability, and dynamic operational environments, may necessitate the development of novel optimization techniques or the adaptation of existing approaches to effectively address these evolving requirements. Future research should focus on developing hybrid algorithms that combine the strengths of different metaheuristics and incorporate problem-specific knowledge to tackle the increasingly complex challenges in AS/RS optimization.

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