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Flexible reconfiguration of AVS/RS operations for improved integration with manufacturing processes

Giulia Bruno[a], Gianluca D'Antonio[a]*

[a]Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy
* Corresponding author. Tel.:+39 011 090 7295; fax: +39 011 090 7299. *E-mail address:* gianluca.dantonio@polito.it

Abstract

The improvements in connectivity and data availability enable to fully integrate all the components of a production system. Manufacturing processes are frequently reconfigured over time, due to changes in lot sizes, process parameters and product customization. Despite this, warehousing operations are often disregarded: usually, automation systems for warehouses are set-up during the installation and their management is hardly ever reviewed. As a consequence, the manufacturing process is adapted to the capabilities of the warehousing system, rather than the other way round. To overcome this issue, this paper aims to propose a method capable to support an easy reconfiguration of warehousing operations based on the current state of the manufacturing process. The method is applied to an Autonomous Vehicle Storage and Retrieval Systems (AVS/RS), one of the most recent and promising automation technologies for warehouses. The proposed approach is based on both discrete-event simulation and analytical techniques and is applied to a real case of an Italian company.

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Keywords: Reconfigurable systems; Production system; Warehousing; System modeling; Simulation

1. Introduction

Due to the ever-changing market needs, manufacturers are required to increasingly adapt their manufacturing processes: lot sizes, process parameters and product features need to be varied even on small time scales. In order to maintain efficient the overall production system, optimizations cannot be focused only on manufacturing processes. Conversely, intra-logistics systems have to support the just-in-time paradigm: raw materials, intermediate products, finite goods must be available at the right place, at the right time.

Since the times necessary for transferring and transporting materials and products are not negligible, compared to production times, an appropriate modeling of the material handling equipment and its activities in the real industrial applications is of crucial importance; the intra-logistics operations should be planned and synchronized with production resources operations [1].

Among the several automation systems developed to support warehouse activities, Autonomous Vehicle Storage and Retrieval Systems (AVS/RS) are a promising solution capable to deal with highly variable workloads. Compared to more common Automated Storage and Retrieval Systems (AS/RS), the AVS/RS deploy lighter, more agile vehicles that enable to achieve a higher throughput with an overall energy reduction. Moreover, vehicles capable of moving within a rack channel are available: therefore, racks with arbitrary channel width can be adopted to improve the efficiency of space exploitation [2].

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In the last 15 years, different techniques have been proposed in literature to evaluate the performance of an AVS/RS in terms of system utilization, time needed to store or retrieve a given number of units, system throughput. Nonetheless, such techniques are mainly devoted to assess AVS/RS performance in the design phase. Fewer attention has been paid to the evaluation of AVS/RS performance in the operating conditions, to promote a higher integration level between the manufacturing process and the intra-logistics operations. This integration is particularly suitable for AVS/RS, as the storage and retrieval tasks can be adapted to fit as much as possible with the current needs of the manufacturing process.

A comprehensive approach to evaluate the performances of an integrated production system, composed by a manufacturing process and the warehousing operations performed by an AVS/RS is still missing in literature. The present paper aims to move a first step in this direction: an approach based on both analytical tools and discrete event simulation has been developed and tested on the operating conditions of an Italian food manufacturer. This approach aims to support the production planner by choosing the best operational strategy for the warehouse depending on the needs of the production system.

The remainder of the paper is organized as follows. The background is presented in Section 2: the most popular approaches available in literature are discussed and system is described. The original methodology is presented in Section 3; the case-study application is shown in Section 4. Finally, in Section 5, conclusive remarks and future works are presented.

2. Background

2.1. System description

The AVS/RS adopted in this work is made of three types of vehicles integrated with each other: (i) a lift that performs vertical movements and provides access to the different rack tiers; (ii) a shuttle performing the movements along the aisle of the operating tier; (iii) a satellite, which autonomously moves through the channels of the rack to store and retrieve unit loads (ULs). The tier-to-tier configuration is dealt, in which the shuttle can change the operating tier by means of the lifting table. It is opposed to the tier-captive configuration, in which the tier assigned to the shuttle is set and does not change. The bay is the place where ULs waiting to be stored are queued and represents the interface between the AVS/RS and the upstream manufacturing process. A scheme of the rack and the AVS/RS vehicles is shown in Fig. 1.

In order to store a UL into the rack, the following operations are performed:

1. The UL is loaded from the bay by the satellite which, in turn, joins the shuttle. Then, the two vehicles move on the lift;
2. The lift vertically moves towards the target tier; as the destination is achieved, the shuttle leaves the lift;
3. The shuttle travels through the aisle towards the target channel; when the destination is achieved, the satellite leaves the shuttle and enters the channel;

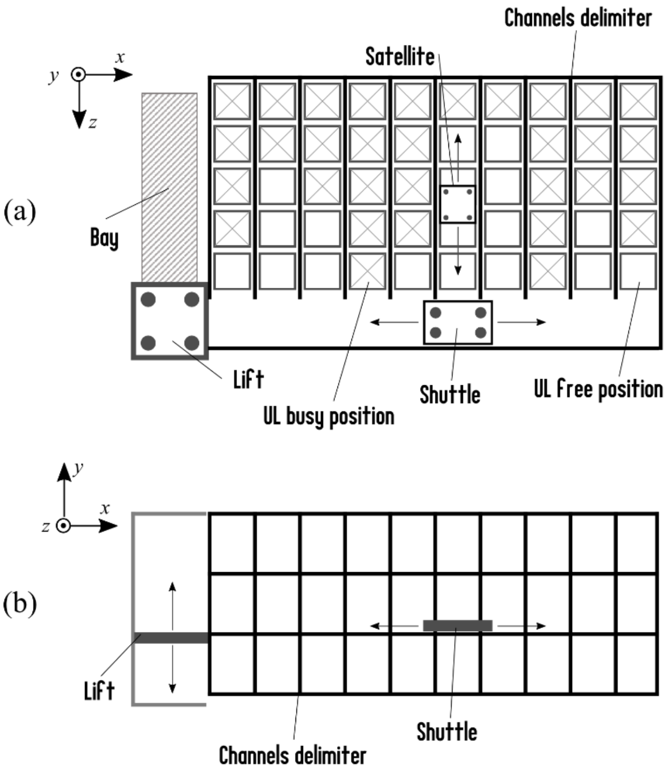

Fig. 1. Representation of the warehouse top (a) and front (b) views and the AVS/RS studied in the present paper.

4. The satellite moves along the channel towards the target position, chosen according to a LIFO (Last In First Out) policy; when the destination is achieved, the satellite unloads the UL.

The term “cycle” implies that the initial and final positions of the vehicles must be the same; therefore, the above list is also performed backwards to close the cycle. The retrieval task is performed symmetrically.

It can be noted that during operation (4) the shuttle is idle. To increase the performance of the system, the lift can be provided with a table capable to host more than a single UL. Thus, when a high storage throughput is required, multiple ULs can be loaded simultaneously on the lift. Then, the shuttle can exploit the time necessary for operation (4) to move back to the lift, load the second UL, travel towards the former channel and join the satellite. The same feature can be symmetrically exploited to manage high retrieval rates.

2.2. Literature review

The first scientific work on AVS/RS is dated 2002: Malmborg presented an analytical model to evaluate system utilization, cycle time and throughput in tier-to-tier configurations. In this work, both Single Command (SC) and Dual Command (DC) cycles, in which one and two ULs are handled, respectively [4]. One year later, the same author developed a mathematical model to evaluate the optimal proportion of DC cycles to be performed in order to match with the demand of storage and retrieval tasks [5].

Another popular approach is based on queueing theory. Kuo et al. developed a model capable to estimate cycle time and vehicles utilization for SC cycles [6]. Fukunari and Malmborg enriched the model by considering the opportunistic pairing of storage and retrieval tasks, to improve the overall system performance [7]. However, non-Poissonian queues generally exhibit higher computational cost and lower accuracy. Therefore, Zhang et al. used approximation techniques to keep analytical simplicity for a model with arrival rates and service times described through general distributions [8].

A semi-open queueing network approach has also been adopted [9]: the lift and the vehicles are modelled as independent queues mutually interacting. This approach initially led to model single-tier systems; then, it has been extended to describe multi-tier racks [10,11].

Ekren and Heragu developed a regression, simulation-based model to tie the mean cycle time of the system to rack topology and to the performance of the vehicles [12]. Marchet et al. developed a hybrid approach made up of analytical techniques and queues network to evaluate the cycle time as the sum of the travelling and waiting times [13].

These researches only consider single-depth racks. Nonetheless, one of the AVS/RS strengths is the capability to feed multi-depth racks with an arbitrary number of UL positions for each channel. At the state of the art, this feature has been taken into account in [2] and in [3]. Manzini et al. [2] adopted an analytical approach to model deep-lane AVS//RS capabilities. D'Antonio et al. [3] developed an analytical model capable to consider simultaneous operations of the vehicles and to take into account realistic criteria for ULs storage and retrieval.

However, currently, there are no researches providing a model for integrated evaluation of an AVS/RS within a manufacturing process. Therefore, this research aims to be a first step towards this purpose.

3. Methodology

The purpose of the present paper is to define an approach to evaluate the performances of an integrated production system, composed by a manufacturing process and the warehousing operations performed by an AVS/RS. The latter system is in charge of storing the finite goods as well as of retrieving ULs at the demand pace. First, the average time needed to perform different types of cycles is evaluated. Second, the impact of such cycles on the surrounding environment is assessed: the average amount of ULs queued to be stored/retrieved and the average time spent in queue are evaluated as the operating conditions of the manufacturing process and/or the AVS/RS change.

Analytical methods – mainly based on queue theory – would lead to models with complex formulation: the flows of ULs to be stored and to be retrieved have to be treated as independent queues sharing the intra-logistics system; in turn, the AVS/RS is made of several integrated vehicles which need to be synchronized. Conversely, a discrete events simulation tool could provide the user with an accurate evaluation but needs a non-negligible time amount to be run: the time required for performance evaluation increases as the number of possible scenarios increases.

Therefore, in this work a hybrid approach is shown: a simulation approach is used to model the overall system; then, the response of the AVS/RS to the different scenarios is described by means of an analytical model, which is capable to estimate the mean cycle time and the variance of an arbitrary warehouse cycle.

3.1. Analytical model for cycle time estimation

The analytical model adopted in this work is based on the work developed in [3]. It is a technique capable to estimate average duration and variance of a cycle involving an arbitrary number of ULs to be stored and/or retrieved. A probabilistic approach is adopted: probability distributions are used to model the criteria driving the selection of rack positions in which ULs are to be stored or retrieved. As an example, the random criterion – which is largely used in literature – would be described by means of a uniform distribution.

The model is based on the following parameters:

- L is the number of rack tiers (or levels) involved in the cycle;
- U_ℓ is the number of ULs involved in the ℓ-th tier visited in the cycle;
- S_ℓ is the number of switches from a storage to a retrieval task on the ℓ-th tier;
- P_ℓ is the number of shuttle-satellite simultaneous operations performed on the ℓ-th tier;

The cycle time estimation is then based on a set of variables; their evaluation is based on the features of the vehicles (acceleration, maximum speed) as well as the probability distributions chosen to model the storage/retrieval criteria:

- (x_M, σ_x^2) are the average duration and variance of the shuttle travel from the lift to the target channel;
- (y_M, σ_y^2) are the average duration and variance of the lift travel from the bay to the target tier;
- (z_M, σ_z^2) are the average duration and variance of the satellite travel from the channel entrance to the storage/retrieval position;
- $(\delta x, \sigma_{\delta x}^2)$ are the average duration and variance of the shuttle travel between two channels on the same tier (e.g. when a switch from storage to retrieval tasks has place);
- $(\delta y, \sigma_{\delta y}^2)$ are the average duration and variance of the lift travel between two different tiers;
- (P_{xz}, σ_P^2) are the average duration and variance of the simultaneous shuttle-satellite operations.

The mean cycle time $E[CT]$ is given by:

$$E[CT] = 2y_M + (L-1)\delta y + \cdots$$

$$\ldots \sum_{\ell=1}^{L}[2x_M + (P_\ell - S_\ell)\delta x + 2(U_\ell - P_\ell)z_M + P_\ell \cdot P_{xz}] \quad (1)$$

The variance of the cycle time $Var[CT]$ is computed accordingly to the Bienayme's formula:

$$Var[CT] = 4\sigma_y^2 + (L-1)^2\sigma_{\delta y}^2 + \cdots$$

$$\ldots \sum_{\ell=1}^{L}[4\sigma_x^2 + (P_\ell - S_\ell)^2\sigma_{\delta x}^2 + 4(U_\ell - P_\ell)^2\sigma_z^2 + P_\ell^2 \cdot P_{xz}^2] (2)$$

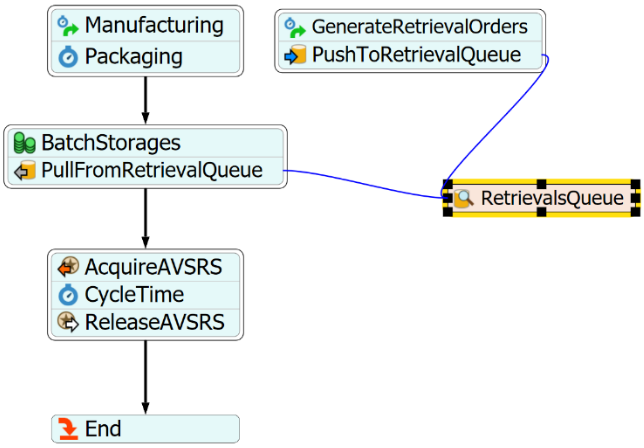

Fig. 2. Sketch of the developed discrete-event simulation model.

3.2. Discrete event simulation

The simulation has been implemented in Flexsim (https://www.flexsim.com), a discrete event simulation tool developed by the U.S. Flexsim Software Production Company and already used in literature to simulate production processes [14]-[16]. In order to reduce as much as possible the computational time, the ProcessFlow tool has been used: it is a flowcharting environment that enables to run models with small computational effort and to quickly develop a novel simulation.

A snapshot of the simulation model is shown in Fig. 2. The production of finite goods is synthesized in two-macro operations: Manufacturing and Packaging. The first operation models the production of finite goods at a defined production rate, while the second one releases the ULs to be stored in the warehouse. Similarly, orders of ULs to be retrieved are generated and queued in a list (the retrievals list). Both the queues of items to be stored and items to be retrieved are managed according to a FIFO policy. Then, the storage and retrieval requests are batched to form a cycle.

The model is able to create cycles made of an arbitrary number of ULs to be stored and retrieved; the size of the cycle is limited by the technical capabilities of the system to be analyzed, and it is a variable of our system. As the cycle is defined and the ULs are ready, the AVS/RS is acquired; if it is not available, the cycle is queued. The cycle time and its variance are computed accordingly to the model provided in Section 3.1; after cycle completion, the AVS/RS is released for the next cycle.

To measure the performance of the system and compare different scenarios, data including system utilization, average time spent in queue by the ULs, and average number of queued ULs are collected.

4. Application

4.1. Use case

The methodology presented in the former Section has been applied to the production process of an Italian food manufacturer.

The warehousing system consists in a single rack made of 6 tiers; two of them are below the ground floor. Each tier provides entrance to 38 channels, and each channel can host 14 ULs. The rack can host EUR pallets (1200 × 800 mm) with a maximum height of 1900 mm. The AVS/RS is made of a single lift capable to host up to two ULs, one shuttle and one satellite with the following properties:

- Lift: acceleration: 0.35 m/s^2; maximum speed: 14 m/min;
- Shuttle: acceleration: 0.55 m/s^2; maximum speed: 120 m/min;
- Satellite: acceleration: 0.60 m/s^2; maximum speed: 72 m/min.

Data concerning the production rate of the manufacturing process have been analyzed. The hourly production rate has been evaluated and the overall distribution has been extracted. The manufacturing process is highly standardized, and process variability is small. It was observed that ULs departure times from the manufacturing process can be described through a lognormal distribution with standard deviation equal or lower than the 10% of the average value. Conversely, the retrieval requests exhibit a higher variability, mainly because such orders contain batches of ULs. Lognormal distributions with standard deviations values close to the average values have been adopted.

To validate the developed approach in the widest number of approaches, the 5^{th}, 25^{th}, 50^{th}, 75^{th}, 95^{th} percentiles of the production rates have been considered. These values represent the five analyzed scenarios. Table 1 reports the average and standard deviation of ULs departure times from the manufacturing process and of retrieval requests used in each scenario.

Table 1. ULs production and retrieval requests rates in the tested scenarios.

	Manufacturing process inter-departure time [s]		Retrieval requests inter-arrival time [s]	
Scenario	Avg.	Std. dev.	Avg.	Std. dev.
1	129	13	129	129
2	147	15	147	147
3	179	18	179	179
4	233	23	233	233
5	434	43	434	434

4.2. Experimental plan

Given the technical capabilities of the system under investigation, the following AVS/RS cycles have been analyzed. First, homogeneous cycles are tested, in which all the activities to be made take place on a single tier.

- Cycle 1: it consists in storing or retrieving a single UL;
- Cycle 2: it consists in one storage and one retrieval tasks, both made on the same tier.
- Cycle 3: it consists in two storages and two retrievals made on the same tier;

Then, heterogeneous cycles are considered, in which multiple tiers are involved in a cycle. The analysis is restricted to cycles involving two tiers.

- Cycle 4: it consists in one storage and one retrieval, made on different tiers;
- Cycle 5: it consists in performing on the two different tiers both a storage and a retrieval.

The choice of the number of tiers to be involved in the cycle may be due, for example, to zoning rules: the manufacturer could desire to keep different products on different tiers.

The model for the evaluation of cycle time average value and standard deviation requires in input some statistical distributions to model the criteria adopted for storing and retrieving ULs. The considered AVS/RS usually operates by selecting the available tiers as close as possible to the ground floor, and the channels closest to the lift, in order to shorten as much as possible the cycle time. Therefore, geometrical distributions have been adopted to model both the choice of the tier and the selection of the channel; the support of these distributions has been limited according to the number of tiers and channels, and densities have been accordingly normalized. Conversely, uniform distributions have been used to model the selection of the position within the channel. Table 2 reports the average time and standard deviation for each cycle type, computed by using the analytical model in Eqs. (1) and (2).

Each scenario has been tested with each type of cycle, for a simulated time equal to 6 hours.

Table 2. Average time and standard deviation for cycle times.

Cycle	Average duration [s]	Std. deviation [s]
1	58.89	20.89
2	82.22	23.30
3	148.99	33.82
4	107.67	25.82
5	154.32	29.66

4.3. Results and discussion

The first result obtained by the simulation is that the system is stable in any of the tested scenarios for any type of cycle. The AVS/RS average utilizations – synthesized in Table 3 – are always lower than 1.

Tables 4 and 5 respectively show the average time spent in queue by each UL to be stored and each by retrieval order, as well as the average quantities.

Table 3. Average AVS/RS utilization in the tested scenarios.

Scenario	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
1	0.98	0.64	0.53	0.83	0.55
2	0.89	0.57	0.45	0.74	0.47
3	0.75	0.47	0.39	0.61	0.39
4	0.56	0.35	0.27	0.46	0.28
5	0.35	0.19	0.14	0.24	0.14

Table 4. Impact of queued ULs to be stored in the tested scenarios.

	Avg. queue time [s] (Avg. quantity [ULs])				
Scenario	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
1	197.87 (1.49)	0.47 (0)	64.9 (0.49)	10.44 (0.98)	64.9 (0.49)
2	67.69 (0.45)	0 (0)	73.1 (0.49)	3.35 (0.02)	73.1 (0.49)
3	31.46 (0.17)	0 (0)	89.1 (0.48)	0 (0)	89.1 (0.48)
4	7.50 (0.03)	0 (0)	117.73 (0.47)	0 (0)	117.73 (0.47)
5	3.43 (0.01)	0 (0)	212.74 (0.47)	0 (0)	212.74 (0.47)

Table 5. Impact of queued ULs to be retrieved in the tested scenarios.

	Avg. queue time [s] (Avg. quantity [ULs])				
Scenario	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
1	195.39 (1.73)	700.34 (6.06)	751.09 (6.52)	710.31 (7.04)	751.09 (6.52)
2	88.56 (0.69)	726.27 (5.66)	795.65 (6.12)	729.62 (5.68)	795.65 (6.12)
3	46.78 (0.32)	741.48 (5.00)	801.49 (5.34)	741.48 (5.00)	801.49 (5.34)
4	11.43 (0.06)	930.55 (4.12)	1044.33 (4.58)	930.55 (4.12)	1044.33 (4.58)
5	4.13 (0.01)	1073.99 (3.51)	1225.89 (3.98)	1073.99 (3.51)	1225.89 (3.98)

The first scenario represents a case of very high productivity. In this case, limiting the AVS/RS to single command cycles (cycle 1) may lead to some criticalities. System utilization is close to 1, leading to have on average 1.5 UL waiting to be stored. For the same scenario, cycles in which multiple tasks are performed reduce system utilization as well as the average time that ULs to be stored need to wait. An opposite trend is found for ULs to be retrieved, due to the higher variability in retrieval requests.

As the productivity decreases, especially in scenarios 4 and 5, the average utilization of the AVS/RS is around or lower 50% even having at disposal only single insertion and retrieval missions (cycle 1).

It can also be noted that, for a given set of tasks, there exist small differences between homogeneous and heterogeneous cycles, in particular for cycles 3 and 5. This result is due to the symmetry of the rack with respect to the ground floor, obtained by installing two tiers below the ground floor. Therefore, the number of rack positions close to the warehouse entrance is increased and the travel time spent by the lift – which is the slowest vehicle – is reduced.

Therefore, in high-productivity scenarios cycles capable to perform multiple tasks are preferable. The small amount of time spent in queue by the ULs to be stored is due to the constant presence of queued retrieval orders.

Conversely, in case of lower production rate, even single command cycles may become convenient: in the last two evaluated scenarios, the impact of queues for cycle 1 is dramatically reduced.

5. Conclusions

The present paper aimed at presenting an approach to support the performance evaluation of an AVS/RS in the operating conditions of a manufacturing process, with the ultimate goal of promoting a higher integration between the manufacturing process and the intra-logistics operations.

The presented tool aims to help production planners and decision makers to quickly compare different AVS/RS deployment scenarios and select the operations configuration that fits as much as possible with the requirements due to the production of finite goods as well as to the pace of orders.

The hybrid technique made of an analytical technique integrated into a discrete event simulation model leads to an intuitive tool requiring low computational efforts: few seconds were necessary to compute the results shown in Tables 3-5 through a common laptop.

Currently the approach is limited to AVS/RS composed by a single lift, a single shuttle and a single satellite, and only symmetrical racks were considered: all the channels here have the same size. Future works will address the extension of the model to manage multiple shuttles and satellites, either with a single lift and with multiple lifts, to support larger warehouses. Furthermore, asymmetrical racks capable to manage ULs with different dimensions – as required by modern customized production – will be considered.

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