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## The study on the automated storage and retrieval system dependability

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### Highlights

- The problem of ARS dependability is discussed for the first time.
- New contribution to discussion on logistics systems dependability is provided.
- New factors influencing the dependability of ASRS are gathered.
- A new simulation model in FlexSim for ASRS dependability analyse is provided.

### Abstract

Automated storage systems have become the basis of warehouse logistics. The article presents a discussion on the reliability and dependability of Automated Storage and Retrieval Systems (ASRS), which are perceived as solutions with high technical reliability. Still, their role in the dependability of the entire warehouse system is to be discussed. The concepts of reliability and dependability in logistics systems like ASRS are defined, and a literature review in this area is presented. On this basis, the factors influencing the dependability of ASRS are discussed in a way not present in the discussion on this topic so far. Then, the ASRS simulation model (based on FlexSim simulation software) is presented. The model tests the influence of ASRS configuration and assigned resources on the dependability of the warehouse as a master system. The summary includes observations on defining the reliability and dependability of ASRS.

### Keywords

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Automated Storage and Retrieval System, ASRS, niezawodność, FlexSim, symulacja, magazynowanie.

## 1. Introduction

Automated storage and retrieval systems (ASRS) are the key components of automated warehouse facilities of high throughput and storage capacity. ASRSs are the automatic solutions around which the warehouse process is built-in or which directly feed high-efficient order-picking or production systems. ASRS defines the physical aspects of the facility, is often an integral part of the picking system, and creates the buffer capacity of the warehouse. The spectrum of ASRS technological solutions and variants is vast. However, the set of common features and mechanisms can be distinguished and put into its definition. ASRSs revolutionize warehousing since the 1970s. One of the most important features of these systems deciding about its usability is the reliability or dependability of this technology.

The system's reliability is a component of its dependability, defined as the ability to perform as and when required [17]. Dependability is then a holistic measure of availability, reliability, maintainability, and maintenance support provided. In some cases, it covers durability, safety, and security [17] to describe how users can trust the services within a time period. Since the ASRS is not an isolated system but a part of the warehousing facility, it should be discussed in the broad context of its dependability (see section 3 for discussion on dependability). In contrast, its dependability is not researched, while reliability research is scarce.

ASRSs are perceived dependable, especially when appropriate maintenance is provided, the system is well configured, and support-

ed by solutions that guarantee the high quality of handled units [24, 40, 48]. But the perception about the dependability of ASRS is a bit warped by the users and developers. In most cases, it refers to the system's uptime (see [24]) and downtime as it results from the definition of reliability. Still, when investigated deeper, the ASRS reliability (or dependability) is rarely explored and usually replaced in the literature and commercial offers by the performance. Performance determines the ability to perform the logistics tasks of the entire ASRS. Usually, it is assumed that it is not significantly affected by the failure of a particular system component so that dependability can be (to some extent) extrapolated by performance bypassing the engineering correctness. Replacing the dependability with the performance requires (or allows for) significant simplifications in research and development, and most important – in selling. When dependability is removed, the performance is easy to measure. But replacing dependability with performance features requires a set of simplifying assumptions that the material flow in ASRS is uniform and homogeneous (without family grouping or selectivity), no slotting mechanisms are used, and the access to all rack aisles is not disturbed by failures or congestion on feeding conveyor system. With this simplified approach, it is possible to express the transition of ASRS to a state of partial unfitness through reduced performance. This approach is applicable only in general considerations, but applied to the operational level can result in process errors in advanced storage systems. These errors will be the result of limited access to selected product or family groups in the

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ASRS, which will disturb the schedule of the warehouse process and shipments (cf. Kłodawski et al. [23] and Jacyna-Golda et al. [21]).

A review of market solutions and currently published scientific studies on the Automated Storage and Retrieval Systems indicates that ASRS dependability is discussed in a simplified manner or only concerns technical functioning. Meanwhile, ASRSs are built into the warehouse process. Their functioning depends not only on their features but also on external conditions imposed by the supplies, order picking organization, schedule, and shipments. The assessment of ASRS dependability needs to consider the organization of the material flows resulting in an uneven load on the ASRS components, their role in the warehouse process, and the effects of a potential shutdown.

The author proposes the simulation study of the dependability of typical ASRS system in the FlexSim environment. The study bases not only on the technical features of the system but also its configuration (different number of corridors to stacker cranes, conveyor system, transferring module), potential damage to working and conveying elements, the condition of material units, warehouse activity profiling, and assortment distribution. The research will determine the impact of the above-mentioned factors on the dependability and performance of ASRS and the value of OTIFEF (on-time, in-full, error-free parameter) embracing logistics time measures and timely execution of warehouse tasks.

The remainder of this article is as follows. Section 2. provides the literature review on the ASRS reliability or dependability in the context of warehouse processes. The 3. section discusses the problem of dependability in logistics systems and in ASRSs and the areas of dependability that should be investigated for a complete picture of the problem. The 4. section contains the assumptions and measures for the simulation experiments described in the section 5. Section 6. is for ASRS dependability simulation and discussion of the results. The article is closed by the discussion of results and conclusions.

## 2. Literature review on dependability of automated storage and retrieval systems

The literature on automated storage and retrieval systems is quite extensive and multi-threaded due to the great importance of these solutions for automated warehouse facilities, but reliability and especially dependability of ASRS as complete systems have hardly been studied in academic literature. The literature can be divided into several cross-sectional research areas, within which analytical, experimental, implementation and review works are present. Despite the fact that reliability is a key technical parameter of industrial installations, this issue is not a popular topic of research in warehousing technology at all. Most of the publications on ASRS, usually in the Introduction section, indicate the high reliability of these solutions, but apart from a single word at the beginning, it is not referred to further.

Nowakowski [36, 38, 37], Werbińska-Wojciechowska [46, 47], Bukowski and Feliks [8, 7], or Quigley and Walls [39] present general considerations on the reliability of logistics systems and complex supply chains on the overall level. These publications provide a certain basis for defining the reliability of elements of logistics systems, including warehouse systems, but are not focused on details of technology and technical solutions. The advantage of these studies is the consolidation of the ASRS dependability issue in the science of the reliability of logistics systems. Numerous studies related to problems of dependability in logistics [3, 4, 21] are focused on the reduced efficiency of the system. Sohn and Choi [43] analyse issues related to managing a supply chain in relation to the reliability of subsequent stages – logistic processes, including warehouse processes. They emphasise the need to include reliability issues already at the stage of designing, but their considerations are on the general level. Jacyna and Semenov [19] discuss the topic from the perspective of information uncertainty. Szaciłło et al. [44] touch the problems of reliability applied to railway systems.

The crucial feature of dependability of supply chain, warehouse or ASRS itself is the determination of the faultless probability [22]. This is difficult for structures like ASRSs, in the case of which classical damage causing lack of fitness of use is not applicable.

The problem of the dependability of warehouse facilities and their elements is discussed in general by Lewczuk [27] and Jacyna and Lewczuk [22]. They define the reliability framework for warehouse facilities and their components that may be useful for the assessment of ASRS systems. The authors discuss the OTIFEF index (on-time, in-full, error-free) that can be used to evaluate ASRS similarly as to complete warehouse since this bodies have common definition points. Neo et al. [34] analyse how the limited warehouse technical efficiency influences criteria of its operation assessment. Werbińska-Wojciechowska [47] presents a model of maintaining technical systems on the example of logistic systems using the concept of time delays. Author points to the effectiveness of the devised model on the example of internal transport devices. In other work Werbińska-Wojciechowska [46] discusses the integration of the system executing the task with the supportive system like the maintenance system.

Focusing on the problem of Automated Storage and Retrieval Systems can already see that it reached the cross-sectional publications presenting the state of knowledge about it. Roodbergen and Vis [41], Gagliardi, Renaud, and Ruiz [14], and Azadeh et al. [2] provided a comprehensive literature review on automatic technologies in warehousing. Still, the reliability is mentioned only without discussion, while the dependability is not mentioned at all. Marchet et al. [32] propose a framework for developing and designing some versions of automated storage and retrieval systems but address mostly the system performance and don't mention the reliability or dependability. The majority of publications deal indirectly with the ASRS dependability and its components. The situation when the high reliability of ASRS is called by the authors in the introduction but never referred to in the text is common and applies to all listed publications. This is typical for research on ASRS, which focuses mostly on time efficiency and performance.

Two important studies relating directly to the reliability of the ASRS were conducted by the Material Handling Industry of America and reported by Kluwec in a White Paper: Reliability of Automated Storage/Retrieval Systems (ASRS) [24]. Studies investigated systems in size from 1 to 25 aisles, with an average size being 7,4 aisles (57% of systems had only 1 to 5 aisles). Both studies confirmed the expected high reliability of these solutions, taking the uncertainty out of a long-standing question about ASRS performance. The top concerns of users formulated in the White Paper are downtime (unreliability), potential low flexibility, sunk costs, customer service, implementation, and maintenance issues. Perceptions of low reliability may be related to the experience during the trying period (about three months), even though new ASRS in most cases have fairly high uptime and full performance gain within the first year. The survey shows that uptime increases insignificantly in the first year of operation from 94.05% to 96.22%, and after ten years of operation is decreasing, but still not significantly. The average uptime for the group of respondents was 97.34% during the full performance period [24].

The White Paper [24] reports that insertion/extraction equipment posed the greatest problems for almost 40% of respondents, and the control software was in second place but only for the first three years. The report shows that fast recovery is crucial for minimizing downtime. To that end, the warehouse must have quick access to skilled personnel and immediate availability of needed repair parts. The scheduled maintenance did not have a significant impact on overall uptime while the majority of system downtime was unexpected.

An important factor of ASRS reliability is presented by Ripple [40], which calls pallet/load condition a cause of ASRS faults. These faults are excluded from availability calculations, similarly to the time between the fault occurrence and addressing the problem by personnel. Ripple concludes that equipment failures are quite rare, and when

totes or high-quality pallets are used, the reliability rate can exceed 99.98% or 99.99%.

Methods aimed at researching and increasing the reliability of warehouses use a variety of techniques. Chung, Chan and Chan [9] propose genetic algorithms for maximizing handling reliability of distribution centers. Fazlollahtabar and Saidi-Mehrabad [12] use multi-objective methods for assessing reliability of AGV systems in a multiple AGV jobshop manufacturing system with fuzzy logic. The methods are applied to ASRS exactly as tool presented by Jacyna, Wasiak and Bobiński [19] and Jachimowski et al. [18]. The tool for integrated modelling and simulation of material handling and storage solutions can simulate ASRS in warehouse and state its reliability-related parameters present in the databases for the tool.

An interesting approach to modelling of reliability of warehouse automatic systems was presented by Yan, Dunnett, and Jackson [49], who investigated the reliability of automated guided vehicles system through Failure Modes Effects and Criticality Analysis and then the Fault Tree Analysis (FTA) to model the causes of phase failure. The authors focus on mechanical and constructional aspects of the system and not on the organization or surroundings influence, but their approach can be developed with these factors.

Yang et al. [50] research the problem of goods location assignment in automatic warehouses. Ekren et al. [11] add the element of class-based storage policy to automatic storage and retrieval systems. Both studies prove that proper assignment function for optimizing the cargo space and optimizing the stacker crane operation route can improve overall operating efficiency, which is a part of uptime rationalization. A similar problem, but formulated concerning order-picking, is presented by Atmaca and Ozturk [1]. They show that the appropriate storage assignment in ASRS impacts picking efficiency, thus discussing dependability of ASRS fragmentarily as an element of a larger system. The class-based storage allocation in ASRS was also the main thread of work [30] by Manzini, Gamberi, and Regattieri. Their multi-parametric dynamic model of a product-to-picker assignment and simulation tool confirmed that ASRS should be considered an important chain in the warehousing process.

Liu et al. [28] represent a wide group of authors focusing on travel time models for different automated storage and retrieval systems versions which are important for reliability assessment. Liu et al. provided an extended comparison of models present in the literature and look for better system efficiency, which forms performance characteristics and influences the reliability expressed through uptime function. The models are not very different than those presented by Sarker and Babu [42] in 1995. Boysen and Stephan [5] present a survey on scheduling methods applied to ASRS cranes work organization, like the one presented by Hachemi and Besombes [15] or Zhang et al. [51]. Different approaches are used in these papers, like statistical modelling [44], analytical modelling [31, 26], simulation [25, 10, 35], model predictive control [33], and optimization of all types [13, 50] including evolution algorithms [6]. These studies aim to model and optimise ASRS cycle time, a base for performance analysis, and touch on the problem of material assignment and its influence on the operation. Authors combine elements of spatial configuration, handling equipment, task interleaving, and material assignment but do not touch the dependability issues.

The literature review showed that the reliability and dependability of ASRS are not raised in the literature. This may be the extent and multifactorial nature of this problem and the inability to indicate unambiguous guidelines regarding the dependability, which depends on several factors external to ASRS. The literature does not discuss the impact of the configuration of ASRS racks and conveyors on dependability and the impact of material assignment or tasks resulting from customer orders.

### 3. The aspects of ASRS dependability

#### 3.1. Dependability of logistics systems

The reliability of the systems is a component of its *dependability* as it results from the definition presented in [17]. This is especially important for logistics systems like ASRS. ASRS is considered a logistics system since it has the buffering capacity, material handling components to transform the material flow, and input and output defined by the qualitative and quantitative material flow structures. In consequence, dependability is a better way to describe its global features than the commonly used reliability. Dependability is a set of features, including readiness, reliability, maintainability, and maintenance support for the system [17, 22]. Nowakowski [38] defines the dependability of any logistics system as a measure of task implementation over time, which may be compared to the reliability of the technical system. He states that no equivalent of maintainability or reliability of the technical system has been formulated for logistics systems of large scale. Still, both terms can be applied to the ASRS when the assumptions are made, especially in a colloquial sense. Nowakowski also defines the dependability of the system through its availability. In technical science, the availability of a recoverable object describes the probability of its proper functioning in a specific moment [22]. Still, the ASRS's availability can be defined as the probability of finding a piece of equipment at any given time during the period of operation, in a state which will allow a requested operation to be carried out correctly and without malfunction [40]. It depends on the availability of resources; cranes, transfers, conveyors, empty storage locations, or required material in the rack (see [46] and *Logistics Management Institute* definitions).

Dependability is a factor difficult to measure considered in designing logistic and warehouse systems. It can be indirectly measured by the disturbances and reduction of the system's performance [16, 37]. The additional measurements are created to reflect the flexibility of the system – its ability to adapt and overcome the difficulties [22], which can be interpreted as the possibility to reconfigure or use other pieces of the system to bypass those unavailable or damaged for task completion.

#### 3.2. Dependability of ASRS

The dependability of ASRS is briefly discussed in the literature, and, as the literature query shows, it is also not an element of the material handling systems design procedure. Both the designers of automatic solutions and a few scientific works refer to the reliability of ASRS, which is based on the failure rate of technical devices that make up the system. Since such a failure rate, especially with appropriate preventive service, is very small, this factor is not considered in designing and is often used as a marketing argument. The rightness of this approach is justified by the industry information materials. Meanwhile, in our opinion, the dependability of ASRS should be treated much more broadly since the system is an expensive component of the warehouse facility and cannot operate separately. This category includes technical reliability of components, condition of cargo units, material assignment (slotting), spatial configuration of the rack system and handling devices, configuration of conveyor system, automation logics, and adaptive algorithms. When these factors are mixed into one with the structure of the material flow, then the system's dependability can be assessed.

For this article, the scope of ASRS solutions was limited to fully automated, combined systems of storage and internal transport consisting of stationary racks (single or double depth fixed-aisle system), stacker cranes equipped with a single or multi-seat fork carriage, a system of conveyors delivering and retrieving units from delivery and collection points, a system of sensors and identification devices, and possible connecting elements. Cranes use the single or combined transport cycles according to the adopted work logic. Carousels, vertical lift modules, and other forms of ASRS are excluded from this

study. A system defined in this way can be treated as a technical system characterized by certain reliability and dependability in the face of a logistic task.

The dependability of the automated storage and retrieval system should be considered concerning the following technological and organizational issues constituting the grounds for the problem formulation:

1. Availability of handling elements of ASRS (stacker cranes, conveyor systems, sensor systems, control systems).
2. Technical condition of ASRS devices and components (drives, control modules, construction frames, power supply).
3. Quality (condition) of handled logistic units (pallets, plastic containers, boxes) and its influence on handling processes.
4. Slotting patterns resulting from warehouse activity profiling and conditioning the flow congestion.
5. Configuration of structural components of ASRS (racking system, aisles, number of cranes, types of fork carriage, crane transfers).
6. Logic of operation.
7. Efficiency of low-level components of ASRS.
8. Information flow irregularities.
9. Material flow irregularities and accumulations resulting from orders structure.

Increased dependability of technical systems requires installed resources that potentially increase its cost or reduce its performance. So, the system's dependability can be influenced by its configuration and scale. Common methods for governing the dependability of the ASRS are as follows:

1. Technological redundancy:
  - Increasing the number of stacker cranes leads to an increased number of working aisles at the expense of the aisles' length and/or height.
  - Permanent assignment of stacker cranes to the aisles or using the transfer bridges and sliding mechanism to move the cranes between the corridors.
  - Use of multi-unit fork carriages.
  - Using single-deep racking systems instead of the double- or more deep lanes.
  - Universal and reconfigurable conveyor systems with redundant passages between main transport routes.
  - Doubled feeding system.
2. Material handling support systems:
  - The restrictive material carriers' quality policy (pallets, containers, boxes) when using units exchanged within the supply chain.
  - Advanced sensors systems detecting units bent out of shape or damaged.
  - Dedicated plastic containers or trays for material handling.
3. Slotting techniques:
  - Representing most popular or key SKUs in more than one aisle.
  - Functional division of the ASRS area into independent warehouse instances (two or more) in which all material groups (family groups) are independently represented.
  - Applying standard material assignment procedures based on warehouse activity profiling.
4. ASRS's place in the material flow organization:
  - Reduction of material flows pile up against the ASRS by rational work plan.
  - Equal load on individual working aisles (related to slotting).
  - Rationalization of the ASRS work schedule.

Redundancy always must be confronted with the effectiveness of the system. Typical ASRS solutions use one stacker crane in one aisle, so the number of stacker cranes equals the number of aisles. Such a configuration, with high relative technical reliability of devices, gives satisfactory results, simplifies the system, reduces the space require-

ment due to the lack of transfer mechanisms, and shortens the average operation time.

Multi-unit fork carriage enables task interleaving and increases system efficiency while maintaining partial efficiency of the stacker crane in non-critical damage to the handling device. The fork carriage is perceived to be quite vulnerable to damage, especially when interacting with a damaged load unit.

The use of single-deep racks ensures full stock selectivity in the ASRS area, which may be important in case of damage to the handling elements. It leads to a significant increase in the number of stacker cranes and space, but in case of failure of one of the devices, the cranes in other working aisles have access to the units of required material. Of course, the use of such a configuration requires an economic calculation of profitability. It is also strictly dependent on the number of SKUs and the number of material groups to be handled.

Conveyor systems are the second key component of ASRS supplying and receiving units from the ASRS. Conveyors can be configured in various ways. In most cases, the mainline system performs material flow, and the input and output separation is realized directly in front of the stacker cranes. To increase the reliability of the conveyor system, it is necessary to introduce the possibility of changing the flow direction of the selected conveyor sections (quite difficult to implement) and to place additional connections that will bypass damaged or congested places on the network. For warehouse process reasons, separated supply and receiving systems are used, as well as duplicated systems.

Practitioners report that potential failures in ASRS are often associated with poorly formed material units that lose stability, shape, or structural integrity during handling. This causes blocking of units in conveyor systems, stacker cranes and racks, damage to the installation, and requires operator intervention. Advanced sensor systems built into the conveyor network detect and withdraw damaged units to avoid problems, or manual quality control stations are used. Such systems increase the cost of installation but eliminate downtime caused by material quality problems. Another solution in this area is dedicated additional material carriers like a doubled pallet, plastic container, or tray, which are easily operable by the system but require additional handling and space.

The last of the essential techniques for increasing the dependability of ASRS is tailored slotting. In ASRS, apart from failures in power or control systems, single installation elements are damaged, making one of the working cranes inoperable. The other ones are functional. For this reason, it is important to represent all the key products in more than one place in the ASRS. Of course, solutions in this area must consider the number and type of products and warehouse activity profiles.

ASRS's place in the material flow organization may also impact the dependability of its work. The uneven workload of the system may temporarily exceed the efficiency of individual working aisles and conveyor systems supplying them. This, in turn, will cause congestion and, in the case of simplified control algorithms, may interfere with the operation of other ASRS elements. It is also important to maximize the available work time of the ASRS, which results from the schedule of the warehouse process.

#### 4. ASRS dependability measures

The dependability of ASRS cannot be measured without the context of the warehouse system in which it works. Synthetic measures should be used to address the above-mentioned factors holistically and at the same time fit into the superior assessment of the warehouse process through OTIFEF (On-time, in-full, error-free) or POR (Perfect Order Rate). The OTIFEF measure is described in detail in [22] and usually if formulated separately for inbound and outbound processes since these processes have a little correlation in short time (daily regime). Still, it can be formulated as the probability of handling all periodical (daily) supplies and shipments on time and free of qualitative and quantitative errors or the percent of all supplies and

shipments handled in a standard way and in line with perfect-order requirements [23]. This measure can be reduced to the needs of the ASRS assessment to the time-related component since qualitative and quantitative errors are not generic to the automatic solutions.

The impact of ASRS operation on the OTIFEF of the entire warehouse can be significant, especially when it feeds the material-to-human picking systems (wave picking) or direct shipments in the same-business day model. A delay in delivery of a single sku delays the execution of the entire order. In extreme cases, the order will be shipped incomplete if ASRS cannot deliver the material before the time window pass. This is strongly related to the warehouse process scheduling problem (as referred in [28]):

$$OTIFEF = P_{OT} \cdot P_{IF} \cdot P_{EF} \quad (1)$$

where:  $P_{OT}$ ,  $P_{IF}$ , and  $P_{EF}$  are the probability of handling all planned shipments on-time, in-full, and with no errors respectively.

To evaluate the  $P_{OT}$  component for ASRS the relation between resources  $R$  put into process realization and volume of orders must be found. Efficient resources assigned to ASRS will increase plausibility of immediate put-away and retrieval – dependability but cost more. Figure 1 shows the exemplary warehouse process in which ASRS is responsible for replenishing the picking area and directly outbound area with materials under the customer's orders. Distribution of resources constituting the dependability of ASRS will then influence the total order realization time  $t_3$ :

$$t_3 = \max\{E(T_{RP},(R_{RP})), E(T_p,(R_p)), E(T_{RS},(R_{RS})), E(T_{SCP},(R_{SCP})), E(T_L,(R_L))\} \quad (2)$$

where:

- $E(T_{RP},(R_{RP}))$  – expected time of retrieving materials from ASRS with resources  $R_{RP}$ ,
- $E(T_p,(R_p))$  – expected time of picking in picking area with resources  $R_p$ ,
- $E(T_{RS},(R_{RS}))$  – expected time of retrieving from ASRS for direct shipment with resources  $R_{RS}$ ,
- $E(T_{SCP},(R_{SCP}))$  – expected time of sorting, consolidation and packing with resources  $R_{SCP}$ ,
- $E(T_L,(R_L))$  – expected time of loading materials with resources  $R_L$ ,

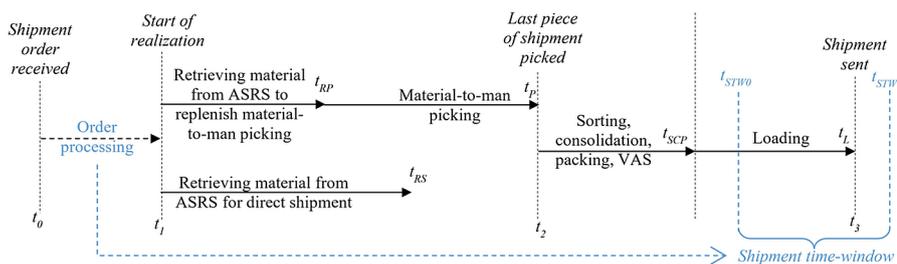


Fig. 1. Warehousing process using ASRS for order realization

In Figure 1, only the outbound processes are shown. In the analysed system, inbound processes requiring the same resources additionally load the ASRS. However, they are not directly responsible for the perfect-order-rate perceived by the client and then the dependability. Thus, inbound processes will affect the execution time of outbound processes, which will be considered in the simulation model.

Resources  $R$  reduced to their monetary value include ASRS equipment, mainly stacker cranes, which impact the productivity of the system. Resources influence directly handling potential (performance) and then the dependability of the system:

$$R = R_{RP} + R_p + R_{RS} + R_{SCP} + R_L$$

The above equation includes all resources in the analysed warehouse process. Still, if the resources not assigned to the ASRS are reduced to constant values, then it is possible to control the dependability of the warehousing system through the ASRS configuration. Then two tangled general criteria functions are used:

$$t_3 - t_1 \rightarrow \min \quad (3)$$

$$R \rightarrow \min \quad (4)$$

bounded by the constrain:

$$t_{STW0} \leq t_3 \leq t_{STW1} \quad (5)$$

where  $t_{STW0}$  and  $t_{STW1}$  are the start and the end moments of shipment time-window resulting from external to warehouse process conditions.

Therefore, the operation time is the main factor influencing the dependability of ASRS and, therefore, will be the basic factor tested in the simulation experiment.

## 5. Assumptions for the simulation experiment

The experiments were carried out in the simulation model prepared in *FlexSim* – 3D simulation modeling and analysis software (v. 21.2.0). Prepared model allows for simulation of single-deep ASRS of any configuration and with any workload.

Model uses 1 to 10 work aisles with fixed or transferred cranes, single-deep racking system, two in/out conveyor systems for separated or combined delivery and retrieval, MTBF and MTTR functions for all elements and range of slotting patters (Figures 2 and 3).

The configuration of the experimental system is based on:

- 20 single-deep rack walls (20 bays, 12 levels, 3 slots per rack cell) for 1200x800 EUR1 pallet units with a maximum height of 1200 mm,
- 1 to 10 pallet cranes ( $V^{\max} = 1,6$  m / s, acceleration / deceleration  $A = 0,3$  m/s<sup>2</sup>),
- 1 transfer for cranes ( $V^{\max} = 1$  m/s, acceleration / deceleration  $A = 0,2$  m/s<sup>2</sup>),

- upper conveyor system (only for optional separated collection,  $V^{\max} = 1$ m/s),
- bottom conveyor system (collection and delivery,  $V^{\max} = 1$  m/s).

Stacker cranes are assigned to working aisles, but the activated stacker cranes are less than 10, the transfer moves them between the working aisles, searching for the nearest stacker crane at idle. The system of conveyors delivering and collecting units from racks is either integrated or separated.

The conveyor system allows the circulation of units addressed into the racks. If it is not possible for the unit to enter the conveyor segment supplying a given rack, the unit will perform a maximum of 3 loops, and after the third attempt, it will leave the system unhandled.

The examined ASRS supplies the dynamic order picking system with required materials and deposits the units leaving this system. It is also used to buffer homogeneous units directly from delivery and releases units outgoing directly to customers. Therefore, delays in the put-away or retrieval of units by ASRS will impact the remaining components of the warehouse process and thus on OTIFEF.

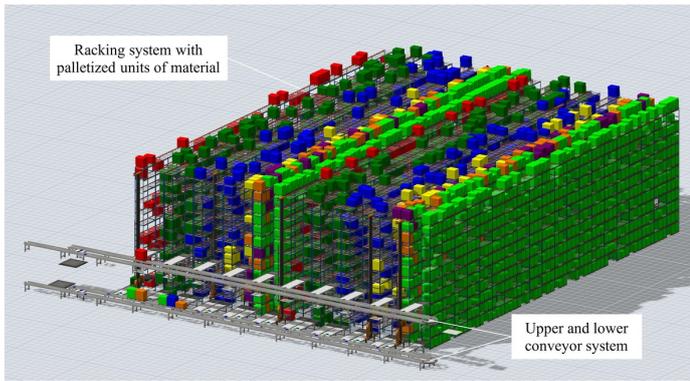


Fig. 2. General view of the ASRS model in operation

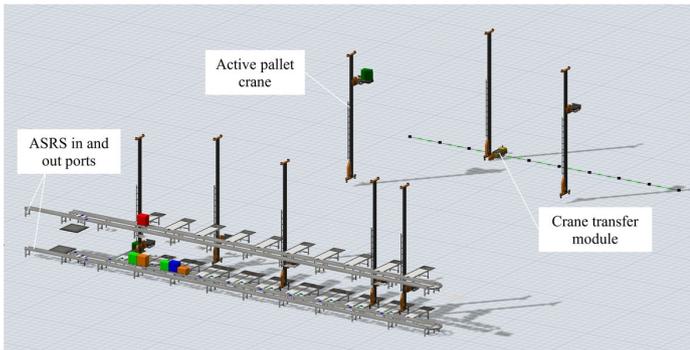


Fig. 3. General view of the pallet cranes in operation

According to the ABC principle, the material in the system was divided into 7 material groups with different turnover and initial stock. The system operates 16 hours a day, while the schedules for deliveries retrievals assume an uneven flow at selected hours (Table 1). It was assumed that the system realizes on average 300 orders of 6 pallets (SKUs) each. Initial stock represents the material structure in line with the distribution of material groups and their parameters (Table 2).

Table 1. Material flow schedule

Hours	% of daily delivery	% of daily retrieval
8.00 – 9.00 <sup>)</sup>	5	1
9.00 – 10.00	5	7
10.00 – 11.00	5	7
11.00 – 12.00	10	7
12.00 – 13.00	20	7
13.00 – 14.00	15	7
14.00 – 15.00	10	10
15.00 – 16.00	10	10
16.00 – 17.00	1	10
17.00 – 18.00	5	8
18.00 – 19.00	5	8
19.00 – 20.00	3	8
20.00 – 21.00	2	5
21.00 – 22.00	2	5
22.00 – 23.00	1	0
23.00 – 24.00	1	0

<sup>)</sup> Intervals are rounded to whole hours.

Table 2. Simulation scenarios

Group of material	% of stock	% of flow (% of total number of units)	Number of SKUs in the group	Initial stock [units]
A	1	10	10	239
B	4	25	40	998
C	10	30	100	813
D	10	10	100	389
E	10	7	100	595
F	10	7	100	345
G	55	11	550	1921

All elements of equipment are described by reliability functions: Mean time between failures (MTBF) and Mean time to repair (MTTR) as it results from [24] (Table 3).

To illustrate the aspects of ASRS dependability discussed above, the 160 simulation runs for 40 scenarios were done. The spectrum of scenarios is based on a changing number of active cranes (2, 5, 7, and 10, respectively), the use of a separate entry and exit system, and five variants of product slotting patterns (Figure 4).

1. Random location (SP1).
2. Volume-based product location along work aisles (SP2).
3. Volume-based left-to-right product location (SP3).
4. Two separated storage areas with a random location (SP4).
5. Two separated storage areas with volume-based left-to-right product location (SP5).

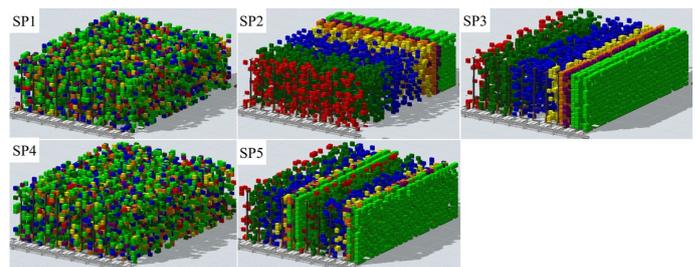


Fig. 4. Stock visualization for different slotting patterns (SP)

Selected slotting patterns will reveal the bottlenecks of the system affecting its actual dependability.

## 6. ASRS dependability simulation

The simulation was presented in a one-day and monthly regime to show the impact of potential damage to the operating components on the system's dependability. During the simulation, the basic parameters determining ASRS usability in the warehouse process were examined: the average put-away time (Table 4 and Figure 5) and the

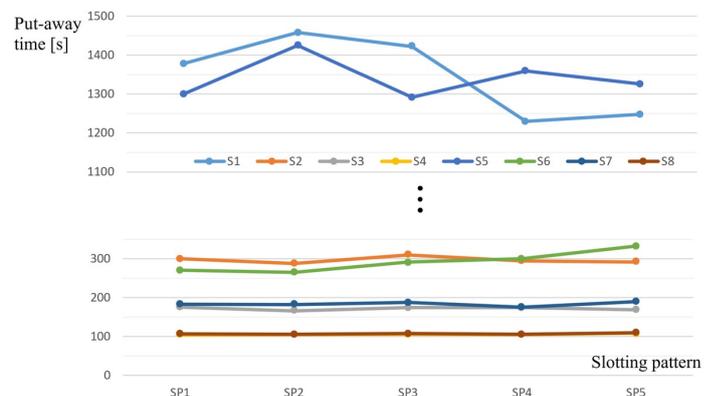


Fig. 5. Mean (95% confidence interval) of average put-away time

Table 3. Statistical distributions of MTBF and MTTR

Type of equipment	Down time [s]	Up time [s] <sup>1)</sup>
Cranes	Uniform (between 1800 and 28800)	Exponential (location 14400, scale 5400000)
Cranes control system	Uniform (between 900 and 57600.)	Exponential (location 403202, scale 1612800)
Transfer	Uniform (between 1800 and 5400)	Exponential (location 52200, scale 1607400)
Lower conveyor set	Uniform (between 1800 and 5400)	Exponential (location 52200, scale 1607400)
Upper conveyor set	Uniform (between 1800 and 5400)	Exponential (location 52200, scale 1607400)

<sup>1)</sup> First failure time equal to up time distribution.

Table 4. Mean (95% confidence interval) of average put-away time [s]

Scenario	No of cranes	Upper conveyors	SP1	SP2	SP3	SP4	SP5
S1	2	Not used	1378,16 ± 105,74	1458,42 ± 210,63	1422,21 ± 314,82	1229,70 ± 206,57	1248,46 ± 161,95
S2	5	Not used	299,77 ± 63,37	287,63 ± 24,97	309,93 ± 81,66	294,22 ± 40,43	291,53 ± 40,65
S3	7	Not used	175,16 ± 25,62	166,30 ± 16,59	174,81 ± 14,64	174,17 ± 16,31	168,62 ± 11,72
S4	10	Not used	104,31 ± 3,50	104,70 ± 6,27	105,67 ± 2,73	104,76 ± 2,69	108,34 ± 2,80
S5	2	Used	1300,00 ± 248,10	1424,91 ± 538,32	1291,54 ± 166,68	1359,02 ± 123,95	1325,65 ± 146,61
S6	5	Used	270,50 ± 22,33	264,58 ± 17,18	291,12 ± 46,92	300,37 ± 85,13	332,45 ± 71,26
S7	7	Used	183,13 ± 28,61	182,47 ± 19,90	188,11 ± 12,80	175,65 ± 22,92	189,79 ± 7,01
S8	10	Used	106,99 ± 3,49	106,28 ± 4,86	107,45 ± 2,88	106,42 ± 2,57	110,13 ± 3,79

Table 5. Mean (95% confidence interval) of average retrieval time [s]

Scenario	No of cranes	Upper conveyors	SP1	SP2	SP3	SP4	SP5
S1	2	Not used	3753,93 ± 1714,11	2759,37 ± 1555,10	3357,70 ± 1502,94	6315,52 ± 5374,42	4713,04 ± 2392,40
S2	5	Not used	1214,31 ± 764,99	1261,35 ± 689,56	1102,20 ± 884,82	1259,55 ± 711,66	1241,70 ± 770,32
S3	7	Not used	333,29 ± 43,13	305,87 ± 89,77	373,19 ± 19,95	352,29 ± 70,50	303,33 ± 92,11
S4	10	Not used	174,12 ± 2,41	172,93 ± 3,37	177,72 ± 5,31	176,09 ± 3,39	175,61 ± 2,86
S5	2	Used	8512,85 ± 5651,78	11458,12 ± 7652,40	8675,32 ± 4258,15	7279,63 ± 3787,02	8321,44 ± 4176,63
S6	5	Used	812,99 ± 503,59	711,26 ± 559,23	1094,83 ± 1042,79	1091,60 ± 945,93	1529,83 ± 596,95
S7	7	Used	336,96 ± 52,08	357,69 ± 54,87	354,88 ± 69,20	325,58 ± 118,36	337,84 ± 73,45
S8	10	Used	174,90 ± 2,91	173,29 ± 3,20	178,49 ± 5,24	176,93 ± 3,06	176,57 ± 2,80

average retrieval time (Table 5 and Figure 6), the number of units handled in a given time, and the number of delayed units (Table 6).

The above data present dependencies between ASRS configuration (assigned resources *R*) and slotting rules at constant loads and device reliability functions. The most important measure for the ASRS dependability is the retrieval and depositing time (Figures 5 and 6). These parameters determine the time component of the material release process, which is crucial for the Perfect Order Rate index, and thus for the quality of customer service (conf. [21]).

Following the assumptions given in point X, the unit service time in the ASRS depends on the speed of unit movement, the availability of the cranes in the working corridor, congestion in the elements of the conveyor system, and technical reliability of the system components.

As shown in Figure 5, the average put-away time is strictly dependent on the number of stacker cranes in the system. When 2 of 10 cranes (scenarios S1 and S5) are used, the unit put-away times range from appr. 1 200 s (20 min) to appr. 1 450 s (25 min), which results from the lack of available stacker crane in the corridor and the need

to move it between corridors. This causes the congestion of units in the conveyor system, which pushes out units from the system after 3 unsuccessful attempts (Table 6).

By increasing the number of stacker cranes to 5, 7, and 10 respectively, the access time is reduced. For 5 of 10 stacker cranes, the congestion in the conveyor system is not visible.

The separation of the input and output conveyors (scenarios S5 to S10) reduces the put-away time with a small number of stacker cranes but does not significantly affect this time with 5 or more cranes.

Average retrieval time is shaped by the same principles (Figure 6). The very long retrieval time is particularly exposed in scenarios with 2 of 10 stacker cranes (S1 and S5), which is an extreme case reached 3,2 hours with a common conveyor system for entry and exit. This is an obvious aberration resulting from the extreme congestion of units, which makes it impossible to complete the ASRS logistics task. As the number of stacker cranes increases, times are normalized. Longer times of retrieval operations result indirectly from the logic of the

Table 6. Mean (95% conf. int.) of average number of put-away / retrieved / not served units

Scenario	No of cranes	Upper conveyors	SP1	SP2	SP3	SP4	SP5
S1	2	Not used	440.25/ 416.50/ 273.50	357.50/ 332.75/ 178.25	398.75/ 380.50/ 229.00	835.75/ 570.50/ 658.00	513.50/ 500.50/ 388.75
S2	5	Not used	1787.25/ 1028.00/ 24.50	1791.50/ 998.00/ 20.25	1779.25/ 1120.50/ 32.50	1791.00/ 990.25/ 20.75	1782.00/ 962.75/ 29.75
S3	7	Not used	1810.00/ 1305.00/ 1.75	1808.25/ 1019.25/ 3.50	1809.00/ 1346.50/ 2.75	1809.00/ 1540.00/ 2.75	1808.25/ 1149.75/ 3.50
S4	10	Not used	1811.75/ 1795.25/ 0.00	1811.75/ 1795.25/ 0.00	1811.75/ 1795.25/ 0.00	1811.75/ 1795.25/ 0.00	1811.75/ 1795.25/ 0.00
S5	2	Used	705.50/ 697.50/ 569.00	645.25/ 986.75/ 511.00	608.50/ 714.25/ 454.00	501.00/ 628.00/ 365.25	546.00/ 675.75/ 435.75
S6	5	Used	1794.75/ 727.75/ 17.00	1801.25/ 655.25/ 10.50	1786.00/ 845.75/ 25.75	1778.00/ 891.00/ 33.75	1766.25/ 1243.50/ 45.50
S7	7	Used	1809.00/ 1537.50/ 2.75	1809.25/ 1440.50/ 2.50	1807.50/ 1795.00/ 4.25	1810.25/ 1249.00/ 1.50	1807.75/ 1791.25/ 4.00
S8	10	Used	1811.75/ 1795.25/ 0.00	1811.75/ 1795.25/ 0.00	1811.75/ 1795.25/ 0.00	1811.50/ 1795.25/ 0.25	1811.75/ 1795.25/ 0.00

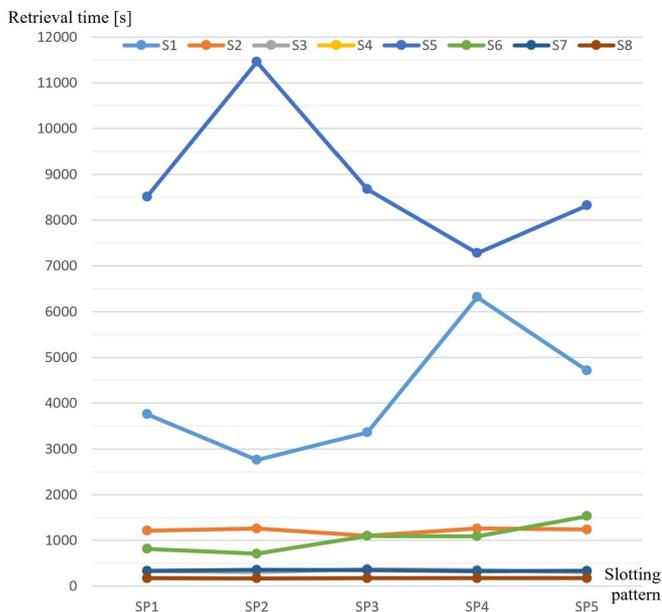


Fig. 6. Mean (95% confidence interval) of average retrieval time

stacker crane. The crane to be moved between the corridors will perform an average of 2 put-away operations per 1 retrieval operation.

Slotting scenarios based on the random distribution of the assortment (SP1) in the locations are characterized by the shortest operation times, which results from the logic of the stacker crane operation. The crane changing the corridors performs combined cycles, and traverses the entire corridor length regardless of the picking address. Slotting patterns using volume-based material assignment (especially SP2) allow for a slight reduction in the operation time, but it is related to the logic of the cranes.

According to the literature on the subject, the technical reliability of the ASRS elements (stacker cranes, transfer, control system, conveyors) does not have a noticeable effect on the ASRS opera-

tion. It is clear especially when scheduled maintenance programs are executed outside the regular work time. Recorded occurrences of damage and recovery times did not affect the reliability of the entire ASRS in this case.

## 7. Conclusions

The article presents a discussion on reliability in logistic systems, which cannot always be used as a measure for the assessment of warehouse technologies. Complex storage systems, especially multi-unit integrated automatic solutions such as Automated Storage and Retrieval Systems, pose new challenges in measuring their reliability. While it is quite clear on the technical level, the complex conditions of the surrounding logistics process make the assessment of ASRS solutions difficult. A much better solution turns out to be the use of dependability measures, which also consider non-structural factors of warehouse technology, especially related to work patterns and allocated labour resources (cost-effectiveness).

The ASRS configuration and allocated resources affect its performance, especially at high workloads. They must be considered as important factors forming the dependability of ASRS and the entire warehouse process.

The simulation studies showed the influence of configuration factors and organizational factors such as material slotting on expected retrieval and put-away times, which in turn are of great importance for the perfect-order-rate of the entire warehousing process.

Therefore, the approach used in practice presented in the Introduction section seems to be right. In this approach, the reliability measures are abandoned in warehouse automation in favour of efficiency measures. However, in this case, they should also be related to specific working conditions, which is postulated in this article.

Further research in this area should include developing a catalogue of standard factors (and their measures) influencing the dependability of ASRS as components of a warehouse system focused on the execution of customer orders.

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