

## Autonomous Mobile Robots in Automotive Remanufacturing: A Case Study for Intra-Logistics Support

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### ABSTRACT

The article focuses on the role of modern logistics 4.0 technologies and lean management in optimizing ancillary processes in intralogistics. The literature review presents critical aspects of intralogistics, including using autonomous mobile robots (AMR) and the challenges associated with their successful implementation. The article also discusses the concepts of Industry 4.0 and Industry 5.0, highlighting the importance of synergies between workers and advanced technologies. In optimizing logistics processes, the authors emphasize the importance of lean management and tools such as 5S and Kaizen. The authors analyze the research gap related to the organization of auxiliary processes, intralogistics, and the introduction of modern technologies. The lack of good practices and strategies for implementing new technologies for ancillary processes makes this a critical issue for managers and production engineers. The article provides practical strategies that can be implemented in companies. It is a valuable resource for managers seeking to manage intralogistics and effectively improve support processes in manufacturing plants. In summary, the article provides a comprehensive look at modern approaches to optimizing support processes in internal logistics. It highlights the importance of integrating modern logistics technologies with lean management principles, which can increase companies' efficiency and competitiveness.

**Keywords:** internal logistics, Industry 5.0, autonomous mobile robots, intralogistics, lean management, automotive industry, simulation.

### INTRODUCTION

The issue of internal logistics is one of the critical concerns of production managers. The suitable raw material, product, and semi-finished product must be at the right time and place, not forgetting the selection of the proper processing technology. This needs particular strategies and algorithms to make intralogistics decisions like choosing the number of transport trips and their organization in time and space required to deliver material to specific loading/unloading points [1].

To fulfill this task, the means of transport and production handling, understood as all those elements without which production could not be carried out, are necessary. Therefore, the challenge is internal logistics supporting manufacturing (the main process) and logistics supporting auxiliary functions. In this dimension, the issue of its optimization is of particular importance. This importance is even more significant the greater the role these processes play in realizing production. Some auxiliary processes are realized sporadically, while others operate in the

same regime as the main processes. Moreover, as a rule, additional processes do not create added value for the customer directly, which causes them to focus less managerial attention on themselves. On the other hand, the value can only be realized with their implementation. In addition, it is difficult to determine the impact of the ancillary process on the final value, so there are many challenges.

Modern technology opens up many ways and opportunities to improve the functioning of production systems [2]. Special attention is paid to Industry 4.0 and 5.0 technologies [3]. In addition, new managerial approaches related to lean production are an additional accelerator of change within production execution methods. Nevertheless, the question arises about how these technologies can be applied and in which areas tangible benefits can be obtained. Thus, the question arises of how modern technology can help support auxiliary processes. For these reasons, the organization's internal logistics for support processes must be correctly organized - i.e., it does not have bottlenecks, does not represent a high cost, or is overlooked [4]. This question is valid both for international context at a global scale and for regional growing economies in perspective of business models and accompanying risks [5–7].

In today's dynamic industrial environment, the evolving technologies of Logistics 4.0 have become a pivotal element in enhancing intralogistics processes. In this context, the discussed case study focuses on implementing Autonomous Mobile Robots (AMR) to optimize the delivery of materials and tools to workstations [8]. However, to more clearly present the potential of these advanced technologies, the authors may contemplate incorporating specific examples. These examples may encompass the application of advanced tracking and monitoring systems, such as Radio-Frequency Identification (RFID) or the Internet of Things (IoT), for precise monitoring and management of material flow [9]. It is also worth considering the presentation of specific scenarios in which Logistics 4.0 technologies are introduced into inventory management processes, reducing the waiting time for material delivery and eliminating overproduction. Additionally, the authors may leverage examples from other industries where Logistics 4.0 is already applied to illustrate potential benefits. For instance, they present a case from the manufacturing sector, where implementing advanced

warehouse management systems has significantly reduced production cycle time or operational cost reduction. Integrating specific examples within the introduction will allow the reader to comprehend better the practical benefits of applying Logistics 4.0 in optimizing intralogistics processes [8, 9].

With this in mind, the authors have attempted to identify a research gap, which is undoubtedly the issue of organizing internal logistics for ancillary processes using modern Logistics 4.0 technologies. The lack of good practices and strategies for implementing new technologies for ancillary processes makes this a critical issue for managers and production engineers, which justifies considering this topic. Therefore, this paper aims to provide an implementation strategy and test it on actual production data (case study) based on industry practice and a literature review. A strategy that managers and production engineers can use in their daily implementation practice. The article describes the elements of the strategy and thus creates a coherent course of action that can be implemented in the company's intralogistics management. The existing body of research on implementing Logistics 4.0 technologies in support production areas, particularly intralogistics, has demonstrated a significant emphasis on integrating Lean Management methodologies. Numerous studies have extensively detailed the application of Lean Management principles to eliminate waste and optimize processes in Logistics 4.0 technologies [10–13]. Several case studies have been conducted to showcase the benefits of applying Lean principles, especially concerning introducing new technologies in intralogistics. These case studies highlight the successful synergy between Lean Management and Logistics 4.0, illustrating how Lean methodologies contribute to the efficient integration and utilization of advanced technologies in intralogistics processes [14–16].

Integrating Lean Management in the context of Logistics 4.0 has proven instrumental in achieving operational excellence, minimizing inefficiencies, and enhancing overall process effectiveness. By incorporating Lean principles, organizations have been able to streamline intralogistics operations, reduce unnecessary resource utilization, and optimize the implementation of new technologies, thereby achieving improved performance outcomes.

## BACKGROUNDS

### Modern intralogistics

Logistics represents a range of company activities that continuously ensure the flow of materials and services throughout the production process. These activities support implementing strategies such as production, utilization, and others. Their form and purpose depend mainly on the technology used by the enterprise in the production process [17].

The primary aim is to ensure high product quality and reduce production and logistics costs. Production logistics management is central to the entire logistics process. Decisions taken at this stage of the logistics process directly impact the level of customer service, the company's ability to compete with others, and the level of sales and, consequently, profit. For this reason, optimizing logistics processes is a topical issue, mainly because of the impact on the product's final price to the customer and the level of customer service [18]. In this dimension, intralogistics, where the share of manual work is still significant, receives particular attention. This is because internal transport, packing, or order picking in many companies is carried out manually [19]. Automation efforts focus on both production processes and the logistics of these processes to increase the efficiency of production systems.

Autonomous internal vehicles in internal logistics enable the independent transport of materials in production plants on demand. However, implementing these flexible production systems efficiently, cost-effectively, and safely is a significant challenge. Therefore, simulations of production and logistics processes are often used to support the planning stage (before production), adapt further, and optimize existing facilities [20, 21].

Since the first introduction of automated tow trucks to automate factory floor processes in the 1950s, automated guided vehicles (AGVs) have been widely used in various industrial sectors, covering warehouse operations, continuous production, and automotive assembly lines. The applications for AGVs can be divided into two main categories. Firstly, AGVs act as suppliers, providing the necessary material handling equipment, transferring and delivering packages in warehouses, and handling the delivery and removal of production components and other tasks. In the second category, AGVs are integrated assembly platforms supporting operations in the production process [13].

As new practical developments in sensors and robot control technology were rapidly adopted, advanced AGV systems gradually emerged. These systems eventually created a new class of (driverless) vehicles called autonomous mobile robots (AMRs). Autonomous mobile robots in industrial settings employ a decentralized decision-making approach to navigate without collisions, offering a platform for tasks such as material handling, collaborative activities, and comprehensive services within a defined area [22].

The autonomous mobile robot (AMR) is characterized by minimal or no human intervention in its movement and is designed to follow a predetermined path both indoors and outdoors. For indoor navigation, the mobile robot uses a floor plan, sonar, inertia measurement unit (IMU), etc. To perform its task effectively, an autonomous mobile robot must be equipped with various environmental sensors, which can be mounted directly on or act as external sensors deployed in the environment [23]. An AMR is a combination of the capabilities of an AGV and a robotic arm. An example of such a solution is illustrated in Figure 1. AMRs equipped with cameras, light and distance detection (LiDAR) sensors, control algorithms, and multidirectional propulsion mechanisms are beginning to emerge as the next generation of AGV technology for material handling applications [13]. The activities performed categorize and differentiate AMR into three main categories:

- 1) covering material handling, such as picking, moving, transporting, and sorting,
- 2) collaborative and interactive activities, and
- 3) service like:
  - Decentralized control – using intelligent, cognitive, and behavior-based control methodologies and technologies to maximize flexibility and efficiency.
  - Platform support – a platform to extend AMR capabilities and enable applications beyond standard material handling operations.
  - Collaboration – the ability to work with humans or other AMR robots in a swarm.
  - Ease of integration: Quick and cost-effective integration of AMR robots into a factory or other facility.
  - Scalability – ability to increase or decrease the number of AMR robots without being hindered by structural changes.
  - Robustness – ensuring resilience, i.e., the ability of systems to recover from failure [22].



**Fig. 1.** AMR platform

AMR systems are often implemented with an inter-operational buffer, where products are temporarily stocked during changeovers so that two consecutive production phases can be decoupled [24].

A single autonomous mobile robot (AMR) may not efficiently meet transport needs in production environments. On the other hand, route planning for multiple AMRs is complex, which can lead to potential traffic jams and conflicts. In addition to the transport tasks themselves, aspects such as the characteristics of the functions, the number of AMRs, their speed under different operating conditions, and their battery state of charge are also important factors in optimizing the logistics system's performance [25].

For a complex and comprehensive material transport system, there is a need to scale the number of AGVs/AMRs efficiently due to operating and maintenance costs. For these reasons, the variety of vehicle models should be kept to a minimum to ensure greater redundancy of alternate means of transport. Nevertheless, there are times when there is a need to use different types of AGV/AMR vehicles depending on the application used, especially in the context of different sizes and weights of the cargo transported [25]. AMRs have opened unique opportunities for autonomizing intralogistics operations [26].

## Logistics 4.0

The broad adoption of Industry 4.0 technologies is bringing fundamental changes to the management and execution of manufacturing operations, including logistics. In traditional planning and control systems, manufacturing and intralogistics processes are usually organized separately, leading to less efficient solutions. In reality, production and intralogistics operations within a single plant are interconnected and interact at different stages of the production process, requiring the synchronization of their organization and activities [25]. As a result, intralogistics is now seen as an area of Logistics 4.0 [27]. This is particularly the case in warehousing, but not only. In addition to mechanization, digital technologies such as software and artificial intelligence enhance automation capabilities. The aim is to minimize the human role in intralogistics processes through system autonomy, which uses computational intelligence [28] and machine learning to adapt to changing situations. This progressive trend requires diverse artificial intelligence techniques [29–31]. These elements are part of the idea of Logistics 4.0, where intralogistics is one of its essential parts [19].

On the other hand, with the advent of Industry 5.0, interest in human-machine collaboration has increased. In such an arrangement, a human working with a machine to ensure stability, efficiency, and safety is seen as a source of innovation [21, 22]. In addition, Industry 5.0 emphasizes the focus on the human through technology and equipment to improve and support operator performance in logistics systems and supply chain operations [32].

## Lean management in the automotive industry

When analyzing the described issue concerning the implementation strategy of an autonomous mobile robot to support the auxiliary processes of intralogistics, it may be crucial to use a management approach to minimize waste in the processes supporting production and operational activities directly at the production nests. The correct work organization at these sites is essential for collaboration between humans and autonomous robots. The answer to a problem addressed in this way is lean management and the techniques offered by this approach, particularly 5S and Kaizen [33, 34]. Lean management is fully integrated into Industry

4.0 and 5.0 [35–37]. Although it is often associated mainly with manufacturing processes, it can be just as effectively applied to the ancillary functions of logistics, mainly due to its [29–32] process optimization, cost reduction, improved production quality, flexibility, and adaptability, focus on added value, continuous improvements, and increased employee engagement.

The term lean originated directly from the automotive industry. Towards the end of the 20th century, both the US and Western Europe saw a significant loss of market share in their markets to Japanese manufacturers, which was particularly evident in the automotive industry in the US market [38].

Womack, Jones, and Roos analyzed the phenomenon and concluded that the causes lay on the side of business management, as described in their 1990 book “The Machine that Changed the World”. The researchers concluded that the reasons were to be found in the tools that were developed and systematized in Toyota’s manufacturing plants in the 1940s and 1950s, collectively referred to as the Toyota Production System (TPS). The Americans called these tools lean manufacturing [39].

In practice, this means producing the right amount of documentation (including procedures) or performing certain activities at the right time, i.e., only when needed. There is, therefore, a need to focus on reducing the three leading causes of loss as much as possible [40]:

- Resources, time, and activities in general that do not represent customer value (*muda*);
- Excessive workload on employees, machines, or processes that lead to frequent downtime due to, for example, depletion (*muri*);
- Irregularity and inconsistency of operations (*mura*).

Lean management distinguishes between five principles that apply to both employees and the entire organization at every level [41]:

- Identification of activities that generate business value;
- Verification of the activities necessary to create business value, thus identifying unnecessary activities (*waste*);
- Creating a value chain free of waste (defects, errors). Reducing downtime and possible risks;
- Performing only those activities that are currently required;
- Striving for perfection and continuous improvement.

Considering the identified research gap based on the abovementioned principles, the authors indicated using Kaizen and 5S approaches directly to support intralogistics with modern technology.

Kaizen is an expression formed from the Japanese words Kai (change) and Zen (good), meaning change for the better [42]. The Kaizen (improvement, betterment) principle continuously improves and streamlines processes. These processes involve all employees, as well as the entire organization, at every level of management. Kaizen should be seen as the foundation of lean management [43]. In market practice, one encounters a depreciation of the Kaizen method by managers. It has been reduced to a description of a tool that consists of submitting improvement requests, which is a significant irregularity. Often Kaizen is wrongly associated with controlling the order of the workplace, posting instructions, measuring working time, and ‘screwing’ standards. As a tool, Kaizen enables individual employees to manage their organization’s working time, contributing to its standardization. This makes considerable repetition, order, and tidiness possible in the work. This, in turn, contributes to the easy identification of emerging problems and the identification of appropriate solutions. Kaizen is used to improve procedures and work organization [39] significantly. Practitioners recommend that the implementation of changes should start with improvements in the sequence of activities and the way work is carried out, and then, when the changes are insufficient, verify the validity of the progress related to the infrastructure part. In summary, Kaizen is the continuous implementation of changes and improvements in small steps directly at the workplace.

5S is a group of five practices that help to promote good workplace organization. 5S involves systematic learning, standardization, discipline, and the pursuit of excellence. The name is an acronym for five Japanese words [34]:

- Selection, tidying up (*seiri*) – involves separating any unnecessary materials at the workstation, such as manuals and tools, from those necessary for the manufacturing process.
- Tidying up (*seiton*) – involves tidying up the workstation, including labeling tools and materials and designating a place for them. Each item should be assigned an individual storage location. Things used most frequently should be within easy reach.

- Tidying up (seiso) – involves clearing the workplace of unnecessary items and taking care of the workplace and its surroundings.
- Standardisation (seiketsu) – keeps the workplace and its immediate surroundings clean and tidy.
- Self-discipline (shitsuke) – involves getting employees to follow the above rules.

The techniques described above are aimed at agreeing and maintaining a high-quality workplace. The 5S practices are essential to lean manufacturing techniques and can be applied at any point in production [44]. They are, therefore, the basis for implementing the lean concept and undertaking improvement activities (Kaizen described above). They also form the basis for implementing more advanced solutions of the lean philosophy. Another advantage is the low cost of implementing 5S techniques [45]. Correctly implementing this technique means implementing the concept of “a place for everything and everything in its place.” It is important to note that the above methods, tools, and concepts are also offered from a different perspective as World Class Manufacturing Practices [46]. They have become part of the core of project management concepts and methods. They are used today by global and multinational corporations that are leading in terms of technology and organization. Using lean management, including tools such as 5S and Kaizen, in ancillary production processes (logistics) is critical in pursuing efficiency, quality, and competitiveness [47]. The 5S tool helps to organize the workplace, eliminate waste, and provide a safe and ergonomic environment. This increases productivity, reduces access time to the tools needed, and minimizes the risk of accidents. Introducing Kaizen, or a culture of continuous improvement, stimulates employee involvement in identifying and solving problems on an ongoing basis. This leads to constant process improvement, improved product and service quality, and waste elimination. The Kaizen approach is critical to competitiveness in today’s dynamic business environment.

In the study, Kaizen and 5S are cited as integral elements of the lean management approach implemented in introducing autonomous mobile robots to optimize intralogistics. Kaizen commences with establishing Specific, Measurable, Achievable, Relevant, and Time-bound (SMART) goals. The study’s primary objective

was to adjust the number of autonomous vehicles to optimize the material and tool delivery process. Kaizen involves, among other things, making data-driven decisions. In the examined case, data on implemented strategies are extracted from the simulation of the production system for analysis, aligning with Kaizen’s emphasis on utilizing data to identify areas for improvement. The simulation in the case study exemplifies Kaizen in practice, enabling the assessment of various scenarios (variants I, II, and III with different numbers of robots) to determine the most efficient process. In the case of 5S, particular attention should be paid to workplace organization. From the perspective of the study, the principles of 5S should be understood as follows:

- Seiri – involves separating necessary items from unnecessary ones, ensuring that only essential materials are present in designated areas for cobots.
- Seiton – cobot loading and unloading points are organized according to lean principles, ensuring efficient material management.
- Seiso – maintaining order in the workplace is crucial. The case study underscores the importance of standardized workspaces to ensure the smooth operation of cobots and prevent obstacles.
- Seiketsu – involves creating and maintaining standardized work practices. Lean management is integrated into the robotic system, ensuring consistency and standardization of practices in the material handling area.
- Shitsuke – sustaining improvement over the long term is a crucial principle of 5S. The case study suggests that 5S practices are continued as they are part of the applied lean approach to optimize intralogistics.

Kaizen and 5S are interconnected in the case study. Kaizen’s philosophy of continuous improvement complements the structural and systematic approach of 5S, ensuring that introduced enhancements are sustained over time. Collectively, these methods contribute to the effective implementation of cobots in intralogistics, improving stability efficiency and reducing waste.

In the context of optimizing intralogistics and implementing Autonomous Mobile Robots (AMR), it is crucial to delve into the principles of lean management, especially those directly impacting intralogistics processes. Several lean tools are essential to improving efficiency and

minimizing waste in intralogistics [48]: the pull system, continuous flow, just-in-time, and the Kanban system. The pull system is a fundamental concept in lean management, emphasizing the production of goods and services in response to actual demand. In intralogistics, the pull system ensures that materials and tools are delivered to workstations based on current needs, eliminating overproduction and reducing unnecessary inventory. Implementing the pull system in the supply chain of materials and tools enhances responsiveness and removes the accumulation of excess goods [49]. Continuous flow is another lean principle focusing on the smooth movement of materials or products through the production process or supply chain. In intralogistics, the continuous flow approach ensures constant and uninterrupted delivery of materials to workstations, minimizing disruptions and optimizing the overall workflow. This is particularly crucial when considering the integration of AMRs, as their effectiveness is maximized in an environment characterized by continuous and optimized material flow [50]. Just-in-Time (JIT) is a lean strategy in production and inventory management aimed at producing items exactly when they are needed in the production process. In the context of intralogistics, JIT principles contribute to the timely delivery of materials and tools to workstations, aiming to minimize waiting times and reduce excessive inventory. The implementation of AMRs enhances JIT strategies by providing timely and precise deliveries in response to dynamic production process needs [51]. The Kanban system is a visual management tool that facilitates inventory control and ensures a smooth production flow. In intralogistics, the Kanban system can be applied to signal the moment when materials or tools need replenishment at specific workstations. Integrating this system with AMRs improves the automated and visual management of materials, contributing to the efficient functioning of the supply chain [52].

In conclusion, a comprehensive understanding of lean tools is crucial for positioning the proposed strategy of introducing AMRs in optimizing

intralogistics processes in the automotive remanufacturing industry. The mentioned tools constitute theoretical foundations for achieving the goals of stability, efficiency, and waste reduction presented in the study.

## AMR SYSTEM DEPLOYMENT MODEL

Within the scope of the article, based on industry practice and a literature review, the authors formulate an implementation strategy for an AMR solution for ancillary intralogistics processes that managers can use in their implementation practice. The developed system consists of five steps (Figure 2.).

The business analysis defines the objective to be achieved by the AMR, and this objective does not have to be purely technical. This objective should realize a business case. It could include reducing logistics costs, improving safety, or increasing productivity. The next step is to identify the area in which the robot will be used. In this step, an inventory and identification of auxiliary processes is necessary. It is recommended to analyze the foundational sources, such as organizational regulations, production descriptions, guides, technology sheets, process registers, or process maps. These activities aim to identify which auxiliary processes are carried out within the main production processes. An identification of potential new additional strategies should then be carried out. Given the analysis, a decision must be made regarding which auxiliary processes will be improved and to what extent. Adequate to this choice, an attempt should be made to reduce wastage and improve the process using the lean management techniques mentioned.

The next step is to select the parameters of an autonomous mobile robot suitable for the organization’s intralogistics specifications. This choice should consider size, load capacity, speed, reach, and other technical parameters. In addition, the implementation of the robot should comply with applicable laws and regulations, including those related to data protection and security. The

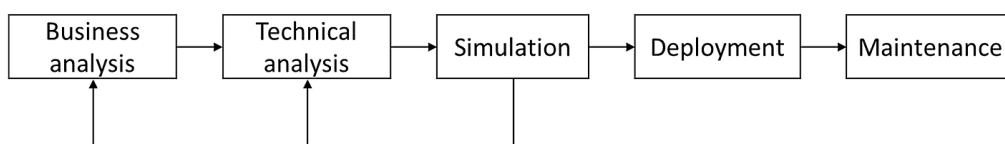


Fig. 2. AMR system deployment model

accumulated range of data, both in terms of the business case and the choice of solution parameters, allows simulations to be carried out.

In this area, it is possible to analyze the options and select a suitable solution for the company’s circumstances. Nevertheless, it is necessary to describe the process chosen to the level of the simulation requirements. An appropriate characteristic should represent each phenomenon in the area of the realized process. The simulation should respond directly to the business objective. According to its results, further steps will be implemented. If the results are unsatisfactory, it is necessary to conduct the business or technical analysis again.

Depending on the simulation results, a solution is recommended for implementation. The implementation includes all the usual elements, including the purchase of the target AMR and testing. At the same time, based on the simulations, the possibility of design as well as organizational errors is significantly reduced. The implementation is followed by the operation and maintenance of the solution, including regular software and technology updates to keep the robot fully operational and practical.

### Case description

To illustrate the strategy identified from the literature and industry practice, the authors conducted a case study. A company involved in the remanufacturing of automotive parts, also known as remanufacturing, was chosen as the test case. This process focuses on restoring used or used parts to a condition that matches new ones in quality and performance. The process is an integral part of the closed-loop economy, as it helps reduce waste and raw material consumption by reusing existing materials and components. The process consists of eight activities presented in Figure 3.

The remanufacturing process is complex, and due to the realized scope and variability of the work performed (resulting from quality control), it is challenging to attempt automation. For these reasons, it requires a significant involvement of the human factor. Nevertheless, this case study focuses on automation opportunities available in auxiliary processes within intralogistics. Regeneration takes place in a work cell. Each cell has its own specific work and material needs. Production staff are supplied with the necessary tools and materials depending on the processes.

The main process is supported by an auxiliary process of supplying tools and materials. Operators at each work cell have a list of the tools and materials they need to carry out their remanufacturing tasks. A material and tool warehouse on the shop floor feeds the entire production. The internal transport process is carried out manually by the bench workers. This means that when the necessary components (e.g., tools) are missing, this fact is reported, and a person stops working to retrieve the relevant part. A variety of products are supplied to the workplaces, such as:

- personal protective equipment – safety glasses, gloves, masks, protective headphones, and other items that workers must wear to protect themselves from potential hazards in the workplace.
- chemicals – chemicals such as cleaners, lubricating oils, paints, or other chemical products used in manufacturing or maintenance processes.
- tools – cutting tools, hammers, screwdrivers, etc.
- consumables – adhesive tapes, paper, packaging, cleaning products, etc.

The availability of these products at workstations is crucial to ensure the continuity of the main process and the safety of workers. At the same time, the way they are delivered generates

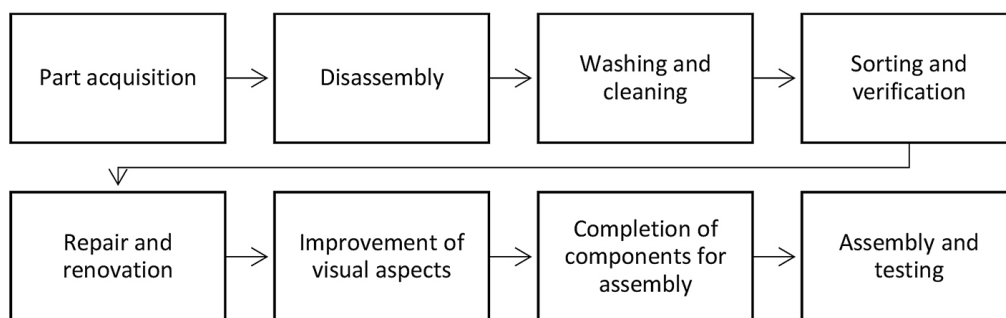


Fig. 3. Remanufacturing process



redundant traffic and can cause defects and downtime because a worker has to stop working for a certain period. Therefore, timely access to the necessary materials and tools is a critical factor for the efficiency of the main process. The ancillary process of supplying tools and materials determines the final quality of the delivered product. This is all the more important as the remanufactured parts are certified, which confirms their quality and compliance with industry standards. For this reason, this process has become the subject of further research.

### Case implementation

The ancillary process of supplying materials and tools is characterized by high variability and, above all, a high volume of delivered products. For this reason, it has become subject to automation. In the case study under consideration, in line with the proposed strategy, it was determined that the primary objective would be to adjust the number of AMR vehicles used to carry out the auxiliary process of supplying materials and tools. A business case was made in the first stage in line with the strategy. To this end, meetings were held with stakeholders regarding the processes in place. A process book was analyzed, and the purpose of the planned AMR system was established. It was determined that this objective would be to maintain stability in the delivery of materials to sites. This choice is due to staffing problems as well as external circumstances. For example, during the pandemic COVID19, a significant proportion of staff could not perform their duties due to sickness or quarantine.

Given the above findings, the acquired data on the implemented processes were imported. For this purpose, the data was extracted from the MES (Manufacturing Execution System). The system stores the data of the primary function but also the additional data of the auxiliary functions. Due to the large variety of supplemental materials, it was determined in the case study (as implementation of the first phase of the research) that the simulation would be carried out for the material with the highest consumption volume. Furthermore, this material is supplied to several workstations or production cells.

As a result of the analysis of the available data volume, a material was selected, and the average material consumption times of the working cells where it is used (S1 – used every 11 minutes,

S2 – used every 16 minutes, S3 – used every 33 minutes) were established. Currently, materials are only distributed at the start of the shift. If there is a need for more materials, it is necessary to replenish yourself. A delegated employee from a particular work cell takes over the task of intralogistics. According to the company, this process usually takes between 15 and 30 minutes. However, it can take even longer if staffing levels remain low. The employee also takes a break from work. This has an impact on the performance of the position.

Next, as a result of the technical analysis, it was determined that a transport AMR would be implemented, which would move at a speed of 1 m/s. There are no narrow passageways or many curves in the AMR's movement range. Therefore, the AMR will move within the scope of the main transport road within the hall. The robot will deliver materials to specially designated zones within the production cells. The AMR will independently load and unload the cargo. It has been assumed that this time will be fixed due to the use of bulk containers for transporting materials, and it will be a total of 5 minutes. The loading and unloading points will be organized according to a lean approach, where employees using the described group of five practices (5S) and continuous improvement (Kaizen) will influence the correct operation of the AMR robot.

The machine can carry out its tasks provided that there are appropriately grouped and arranged materials, both used and new, in the designated areas within the working cells. AMR's path of movement must be free of obstacles. Thus, the organization and standardization of the workplace based on lean management will significantly impact man-machine cooperation. The proper organization of the workstation takes on particular importance, as it is assumed that with the increase in the number of AMRs, it will be possible to transport diverse loads.

In the next step, the collected data and described conditions were used to determine the simulation parameters, which are the evaluation and decision components of the assumptions made. The model was drawn up using the Technomatic Plant Simulation system. The simulation included three working cells, an internal warehouse, and an order waiting track (Figure 4, Figure 5). It should be noted at this point that the presented model is a close representation of a natural production line of an automotive

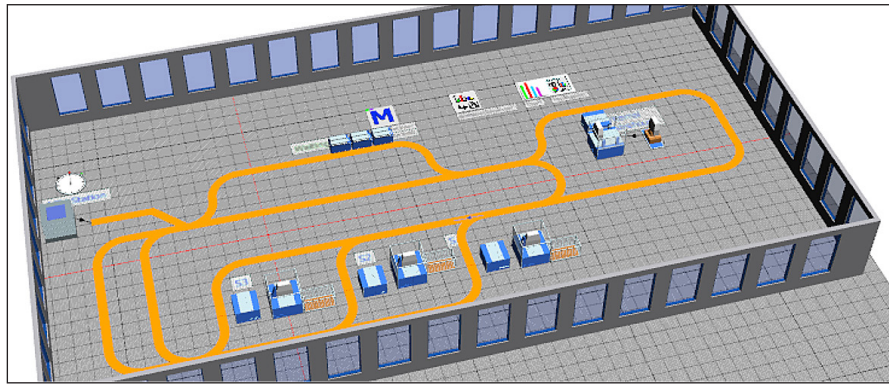


Fig. 4. Intralogistics auxiliary processes – model 3D

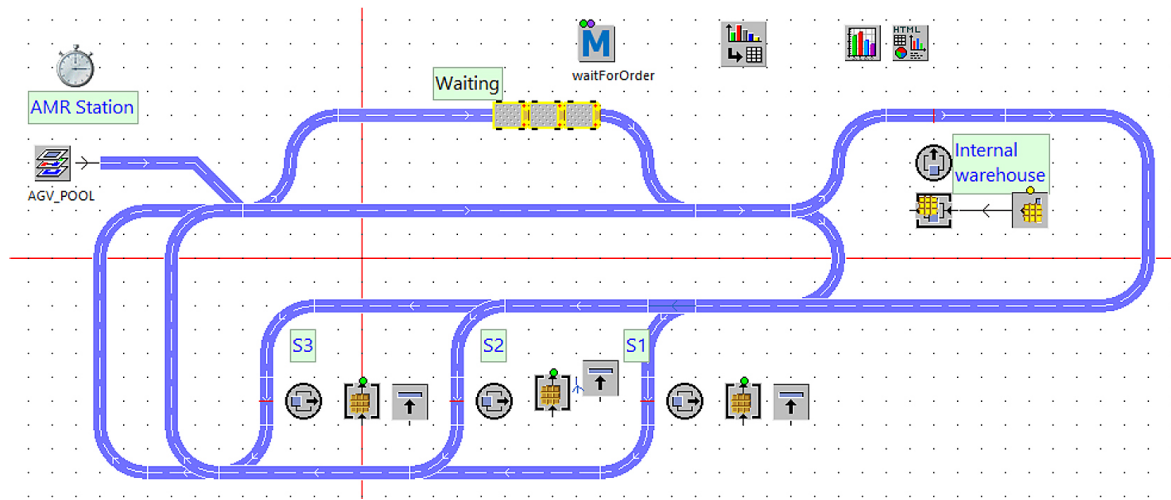


Fig. 5. Intralogistics auxiliary processes – simulation model

company specializing in the professional re-manufacturing of parts. As mentioned above, the data (including times and volumes) are also actual and come from the company.

The technical analysis showed that a maximum of three AMRs can be parked (loading, maintenance). This is due to the positioning possibilities in the production hall. A larger number of AMRs would mean a need for more space or the construction of a new part of the hall. The same reason was used to select the criteria for evaluating the research. It was decided that the AMRs would have to be mobile most of the time. This would allow them to carry out production tasks without blocking communication routes. Therefore, their adequate working time was used as the evaluation and decision criterion for the number of machines implemented. The longer the working time, the better the company's requirements for the hall can be met. The higher the number of machines, the better the fulfillment of the company's hall requirements

and, consequently, the greater the success in implementing the strategy under analysis. For this reason, the simulation was carried out for three variants of the number of AMR for production realization: variant I – 1 AMR, variant II – 2 AMR, and variant III – 3 AMR. It was assumed that the number of AMRs increases in each variant while their parameters remain the same (the same robot model was used).

## RESULTS

In order to represent the actual industrial conditions in the company, the simulation was run four times and lasted 16 hours as two 8-hour shifts. The processing times of the tasks at the workstations were generated using a negexp distribution, while the distance of the paths corresponded to the actual dimensions of the company hall. The experimental results for each variant are presented in the following Tables 1–3.

The results obtained were normalized to make a comparative analysis of the results obtained in the subsequent variants. As a result of the studies, it was observed that as the number of AMRs increased, on average the working time for each successive AMR decreased while the waiting time increased significantly.

Thus, it can be predicted that, by executing the process with an increasing number of AMRs, on average the robot would spend a significant proportion of its time waiting (Figure 6).

The structure of waiting time shows that on average both means and standard deviation increase with growing number of AMR in each variant (Figure 7). In other words, the AMRs have a longer waiting time between each task.

To deepen the research, a summary was prepared regarding the distance realized by each AMR (Figure 8) and means and standard deviations (Figure 9). Interestingly, as the number of robots increased, the dimension of the recognized length also increased. The result obtained is consistent with the range of waiting times. After completing its work, the AMR returns to the waiting track rather than constructing a new order. Thus, an empty run is generated.

Thus, for the analyzed case, the efficiency of robot operations based on the increased number of AMRs changed significantly to the number of robots. The results show that the increase in the number of robots reduces the working time for each AMR. In addition, it increases the waiting time. The results obtained transparently indicate that, in terms of use (relevant to actual production data), one AMR will fully accomplish the task. The simulation shows that increasing the number of AMRs (in the described company) does not result in a significant increase in value but, on the contrary, can generate increased usage and operating costs.

**Table 1.** Variant I – I AMR

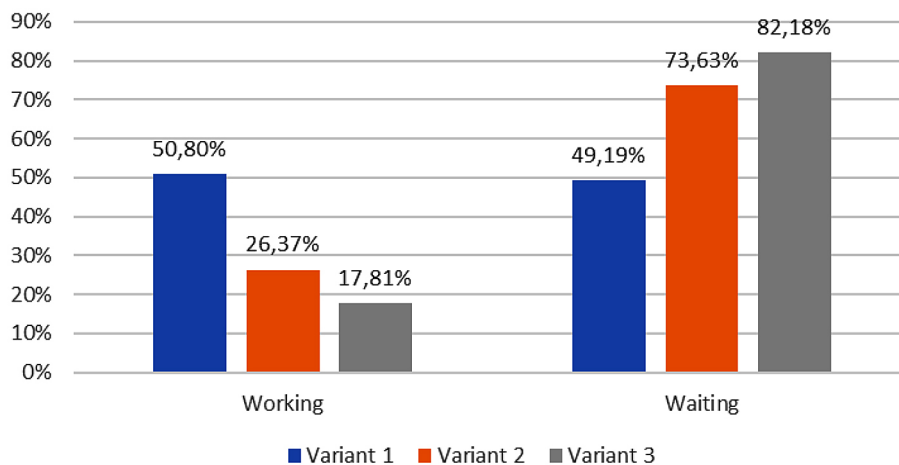
| Variant 1 | AMR:1<br>[% of total simulation time] | Sum of traveled distance [m] |
|-----------|---------------------------------------|------------------------------|
| Working   | 50.80                                 | 29 262                       |
| Waiting   | 49.19                                 |                              |

**Table 2.** Variant II – II AMR

| Variant 2 | AMR:1<br>[% of total simulation time] | AMR:2<br>[% of total simulation time] | Sum of traveled distance [m] |
|-----------|---------------------------------------|---------------------------------------|------------------------------|
| Working   | 26.99                                 | 25.74                                 | 30 373                       |
| Waiting   | 73.00                                 | 74.25                                 |                              |

**Table 3.** Variant III – III AMR

| Variant 3 | AMR:1<br>[% of total simulation time] | AMR:2<br>[% of total simulation time] | AMR:3<br>[% of total simulation time] | Sum of traveled distance [m] |
|-----------|---------------------------------------|---------------------------------------|---------------------------------------|------------------------------|
| Working   | 18.57                                 | 17.25                                 | 17.60                                 | 30 767                       |
| Waiting   | 81.43                                 | 82.74                                 | 82.38                                 |                              |



**Fig. 6.** Comparison of average working vs. waiting time

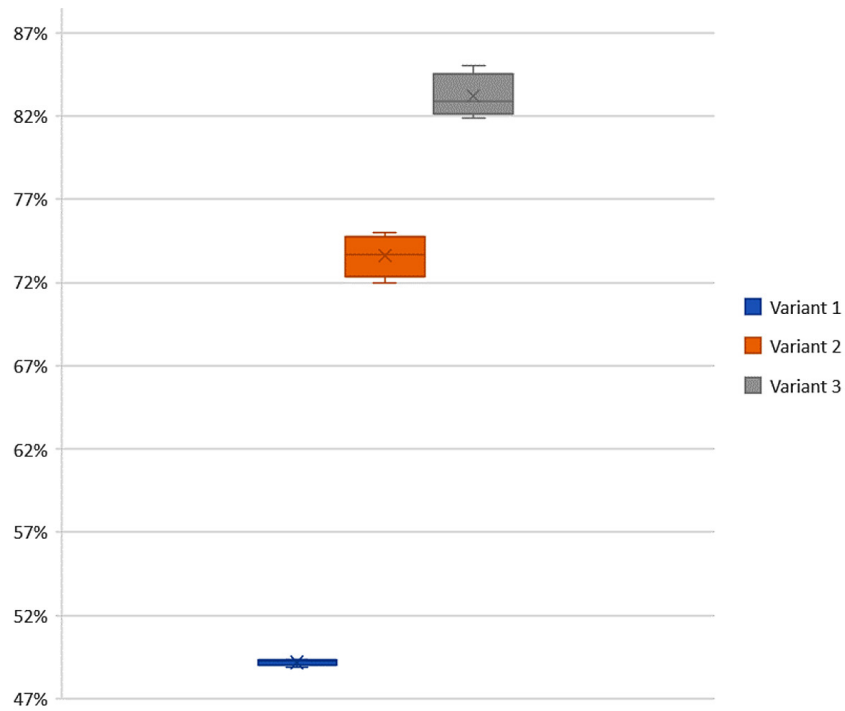


Fig. 7. Mean values and deviations of total waiting time

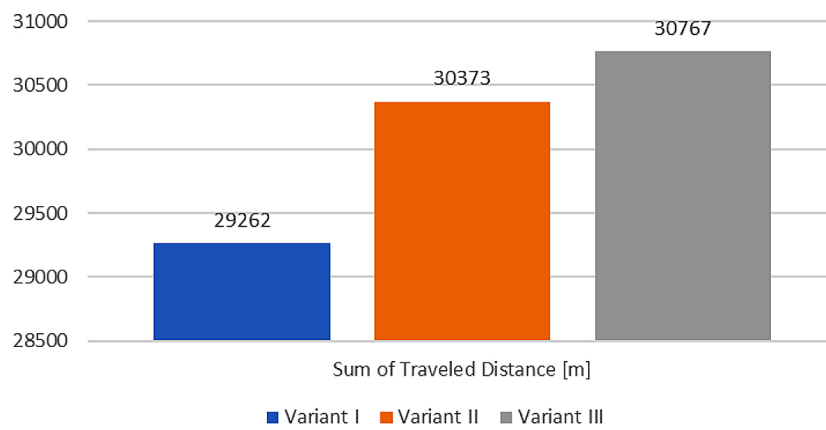


Fig. 8. Sum of travel distance

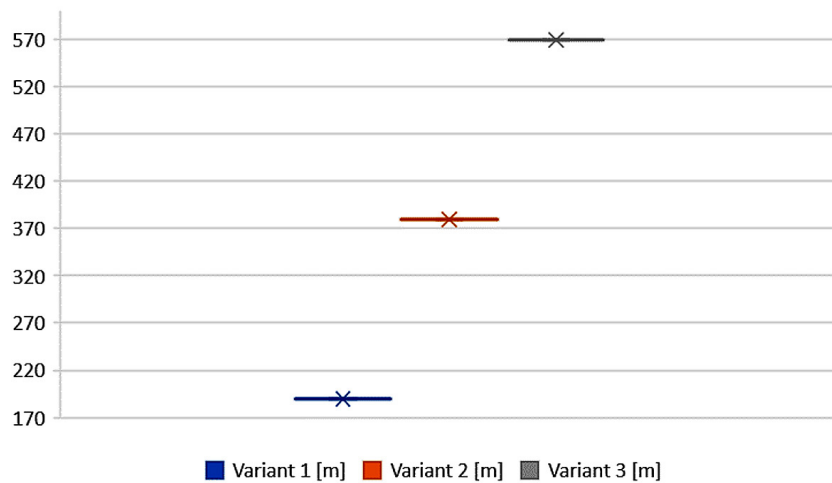


Fig. 9. Means and standard deviations for travel distance in each variant

On the other hand, compared to the initial state, the implementation of AMRs has meant that support materials are always available. There is no need for the selected employee to leave the work cell. In addition, the process is not conditioned by the number of employees present on a given shift. Thus, the stability of the process has been significantly increased – even though, ultimately, only one AMR can perform the required tasks successfully.

In summary, the above results can be used to implement the system in a production setting or as a basis for further business or technical analysis. Nevertheless, in the case of the case study, the objective was to ensure the stability of internal delivery. The last goal will be achieved using a single AMR (Variant I).

## DISCUSSION

The authors have presented strategies and concepts that can be used by managers in managing the intralogistics of a company. The issues discussed, such as intralogistics, AMR, and lean management, are relevant for organizations seeking to increase productivity, quality, and competitiveness in a changing industrial environment. The authors emphasize that internal logistics in the modern industrial context is a critical element of industrial production. Adequate flow of raw materials, products, and semi-finished products is essential to ensure the smooth functioning of production processes. Internal logistics plays an even more significant role in the era of Industry 4.0 and Industry 5.0, where digital technologies and automation play a crucial role in process optimization [53,54]. The presentation of AMR as the future solution for internal logistics is interesting. The authors point out that the autonomy of AMR and the ability to perform transport tasks can contribute to a significant increase in efficiency and flexibility inside production facilities.

However, there still seem to be challenges in planning and managing AMR fleets in large plants. The role of lean management, including tools such as 5S and Kaizen, is also an essential aspect of the problem. Organizations can minimize waste, streamline operations, and strive for excellence by adopting a lean approach to logistics support processes. This approach is essential in both Industry 4.0 and Industry 5.0, where efficiency and quality play a significant role [55].

In this respect, performing an economic analysis, part of the business analysis described as part of the proposed AMR implementation model will be crucial. The analysis will show a given investment's payback time (ROI) in view of current prices. In this dimension, it is necessary to consider both investment costs (purchase of equipment, installation, and adaptation of infrastructure or training) and operating costs (maintenance and servicing, updates).

As well as the expected benefits such as increased production due to more efficient logistics, shortening the time of delivery of products to customers, or reduction of labor costs thanks to automation. At the same time, the choice should also consider strategic issues in the scope of the entire company. An AMR solution is the answer to uncertain times in production. AMR may attempt to fill the gap as part of emerging problems with staff availability. Therefore, the economic analysis should be adjusted for costs related to the reduced volume of production or its complete disappearance (observed during the pandemic) – in the event of a staff shortage. Therefore, the decision to implement an AMR should be embedded in the cost analysis, but it should also depend on the business strategy of a given company. In addition, AMR, as a flexible tool, can be implemented to perform several tasks for the company's benefit – in this way, its ROI will increase.

The challenges of applying modern technology to internal logistics [56]. Route planning for multiple AMRs, fleet scaling, and managing different types of AGVs/AMRs are all critical issues that may require further research and development. On the other hand, there are many advantages to using autonomous mobile robots (AMRs) in industrial intralogistics. For this reason, the authors identify benefits such as:

- Elimination of confusion during the implementation phase  
Safety and quality, expressed through introducing an AMR system, eliminates the risk of human error in the material handling process, resulting in higher safety and quality of service. Moreover, autonomous vehicles work according to specific algorithms, ensuring consistent quality of tasks performed regardless of fatigue or emotional instability of employees. Eliminating human intervention in the transport process eliminates errors resulting from unclear communication between employees.

- Accelerated implementation  
Faster deployment, as AMR systems are relatively easy to implement in a production facility. This is because there is no need to rebuild infrastructure. Autonomous vehicles are flexible and do not require costly infrastructure changes, unlike traditional solutions with belts or fixed routes.
- Clarifying the scope of implementation  
AMR systems are scalable, allowing companies to start with a small deployment and gradually scale it up. Customizable to specification, as selecting and configuring the suitable types of autonomous vehicles and tailoring them to the unique needs of a production facility allows the deployment scope to be fine-tuned to meet specific requirements.
- Planned feedback  
Implementing an AMR system can be preceded by advanced simulations that help determine what changes will be necessary and what benefits can be achieved. Simulations allow the route plan, vehicle deployment, and other parameters to be optimized before full implementation. Based on the results of the simulations, modifications can be planned to minimize risk and ensure the success of the implementation.
- Implementing AMR systems is not only an effective tool for automating intralogistics but also enables the solution to be perfectly tailored to the specific needs of the production facility. Eliminating errors, rapid implementation, flexibility, and planned feedback make these systems an innovative solution for the industry, increasing its productivity, competitiveness, and service quality. However, the study and simulations carried out on the implementation of AMR in industrial intralogistics are promising, but they are subject to certain limitations, in particular:
  - The implementation of AMR systems can require a significant initial financial outlay, which can be difficult for smaller companies to meet.
  - The systems are technically advanced, which can be challenging to operate and maintain. This requires specialized knowledge and skills.
  - The introduction of autonomous vehicles may affect changes in work organization and require staff training, which can be time-consuming and costly.
  - In some cases, existing infrastructure may need to be adapted, for example, by adding signage or changing the layout of premises.
  - Although AMR systems are designed with safety in mind, there is a risk of collisions with people or other objects, requiring sophisticated safety and monitoring systems.
  - Introducing different types of AMRs from other suppliers can lead to problems with interoperability and managing them.
  - The internal conditions of a production facility may change, which may affect the ability of an AMR system to navigate and perform tasks effectively.
  - Employees may be concerned about job losses or a reduced role due to implementing automation, which may affect employee motivation and engagement issues.
  - In the short term, implementing an AMR system may have benefits; long-term gains may be more challenging to predict, and the investment may require patience.

Despite these limitations, implementing AMR systems still represents a promising direction in intralogistics automation [57]. It brings significant benefits to businesses, as demonstrated in the case study. It is essential to carefully consider these limitations and tailor the implementation strategy to an organization's unique needs and capabilities.

The discussion summarises the critical aspects of the article, with many issues that could be further explored and analyzed in the context of increasingly advanced industrial technologies. The article's authors point to the importance of optimizing the ancillary logistics processes in the era of Industry 4.0 and Industry 5.0, which poses many exciting research and practical challenges for researchers and practitioners. Particular attention is paid to aspects such as integrated AGV/AMR systems, extensive AMR fleet management, artificial intelligence in intralogistics, the role of humans in the context of Industry 5.0, cost-benefit evaluation, ethical aspects of automation, the concept of the digital twin in intralogistics or the use of blockchain in logistics data management.

## CONCLUSIONS

This paper aims to provide an implementation strategy and test it on real production data (case study) based on industry practice and a literature

review. To achieve this, the paper analyzed the industrial automation process in the context of tool and material supply in a company specializing in remanufacturing automotive parts. This process is a critical component of the remanufacturing industry, which plays a vital role in the circular closed economy, reducing waste and raw material consumption by reusing existing materials and components.

In the case study, a simulation was conducted to evaluate the effectiveness of introducing mobile robots (AMR) to deliver tools and materials to workstations. Findings suggest that with one AMR, it is possible to ensure the stability of in-house deliveries with minimal waiting time for delivery. Increasing the number of AMRs, although reducing the operating time of each robot, significantly increases waiting times, which can lead to increased operational costs.

The study concludes that, in the case studied, a single mobile robot is sufficient to maintain the stability of the internal supply. However, these results can be a starting point for further process optimization research and provide valuable business and technical analysis input. The study illustrates how process analysis and simulations can help companies make decisions regarding automating and optimizing internal intralogistics processes. This opens up the perspective for new research. Therefore, future research perspectives comprise several crucial areas that deserve in-depth exploration to advance our understanding and implementation of Logistics 4.0 technologies in intralogistics. The following key areas will focus future research:

Future research endeavors should comprehensively examine safety aspects associated with integrating Logistics 4.0 technologies in intralogistics. This involves an in-depth analysis of safety protocols, risk mitigation strategies, and compliance with industry regulations. By scrutinizing the safety implications, researchers can contribute to developing robust safety frameworks that ensure the well-being of human operators and the seamless coexistence of autonomous systems within industrial settings.

The advent of Logistics 4.0 technologies, particularly the integration of autonomous systems like AMRs, necessitates a paradigm shift in workforce skills and competencies. Future research should focus on designing and implementing effective training programs that equip employees with the requisite skills to collaborate with automated

systems. Investigating the most efficient methods for workforce upskilling and addressing potential challenges in the transition to computerized environments will be crucial for successfully integrating Logistics 4.0 technologies.

As technology evolves, future research should explore the potential integration of emerging technologies in the intralogistics landscape. This includes investigating the applicability of technologies such as artificial intelligence, advanced data analytics, and blockchain in conjunction with Logistics 4.0. Understanding how these technologies can complement and enhance the existing framework will be essential for staying at the forefront of innovation and ensuring sustained improvements in intralogistics processes.

Addressing these future research perspectives will contribute significantly to the ongoing evolution of Logistics 4.0 in intralogistics, fostering safer, more efficient, and technologically adept industrial environments.

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