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Configuration of an automated storage and retrieval system via simulation

Annarita De Maio[1], Francesco Longo[2], Roberto Musmanno[2] and Pierpaolo Veltri[2]

[1] Department of Economics, Statistics and Finance “Giovanni Anania”, University of Calabria, 87036 Arcavacata di Rende (CS), Italy
[2] Department of Mechanical, Energy and Management Engineering, University of Calabria, 87036 Arcavacata di Rende (CS), Italy

*Corresponding author. Email address: pierpaolo.veltri@unical.it

Abstract

The automation of warehouse operations has become essential for boosting efficiency and competitive edge in logistics management. Among the range of technologies available, Automated Storage and Retrieval Systems (AS/RS) have proven to be effective in enhancing inventory control and minimizing handling durations. This study presents the development of a simulation model using Tecnomatix Plant Simulation, a Discrete Event Simulation environment, to configure AS/RS in warehouse operations. The simulator is designed to support strategic, tactical, and operational decisions in the management of warehouse handling operations. It employs a Genetic Algorithm (GA) to efficiently manage sequences of dual cycles, where pairs of storage and retrieval tasks are combined to reduce overall handling time. The performance of this algorithm has been benchmarked against solutions obtained from optimally solving some test instances in simple cases. Computational experiments show that the genetic algorithm approaches optimal performance, with average gaps in handling time ranging from 1.00% for lower capacity utilization to 2.11% for higher loads. These results empirically demonstrate the validity of the approach, making a significant step forward in the optimization of warehouse operations through advanced AS/RS configurations.

Keywords: automated storage and retrieval system; simulation; dual cycle; optimization; assignment problem

1. Introduction

In recent years, the automation of warehousing processes has become a key component for enhancing the efficiency and competitiveness of logistics operations. Among the various available technologies, Automated Storage and Retrieval Systems (AS/RS) have emerged as an effective solution for optimizing inventory management and reducing goods handling times (Ananthi et al., 2023).

An AS/RS is an integrated system composed of computer and mechanical equipment designed to automate the storage and retrieval of unit loads. This type of system can include stacker cranes and other advanced technologies that work together to position and retrieve goods with greater precision and speed compared to traditional methods. Implementing an AS/RS in a warehouse brings numerous advantages, including optimized space utilization, enhanced operational safety, and significant reductions in operational costs.

The evolution of industrial practices has now reached the era of Industry 5.0, where the focus shifts from automation alone to human-centric and sustainable manufacturing. Industry 5.0 emphasizes collaboration between humans and advanced technologies, aiming to create more personalized and efficient production environments (Maddikunta et al., 2022). In this context, AS/RS systems play a critical role by seamlessly integrating with human operators and other automated systems to enhance productivity and responsiveness in warehousing operations.

The introduction of advanced technologies such as AS/RS not only revolutionizes warehousing operations but also represents a crucial step toward the realization of smart warehouses, capable of responding to the growing demands of the global market with speed and flexibility. Furthermore, in line with the principles of Industry 5.0, these technologies facilitate a more harmonious interaction between human workers and automated systems, promoting a safer, more efficient, and sustainable working environment.

The use of AS/RS technology within warehouses involves a significant number of managerial decisions. These decisions impact both the planning phase (strategic and tactical decisions) and the operational management of a warehouse.

In Section 2, the main decisions in AS/RS will be illustrated, with a focus also on the relevant scientific literature. Section 3 is devoted to the description of the simulator implemented to configure the parameters of an AS/RS. The simulator is also based on a genetic algorithm invoked when it is necessary to determine the best order in which to execute a sequence of several rack storage and rack retrieval tasks. A storage task followed by a retrieval task can be performed by the stacker crane in a single combined cycle, named dual cycle, consisting of three sequential movements: 1) from the I/O station to the storage location; 2) from the storage location to the retrieval location; 3) from the retrieval location to the I/O station (see Figure 1).

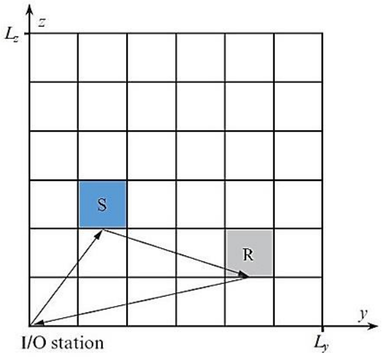

Figure *1*. The AS/RS dual cycle: the storage location in blue, the retrieval location in grey.

In some cases, the problem of coupling storage and retrieval tasks to minimize overall travel time (noting that the time required for forking/deforking the palletized unit loads is constant in any dual cycle) can be formulated as a combinatorial optimization problem. This problem can be ascribed to a classical assignment problem, which is the topic of Section 4. In this section, we also determine the performance of the genetic algorithm on several instances that simulate sequences of storage and retrieval tasks to be coupled. The results obtained have been compared with those obtained by optimally solving the same instances as assignment problems in Section 5. Finally, Section 6 reports the conclusions and the future possible developments.

2. State of the Art in AS/RS decisions

In this section, we illustrate the main decisions in the configuration of an AS/RS. We partially follow the same methodology illustrated in Ritzqi et al., 2024, which has inspired this work.

We assume that the AS/RS serves a single-deep pallet rack, allowing direct access to each palletized unit load without moving others.

At the strategic level, the main decisions when designing an AS/RS are the determination of the length L_y and the height L_z of the rack (see Figure 1). This is followed by the setting of the number of layers and the dimension of the loading bays. Other aspects at the design phase are of an engineering nature (e.g., the size of the beams and frames) which, however, are beyond the scope of this paper.

Another strategic decision concerns the positioning of the input-output (I/O) stations. This involves determining where the pick-up of the palletized unit loads for storage tasks takes place and where the release of the unit loads retrieved by the stacker crane takes place. Generally, there are two possible configurations for I/O stations: single-side docking, whereby both input and output stations are on the same side of the aisle at different heights, and double-side docking, whereby the two stations are on opposite sides of the rack at the ends of the aisle (Randhawa et al., 1991).

Fixing AS/RS speeds and accelerations is another strategic decision, referring to both the horizontal and vertical displacement of the stacker crane. These parameters affect the timing of goods handling in the warehouse, but they also have a significant impact on the energy consumption of the AS/RS.

The assignment of palletized unit loads to storage locations is a tactical decision. According to the classification defined by Gagliardi et al., 2012, there are several rules for the storage assignment, which can be grouped into three categories: 1) random storage policy, whereby any palletized unit load can be assigned to any storage location; 2) row-based policy, whereby palletized unit loads are divided by classes as well as by storage locations, and the filling of storage locations of the same class is done by rows; 3) column-based policy, similar to the previous one, with the only difference being that the filling of storage locations of the same product class is done by columns.

Another tactical decision is the dwell point positioning. It refers to the problem of finding the location where the AS/RS should reside when the system is idle. Static rules are defined as possible locations of the dwell point at the input station, the barycenter, or the output station, while there are several dynamic rules, the simplest of which places the dwell point at the last visited storage location (Bozer and White, 1994). Van Den Berg, 2002 proposed analytic expressions to minimize the expected travel time from the dwell point to the position of the next operation.

In operational decision-making, the focus is on policies for managing request sequencing, slot selection, and retrieval selection. Request sequencing involves determining the order in which the AS/RS processes storage and retrieval requests. Eight policies can be considered (Han et al., 1987): Storage Priority (SP), Retrieval Priority (RP), First Come First Serve (FCFS), Last Come First Serve (LCFS), Nearest Neighbor (NN), Furthest Neighbor (FN), Shortest Leg (SL), Longest Leg (LL). The FCFS, LCFS, SP, and RP policies are straightforward. The NN policy selects the request (either storage or retrieval) closest to the AS/RS's current position, whereas the FN policy selects the one farthest away. Unlike the NN policy, the SL policy considers the next task and chooses the request such that the AS/RS will have the shortest distance to the subsequent task upon completing the first. Conversely, the LL policy selects the request that results in the longest distance to the next task.

Slot selection involves choosing the storage location in the rack where an incoming palletized unit load will be stored when multiple positions are available. Retrieval selection refers to choosing the storage location from which an item will be retrieved (Yue et al., 2017). Both processes utilize the same seven rules: Closest Open Location (COL) with row order, Furthest Open Location (FOL) with row order, COL with column order, FOL with column order, Random-based, Nearest to AS/RS, Farthest to AS/RS. In slot selection, the COL rule selects the storage location closest to the input station, while in retrieval selection, it selects the storage location closest to the output station.

3. Simulation model

The AS/RS simulation model has been created using Tecnomatix Plant Simulation (Student Version), a Discrete Event Simulation (DES) software provided by Siemens (https://www.siemens.com/global/en/products/automation/topic-areas/use-cases/simulation.html). An advanced modeling approach has been employed to customize default objects such as Store, Mobile Unit, and Transporter. This approach, which incorporates programming code, enhances the flexibility of simulation models.

Known as Automated Simulation Model Generation (ASMG) (*Schlecht et al., 2023*), this modeling technique allows for modification of the simulation model without requiring expert skills, thus facilitating model reuse over time, even when system parameters change.

Once the design parameters are established, the simulation model depicts the AS/RS in a 3D environment (see Figure 2). In addition to the three-dimensional representation, the simulation model computes various KPIs, including travel times for rack storage and retrieval tasks, AS/RS waiting time and working percentages, and energy consumption.

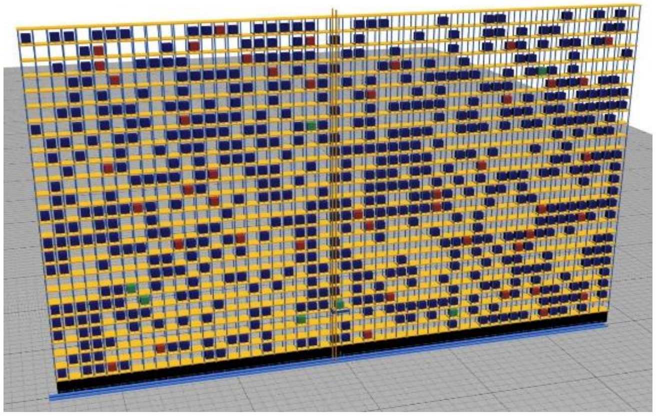

Figure *2*. The AS/RS in 3D environment

3.1. Parameters

The implementation considers input parameters for both the pallet rack and the AS/RS, based on the main strategic, tactical, and operational decisions illustrated in Section 2. These parameters allow for "What-If" analysis scenarios to support comprehensive decision-making.

Specifically, at the strategic level, input parameters that can be set by the user include the type of palletized unit load (six different types according to ISO6780), the number of levels, the height of each level, storage locations per loading bay, and the number of loading bays per level. Although these are configurable parameters, a default value of 10 cm has been set for the upright width and beam thickness, enabling the automatic calculation of rack length and height.

Another parameter allows the positioning of the I/O stations. By default, the single-side docking option is assumed, with the input station 50 cm above the floor and the output station at a height corresponding to a rack level.

Input parameters also include the maximum speed and acceleration of the AS/RS in both horizontal and vertical directions, as well as the average time expected for the forking and deforking of palletized unit loads.

The current version of the simulator uses the random storage policy for assigning palletized unit loads to rack storage locations. In the case of combined storage and retrieval tasks, the DES software's planning module, based on a Genetic Algorithm (GA, see Section 3.2), has been configured to identify the sequence of dual cycles that minimizes the completion time of these operations.

Finally, an additional input parameter allows the establishment of the dwell point position, with the default value coinciding with the input station position.

3.2. Genetic Algorithm for management of dual cycles

As mentioned in the previous sections, a dual cycle is executed by an AS/RS when an ordered pair of storage and retrieval tasks is performed. The corresponding overall handling time depends on the initial position of the stacker crane, the I/O stations, and the storage locations of the palletized unit loads to be stored and retrieved. Let n be the number of storage tasks. We assume the simultaneous availability of n retrieval tasks, which can be combined with the storage tasks, resulting in n^2 different possible dual cycles.

The management of the dual cycles can be efficiently handled in the simulation model by using "GA wizard" an integrated tool of Plant Simulation. It is a powerful tool for optimizing complex problems by mimicking the principles of biological evolution. In a GA, a potential solution to a problem is represented as a chromosome, and the quality of these solutions is assessed by a fitness function.

In the context of managing the dual cycles, the GA seeks to find the sequence of paired storage and retrieval tasks with the aim of minimizing the overall processing time. In this specific implementation, a chromosome is represented by two lists: one for storage tasks and one for retrieval tasks. The initial chromosome is created by randomly ordering these tasks. The GA then simulates the execution of dual cycles by pairing storage and retrieval tasks in a FIFO (First In, First Out) manner, following the order of the lists.

The crossover operation involves exchanging segments of these ordered lists between two parent chromosomes, potentially creating new and improved task sequences. Mutation, on the other hand, randomly alters the position of tasks within each list, introducing diversity into the population and helping to explore new potential solutions. By iteratively applying these operations and evaluating the resulting chromosomes based on the total handling time, the GA continuously refines the task sequences. This process allows for the exploration of various combinations of storage and retrieval task pairings, progressively moving towards an optimal or near-optimal solution.

As shown in Figure 3, the GA continually optimizes the fitness function intending to reduce the processing time of the dual cycles (y-axis). By iterating through generations (x-axis), the algorithm modifies the solutions based on the fitness evaluations from the previous cycles. This iterative process continues until a predetermined stopping criterion is met, such as a set number of generations or a satisfactory fitness level.

4. Optimization model

The problem of determining the best possible pairings of storage and retrieval tasks when the involved storage locations are known in advance corresponds to an assignment problem that can be formulated as follows. Let c_{ij} be the overall handling time of the dual cycle when the storage location is i ($i = 1,..,n$), and the retrieval location is j ($j = n+1,..,2n$). Let x_{ij} be the binary decision variable, equal to one if the storage task related to the storage location i ($i = 1,..,n$) is combined with the retrieval task from the storage location j ($j = n+1,..,2n$), zero otherwise.

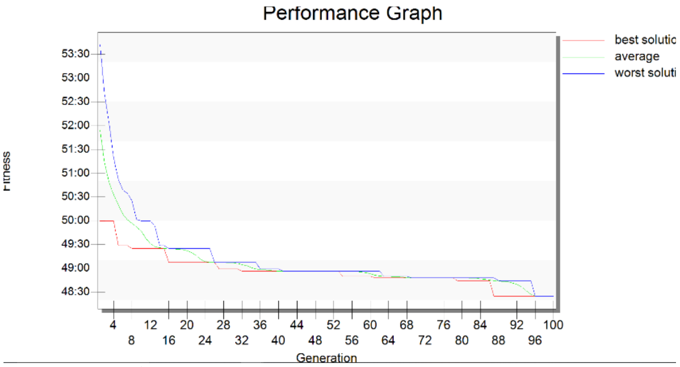

Figure 3. GA Performance Graph

$$\min z(x) = \sum_{i=1}^{n} \sum_{j=n+1}^{2n} c_{ij} x_{ij} \qquad (1)$$

subject to

$$\sum_{i=1}^{n} x_{ij} = 1\,, j = n+1, \dots, 2n \qquad (2)$$

$$\sum_{j=n+1}^{2n} x_{ij} = 1\,, \qquad i = 1, \dots, n \qquad (3)$$

$$x_{ij} \in \{0,1\}, \;\; i = 1, \dots, n; \; j = n+1, \dots, 2n. \qquad (4)$$

In the assignment problem (1)-(4), the goal is to assign one storage task to each retrieval task and one retrieval task to each storage task. The objective is to minimize the total handling time for all assignments. Note that constraints (4) can be replaced by the simpler conditions

$$x_{ij} \geq 0, \;\; i = 1, \dots, n; \; j = n+1, \dots, 2n. \qquad (5)$$

This implies that the assignment problem is a linear programming problem, which can be efficiently solved even for large-scale instances using a general-purpose solver.

The parameter c_{ij} is computed as:

$c_{ij} = t_{Ii} + t_{ij} + t_{jO}$,

where t_{Ii}, t_{ij} and t_{jO} are, respectively, the handling times of the stacker crane from the input station to storage location *i*, from storage location *i* to storage location *j* and from storage location *j* to the output station.

The ability to optimally solve the problem of determining the sequence of dual cycles in the specific case under consideration provides a highly useful tool for generally testing the efficiency of the GA implemented to manage the task sequencing operations in the simulator.

5. Simulator configuration and validation

In order to validate the AS/RS simulator described in Section 3 and, in particular, to test the GA used to pair storage tasks with retrieval tasks, an AS/RS system equipped with telescopic forks from a well-known Spanish company has been examined to serve a single-deep pallet rack. The features of the AS/RS and the rack system are as follows (default input parameters are omitted for brevity).

<u>AS/RS</u>

- Maximum length: 70 m;
- Maximum height: 33 m;
- Maximum horizontal speed v_y: 220 m/min;
- Maximum horizontal acceleration a_y: 0.5 m/s^2;
- Maximum vertical speed v_z: 66 m/min;
- Maximum vertical acceleration a_z: 0.6 m/s^2;
- Maximum load: 1200 kg;
- Palletized unit load type: Eur1 (800 mm × 1000 mm);
- Average forking/deforking time: 3 s.

<u>Single-deep pallet rack</u>

- Number of levels (including floor): 15;
- Level height: 210 cm;
- Storage locations per loading bay: 3;
- Width of a loading bay: 270 cm (considering a clearance between palletized unit loads or between palletized unit load and frame of 7.5 cm);
- Number of loading bays per level: 20.

Based on the above parameters, the height and length of the pallet rack are determined to be L_z =33.5 m and L_y =56.1 m, respectively. The number of storage locations is 15×60 = 900.

It is also possible to calculate the time t_y for a movement s_y along the horizontal direction *y* (see Figure 4).

In detail, considering that the AS/RS moves with uniformly accelerated motion, the movement is described by the following equations for traversed space and speed:

$$s = \frac{1}{2} a_y t^2 \,;$$

$$v = a_y t.$$

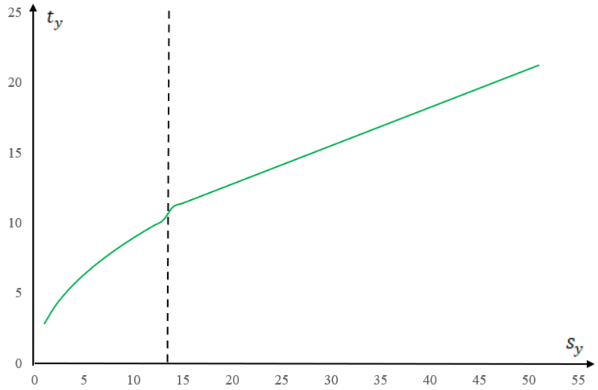

Figure 4. Travel time as a function of the movement along the *y*-direction

It is possible to easily derive the space traveled by the stacker crane to reach its maximum speed $\bar{s_y}$ = 220m/min = 13.3956 m/s. Note that, if the distance traveled exceeds this threshold value, the stacker crane will move with uniform linear motion until the deceleration starts. Therefore, the time t_y for a movement s_y along the horizontal direction *y*, is derived, considering two different cases:

$$t_y = 2\sqrt{\frac{s_y/2}{a_y/2}}\text{, if } s_y \leq \bar{s_y} \text{ m;}$$

$$t_y = 2\sqrt{\frac{\bar{s_y}}{a_y/2}} + \frac{(s_y - 2\bar{s_y})}{v_y}\text{, if } s_y > \bar{s_y}\,.$$

Similarly, considering that $\bar{s_z} = 1.00\bar{8}$ m/s, the time t_z for a movement s_z along the vertical direction *z* is:

$$t_z = 2\sqrt{\frac{s_z/2}{a_z/2}}\text{, if } s_z \leq \bar{s_z}\,;$$

$$t_z = 2\sqrt{\frac{\bar{s_z}}{a_z/2}} + \frac{(s_z - 2\bar{s_z})}{v_z}\text{, if } s_z > \bar{s_z}.$$

Since the stacker crane can move simultaneously and independently along the horizontal axis *y* and along the vertical axis *z*, the travel time of the AS/RS follows the Chebyshev metric and is given by max $\{t_y; t_z\}$.

Computational experiments have been conducted considering three groups of instances with an increasing number *n* of storage tasks, equivalent to 5%, 10%, and 20% of the total number of storage locations, respectively. Each group consists of 20 instances. This approach aims to evaluate the performance of the GA under different operating conditions.

The average overall handling times for the dual cycle sequences determined by the GA and by optimally solving the corresponding assignment problems are reported in Table 1. The same table also reports the percentage gap between the average travel times computed by the GA and the optimal values and the results collected in the worst and best scenarios.

Table 1. Numerical results

Problem group	GA average handling time [s]	Optimal average handling time [s]	Average Gap [%]	Worst case GAP [%]	Best case GAP [%]
5%	1913.56	1894.59	1.00	1.61	0.63
10%	3785.55	3723.93	1.66	2.35	1.02
20%	7483.40	7328.65	2.11	3.28	1.40

The values presented in Table 1 demonstrate the effectiveness of the GA used to manage dual cycles in AS/RS. The algorithm has been configured to perform runs across 30 generations with a generation size of 40, aiming to minimize the total handling time in warehouse operations.

The data analysis indicates that the average handling time calculated by the GA, while not achieving optimality, closely approaches optimal values, with an average gap that progressively increases with the percentage of capacity used (1.00% for 5%, 1.66% for 10%, and 2.11% for 20%). This increase in the gap is attributed to the rising complexity of the problem, as a greater number of tasks implies a broader exploration field, searching for the optimal solution more challenging.

The increase in the deterioration gap from 1.61% to 3.28% further highlights how the algorithm may struggle in more loaded scenarios, although it still maintains a performance close to optimal as shown by the best case, which improves from 0.63% to 1.40%.

The duration of the simulations is proportional to the number of tasks, ranging from approximately 2 minutes for 5% up to about 4.10 minutes for 20%, confirming that the computational intensity of the GA scales with the problem size. Despite the challenges posed by increasing complexity, the adopted approach appears robust and well-suited to effectively handle a wide range of operational scenarios, while maintaining manageable computation times.

These results underscore the effectiveness of the simulation model and the use of genetic algorithms for optimizing AS/RS operations. This makes the algorithm particularly suitable for dynamic environments where static and theoretically optimal solutions may not be feasible due to inherent uncertainties.

6. Conclusions

This paper has presented the development of a simulator designed for the configuration and management of an AS/RS in warehouse operations. The simulator's primary objective is to facilitate strategic, tactical, and operational decision-making to enhance the efficiency and effectiveness of warehouse handling operations. By employing a genetic algorithm, the simulator can efficiently manage sequences of dual cycles, thereby optimizing the overall handling time.

The empirical results obtained from our computational experiments validate the effectiveness of the genetic algorithm. Specifically, the algorithm's performance has been benchmarked against optimal solutions derived from test instances of the assignment problem, demonstrating its capability to always produce near-optimal solutions. This confirms the utility of the proposed approach for real-world applications where the task sequencing operations are not so simple.

The simulation model developed in this paper represents a significant step forward in the optimization of warehouse operations through advanced AS/RS configurations. It underscores the importance of continuous innovation in logistics technology to meet the growing demands of the global market efficiently and sustainably.

The results enable the application of this methodology also in stochastic and variable environments, demonstrating its ability to adapt and function effectively under dynamic and unpredictable conditions. This characteristic greatly increases the practical application potential of the simulator in real-world contexts, making it a valuable tool for the future of logistics optimization. Note that, by incrementally complicating the model defined in the simulator, it is possible to investigate the various effects of logistical decisions, ranging from layout design to racking size, from the allocation of unit loads unit to the analysis of different stock management policies. This approach also integrates different decision-making levels (strategic, tactical and operational) to verify their interactions.

Future research directions may include further refinement of the GA to handle even more complex scenarios and larger datasets, integration with other advanced technologies such as AI and machine learning for predictive analytics, and real-world testing in diverse warehouse environments to generalize the findings. Additionally, exploring the human-machine collaboration aspect in greater detail will be crucial for developing more personalized and adaptive warehouse systems that align with the evolving landscape of Industry 5.0.

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