Sustainability Analysis of Autonomous Vehicle Storage and Retrieval Systems

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Abstract: - In the last years, huge efforts have been performed in developing innovative solutions to support warehouses automation. Although a variety of approaches addressed the performance evaluation of storage and retrieval systems, e.g., cycle time and machine utilization, no contribution has highlighted the sustainability of this class of systems yet. The aim of this work is to propose a methodology to allow the evaluation of energy consumption of such systems, with particular concern for Autonomous Vehicle Storage and Retrieval Systems (AVS/RS); such evaluation is supported by the design and execution of a simulation model representing the warehouse behaviour under different scenarios. The application of the approach in a real warehouse is also presented.

Key-Words: - AVS/RS, discrete event simulation, autonomous vehicles, shuttle-based systems, manufacturing systems, automatic warehouse, UML activity diagrams.

1 Introduction

Automated Storage and Retrieval Systems (AS/RS) traditionally consist of cranes travelling along aisles, capable to transfer unit-loads from the gate to the proper cell in the rack, and vice versa, by moving simultaneously into horizontal and vertical directions. In spite of their speed and reliability, they show important drawbacks: firstly, they involve a large amount of energy because of both the big equipment masses to move, and the large building space engaged by cranes; moreover, they hardly match the flexibility and responsiveness requirements posed by lean and intelligent logistic.

A variation of the classic AS/RS systems is presented by shuttle-based storage and retrieval systems (SBS/RS), which are used in practice when a variable demand for the throughput capacity is forecasted. The basic components of SBS/RS are storage racks (SR), an elevator with the lifting table for feeding the SBS/RS with totes, shuttle carriers, which are operating in each tier (tier-captive system), buffer positions at each tier, input/output (I/O) location and accumulating conveyors [9].

The innovative breakthrough introduced by AVS/RS pertains the exploitation of lighter, more flexible vehicles (lifts, shuttles and satellites) moving in different directions [10]. This architecture enables the simultaneous execution of different activities, resulting in higher efficiency and improved throughput in case of random demand. However, today such systems are still at an early stage of development. ROIs are promising, even if only few configurations - tailored on specific industrial cases - have been implemented until now. Therefore, more investigation is needed to provide design rules and evaluation methods, especially by taking into consideration an energy consumption analysis.

Available literature highlights that the methodologies currently used to assess an AVS/RS are based on performance measures such as the cycle time and the utilization of the machines. At the moment, there are no techniques taking into account the sustainability of the system. Hence, the original contribution of this work is the proposal of a methodology to include the energy consumption in the performance evaluation of an AVS/RS.

The rest of the paper is organized as follows. Section 2 describes recent related works, while Section 3 presents the proposed methodology to analyse the sustainability of AVS/RS systems. After that, Section 4 provides the formal description and conceptual models of the analysed systems, while Section 5 describes the implementation of the simulation model. Section 6 presents a use case in which the developed simulation model is adapted to a real warehouse. Finally, Section 7 draws conclusions and states future works.

2 Related works

The first AVS/RS have been introduced in European facilities in the late 1990s. Since then, several approaches have been proposed to evaluate the performance of such systems. A first analytical model has been developed by Malmborg [11]: he focused on tier-to-tier configurations, i.e. racks in which vehicles are able to move through different levels using a lift, aiming at comparing AS/RS and AVS/RS performances. Malmborg also developed analytical tools to estimate the proportion of DC cycles to be performed, based on the demand of storage and retrieval tasks, and the estimated cycle times for single command (SC) and dual command (DC) cycles [12]: these two expressions refer to the number of items transported during the cycle. In the former case, one storage or one retrieval task are performed; in the latter, both the tasks are executed.

Other existing approaches are based on queuing theory. Kuo et al. [8] developed a model for performance evaluation in SC cycles. Fukunari and Malmborg considered opportunistic pairing of storage and retrieval task [4]. They also developed a network queueing approach to reduce the computational cost of the model [5]. Zhang et al. [15] introduced approximation techniques to solve a model with non-Poissonian queues keeping analytical simplicity. The semi-open queueing network has been discussed [14]: the lift and the vehicles are modeled through independent queues interacting with each other. A regression, simulation-based model was also developed to tie the average cycle time of the system to rack topology and the performance of the vehicles [2]. Marchet et al. [13] provided a hybrid approach made by analytical techniques and queues network to evaluate the cycle time as the sum of travel and waiting times.

These papers all consider single-depth racks, i.e. racks in which only one item can be stored per each channel. In the only work that takes into account multi-depth racks, an analytical model is presented to evaluate the performance of a rack with arbitrary width [10].

Although this variety of approaches, the attention of researchers has been focused on the evaluation of system performance. The most commonly studied parameters are the cycle time and the utilization of the machines; the literature review highlighted that there are no contributions taking into account the sustainability of this class of systems.

3 Methodology

In order to include the sustainability within an overall performance evaluation, two approaches are feasible. One possibility is to develop analytical models. However, this approach allows to accurately describe only simple cycles. Conversely, analytical models are not reliable to fully describe the complexity dealt by an AVS/RS. Hence, an approach based on simulation techniques is preferable.

The methodology proposed in this paper to estimate the energy consumption of an AVS/RS is composed by the following three steps.

1. AVS/RS system analysis: the features of the system and its decisional schemas are analysed and a conceptual model of the interactions among transport machines is defined.
2. Simulation implementation: the conceptual model is implemented in a simulation software. Since the state of the system changes in response to a finite set of events, a discrete-event simulation approach is deployed.
3. Simulation execution: by analysing the details of a use case, the parameters of the model are set and the simulation is executed to obtain the results in terms of cycle time, machines utilization and energy consumption.

A graphical representation for the methodology is shown in Fig.1. These three phases are detailed in the following sections.

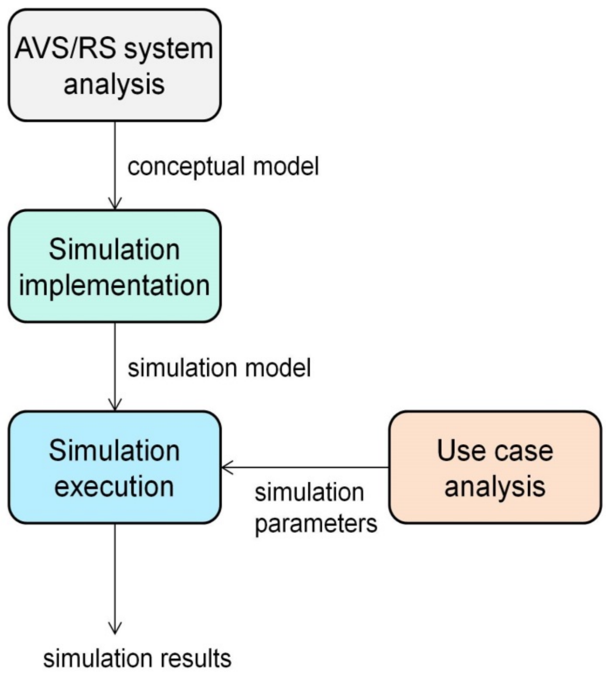

Fig.1. Steps to evaluate the performance of an AVS/RS system.

4 AVS/RS system analysis

As stated in the Introduction, AS/RS exhibit low flexibility and poor performance in case of highly variable requests for storage and retrieval. Nonetheless, in order to approach a just-in-time flow of items, the capability to deal with great variability keeping high system efficiency is necessary: this is the strength of AVS/RS. This kind of system is able to separate the movements along the different directions by using a set of autonomous vehicles devoted to the vertical, the longitudinal and the transverse directions. Each level of the rack has a single cross aisle that goes from one side to the other, to provide access to the channels.

4.1 System conveyors

Three different kinds of vehicles are used:

1. The lift, in charge of the vertical movement (*y* direction);
2. The shuttle, which performs the movement through the aisle (*x* direction);
3. The satellite, which is the storage/retrieval machine: it moves through the channels, to deposit or pick an item at/from the target position (*z* direction).

Hence, the whole system consists of several autonomous vehicles integrated with each other: the shuttle moves through the aisle transporting the satellite in front of the target channel. The satellite, in turn, transports the unit load (UL): it leaves the shuttle and enters the channel, to perform the storage or retrieval task. The shuttles change the operating level through the lift: this kind of configuration is named 'tier-to-tier', as opposed to 'tier-captive' configurations, in which shuttles cannot change level. There also exists a gate, which is the interface of the system with the external world. A graphical representation of the rack and the AVS/RS system is provided in Fig.2.

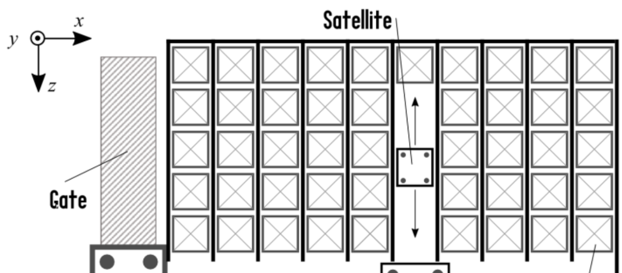

Fig.2. Schematic representation of a rack and an AVS/RS system.

The sequence of the operations to store a UL is the following:

1. The UL is carried in the gate;
2. The UL is loaded by the satellite; the satellite joins the shuttle, and they move on the lift;
3. The lift moves to the target level, and the shuttle leaves the lift;
4. The shuttle moves through the aisle and stops in front of the target channel;
5. The satellite leaves the shuttle and enters the channel;
6. The satellite moves along the channel towards the last pallet stored;
7. The satellite unloads the pallet at the last empty location, according to a LIFO (Last In First Out) policy;
8. The satellite moves back through the channel and joins the shuttle.

The retrieval task is performed symmetrically. The capability of uncoupling movements enables to perform, at the same time, different storage or retrieval tasks to minimize wasted times. For example, in the time necessary for operations (6) to (8) the shuttle is idle. In case another UL to be stored is already on the lift, the shuttle can deploy this time to go to the lift, load the waiting UL, and move back in front of the previous channel to join the satellite. Hence, the flexibility provided by an AVS/RS system is much higher than an AS/RS.

However, beside improved system reactivity, AVS/RS also exhibit reduced energy consumption, due to the deployment of lighter vehicles. The mass involved by AS/RS and AVS/RS is similar in the movements along the *y* direction (the whole transport system is moving in both the cases) and through the *z* axis (only the portion of system devoted to UL picking/retrieving is involved). Conversely, the deployment of shuttles into an AVS/RS allows to strongly reduce the mass involved in the movements through the *x* axis, which is usually the prevalent dimension of the rack.

4.2 Conceptual model

The behaviour of the AVS/RS system is modelled both for storage and retrieval cycles. The models, accordingly to the UML Activity Diagram formalism [3] are shown in Fig.3 and Fig.4.

When a storage request is input, the management system has to: (i) identify the best rack position to deposit the UL; (ii) evaluate its *x*, *y*, and *z* coordinates; (iii) recall the three conveyors to the input gate; (iv) use them to transport the UL to the selected location. Step (iii) is optional: in case the conveyors are not in the gate position, the lift moves to the position of the shuttle (*Ysh*), while the shuttle moves to the position of the satellite (*Xsa*). The satellite moves to the channel border and it joins the shuttle; they both move towards the floor edge, get on the lift and reach the picking position. As the UL is picked, the lift moves to the selected floor (coordinate *Y*), where it unloads the shuttle and the satellite. The two latter machines carry the item to the selected channel (at the coordinate *X*) and cell (coordinate *Z*).

When a retrieval request arrives (i.e. picking up an item from the position with coordinates X, Y and Z), if the shuttle is not on the right floor the management system has to send the lift to the shuttle floor, pick up the empty shuttle with the satellite and bring them to the right floor, where they reach the position of the item and take it back to the lift for the retrieval. If the shuttle is already at the right floor, it has to recall the satellite in case it is inside a channel, move it to the right channel to take the item.

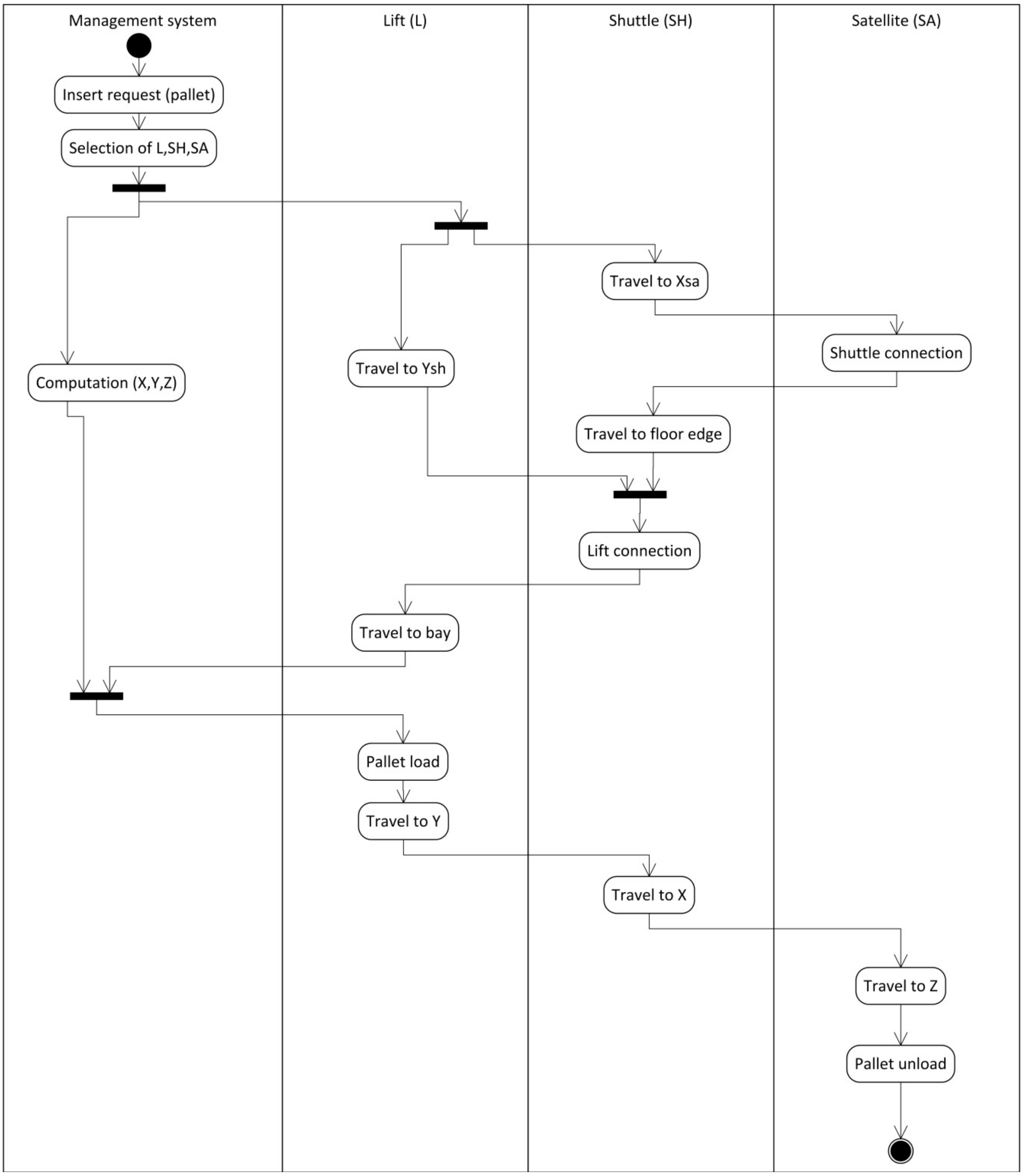

Fig.3. UML activity diagram of a storage mission.

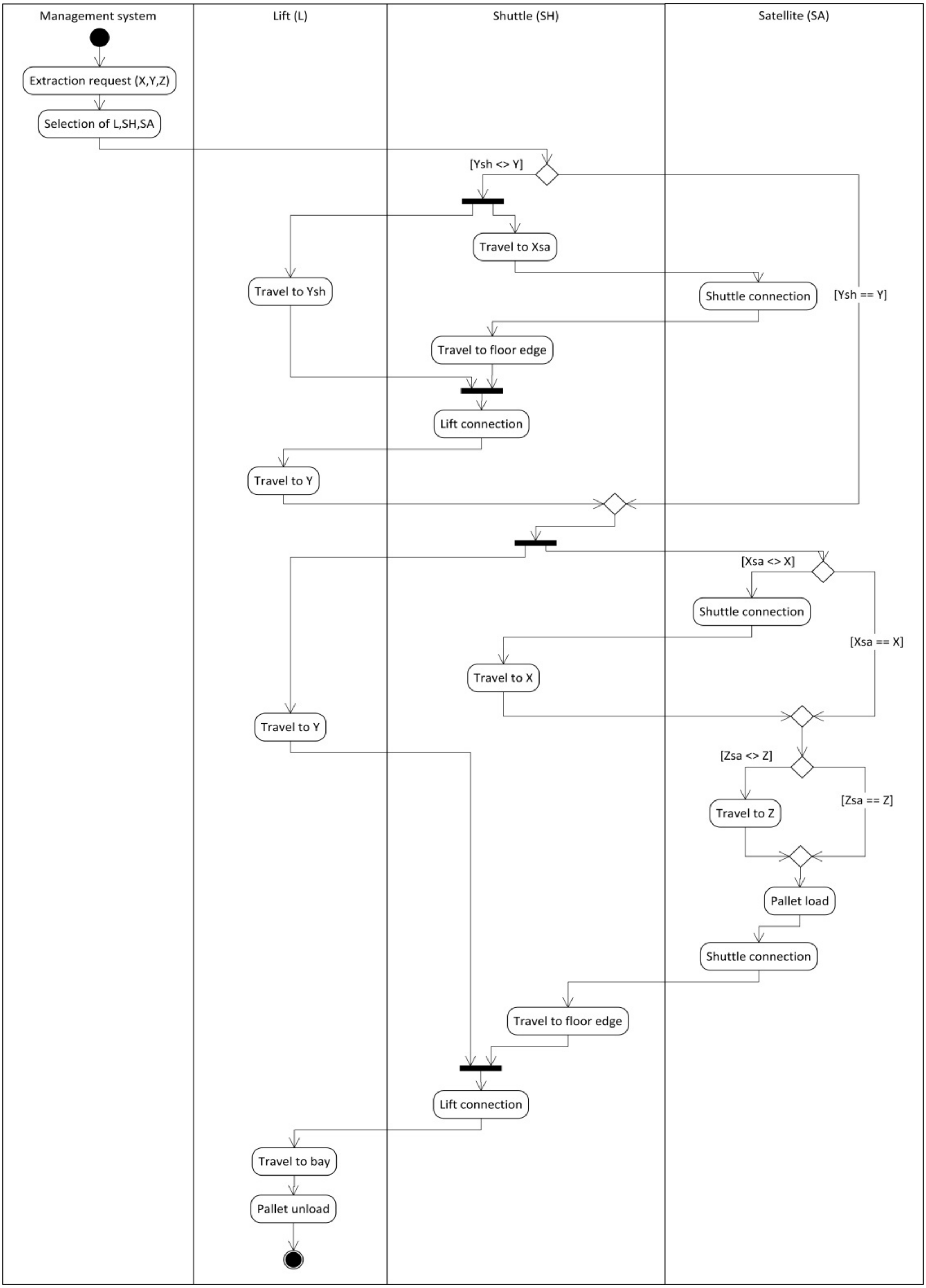

Fig.4. UML activity diagram of a retrieval mission.

5 Simulation model

To model the AVS/RS, the discrete-event simulation (DES) approach was chosen, since events changing the state of the system occur at a finite set of time instants, and between consecutive events no change in the system occur. This approach is opposed to time-continuous simulation, in which the system dynamics is continuously tracked over time and the state of the system is updated at fixed time steps. Hence, DES can jump in time from one event to the next; since discrete event simulations do not have to simulate every time instant, they typically run much faster than the corresponding continuous ones.

The AVS/RS system described in the previous section was implemented in the Rockwell Automation Arena simulation software [1][7]. The main elements forming an Arena models are the following:

- *entities*, i.e., objects moving within the system during the simulation causing the variation of the status of the system; entities can have associated *attributes*, to specify the characteristics and properties of individual units;
- *resources*, i.e., system components allocated to entities to perform operations and released after usage;
- *queues*, i.e., waiting areas where the movement of the entity is temporarily suspended while waiting for the resource to be free; the existence of a resource usually implies the exist of an associated queue;
- *global variables*, i.e., variables containing information describing the process states, used to allow the communication among the different subsystems of the model;
- *events*, i.e., actions that happens in a well-defined time and that changes the system status.

These elements are used to implement the simulation model of the AVS/RS system. In order to analyse the results of this system, several output variables were registered, particularly, for each type of conveyor, the starting and arrival coordinates of each movement, the cumulative handling active time (in which the conveyor is consuming energy) and not active one (when the conveyor is transported by another conveyor, so it does not directly consume energy).

6 Case study

The warehouse of an Italian company working in the paper industry was chosen as a case study. The rack consists of 6 tiers, each tier being made of 14 channels. In each channel, 8 storage positions are available. Thus, the total capacity of the warehouse is 672 storage positions.

The height of each tier is 1.58m. The width of each channel is 1.22m, while its length is 5.25m. The ULs managed by the company respect the EUR 6 standard pallet size [6].

A single loading and unloading position is present, and it is located 3.5m from the gate location.

The company manages three kinds of raw materials, which are used to produce two kinds of final products. The rack is also used to store the finished products - waiting for the delivery to customers. The first kind of final product needs only the third kind of raw material to be produced, while the second kind of final product requires the other two kinds of raw materials.

6.1 Simulation design

The Arena model described in the previous section was used to simulate the warehouse utilization. In order to allow the comparison with a traditional transport system, also a simulation model of a crane-based system was developed, by using the same elements described in Section 5.

In the simulation, the storage and retrieval requests follow the real behaviour of the warehouse and are set as follows:

- storage of RM-Type1, 1 lot of 16 ULs;
- storage of RM-Type2, 1 lot of 16 ULs;
- storage of RM-Type3, 1 lot of 16 ULs;
- retrieval of RM-Type3, 1 UL, inter-arrival time between two consecutive request follows an exponential random distribution with average time equal to 1 minute, limit to 1000 requests;
- storage of FP-Type1, 1UL, generated after 40 minutes from the extraction RM-Type3;
- retrieval of RM-Type1&RM-Type2, 1 UL per type, inter-arrival time between two requests follows an exponential random distribution with average time equal to 1 minute, limit to 1000 requests;
- storage of FP-Type2, 1UL, generated after 60 minutes from each retrieval of RM-Type1&RM-Type2;
- retrieval of FP-Type1, 7 ULs, inter-arrival between two entities follows an exponential random distribution with arrival rate 0.5 units/hour, limit to 1000 requests;

- retrieval of FP-Type2, 3 ULs, inter-arrival between two entities follows an exponential random distribution with arrival rate 0.5 units/hour, limit to 1000 requests.

The system was simulated for a total of 48h, and the total number of units loaded and unloaded was 157. The results are presented and compared in the following section.

6.2 Analysis of results

The results showing the distances and travel times of each conveyor of both the crane-based and the shuttle-based systems are reported in Table 1.

Table1. Simulation results.

Crane based system		
Conveyor	**Parameter**	**Value**
Stacker crane	Travel distance (with load)	2239,94m (54.7%)
	Travel time (with load)	0,3h (53,3%)
Satellite crane	Travel distance (with load)	1767,92m (58,1%)
	Travel time (with load)	0,21h (57,1%)
AVS/RS		
Conveyor	**Parameter**	**Value**
Lift	Travel distance (with load)	456,75m (54,1%)
	Travel time (with load)	0,25h (56%)
Shuttle	Travel distance (with load)	2199,08m (53,1%)
	Travel time (with load)	0,24h (54,2%)
Satellite	Travel distance (with load)	1668,86m (59,2%)
	Travel time (with load)	0,31h (58,1%)

Knowing the power consumption rate of each conveyor, it is possible to compare the energy consumption of the both systems. Table 2 reports the comparison of energy consumption along the *x* axis. Conversely, the lift energy consumption is similar to the *y*-component of the crane, as well as the energy consumption of the two kinds of satellites, since they have similar mass.

The highest energy saving occurs on the *x* axis, since the shuttle consumption is significantly lower than the *x* component of the crane.

Table2. Energy consumption along the X-axis.

	Crane	**Shuttle**
Travel distance with load	978,86m	1184,87m
Travel distance unload	810,64 m	1014,21 m
Travel time with load	0,09h	0,13h
Travel time unload	0,08h	0,11h
Power with load	18 kW	2 kW
Power without load	16 kW	1 kW
Energy with load	1,63 kWh	0,26 kWh
Energy without load	1,20 kWh	0,11 kWh
Total energy	*2,83 kWh*	*0,37 kWh*
Average energy per UL	*0.018 kWh*	*0.002 kWh*

7 Conclusion

In this paper we proposed a methodology to model and simulate the behaviour of autonomous vehicle storage and retrieval systems, and extract data concerning the energy consumption of the system. To highlight the energy savings provided by AVS/RS and to underline the importance of defining a methodology to evaluate its energy consumption, a comparison with a traditional crane-based system has been performed. The methodology has been applied to an industrial case-study in which an AVS/RS has already been implemented. The purpose of the tool presented in this paper is twofold. First, it can be useful for designers and marketing operators, to provide a potential customer with quantitative measures for energy consumption of the automation system. Second, this tool can be used to forecast the energy need of an already existing system in different scenarios.

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