Journal of Industrial Intelligence
https://www.acadlore.com/journals/JII

The Challenges of Integrating AI and Robotics in Sustainable WMS to Improve Supply Chain Economic Resilience

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Received: 05-14-2024 **Revised:** 06-15-2024 **Accepted:** 06-20-2024

Citation: S. Dabic-Miletic, "The challenges of integrating AI and robotics in sustainable WMS to improve supply chain economic resilience," *J. Ind Intell.*, vol. 2, no. 2, pp. 119–131, 2024. https://doi.org/10.56578/jii020205.

Abstract: The integration of artificial intelligence (AI) and robotics into the warehouse management system (WMS) has substantially advanced supply chain (SC) operations, offering notable improvements in efficiency, accuracy, and economic resilience. In warehousing environments, AI algorithms and robotized systems enable rapid and precise product retrieval from storage while optimizing routing and packaging, thereby reducing order preparation time and enhancing delivery reliability. The implementation of these advanced technologies also results in fewer errors, improved customer satisfaction, and streamlined SC processes, empowering organizations to better manage inventory and respond swiftly to fluctuating market demands. Such innovations allow for reduced operating costs, enhanced productivity, and increased sustainability. Autonomous mobile robots (AMRs), automated guided vehicles (AGVs), and drones, among other cutting-edge solutions, are increasingly incorporated into the WMS to minimize physical labor and mitigate workplace injuries. Despite these benefits, considerable challenges remain, including the high initial costs and requisite technical expertise for ongoing maintenance. The integration of new AI and robotic technologies into pre-existing systems necessitates careful evaluation, substantial employee training, and process adaptation. Nonetheless, these technologies play a crucial role in fostering environmentally and socially sustainable operations within warehouses and broader SCs, contributing to reduced carbon emissions and the elimination of hazardous tasks for human workers. This study aims to identify the most effective AI and robotic technologies for a sustainable WMS, with recommendations tailored to maximize SC value through automation. A detailed examination of existing warehouse practices is essential to pinpoint areas where automation can yield the most substantial impact and deliver long-term resilience and value for SCs.

Keywords: Warehouse management system; Supply chain; Robotic technologies; Benefits

1 Introduction

Robots and AI-based systems have significantly contributed to the improvement of all SC activities. They especially provide benefits to warehouse activities because they can significantly improve efficiency and accuracy, making the order fulfillment process significantly faster and more reliable. Robots can quickly and accurately pick products from shelves, while AI algorithms optimize routes and packing sequences, reducing the time needed to prepare orders for delivery to end users and increasing the efficiency of warehouse activities [1, 2]. In addition, these systems reduce the possibility of errors, resulting in greater customer satisfaction and SC efficiency. Warehouse automation enables companies and SCs to effectively manage inventory and respond to growing market demands, increasing overall productivity and reducing operating costs [2, 3]. In recent years, robots and AI-driven systems have improved the operations of warehouses. These advanced technological systems are reasonable in all warehouse activities, especially enabling faster and more accurate sorting, order picking, and packing of products, significantly enhancing the efficiency and accuracy of the order fulfillment process [4]. Automation as the base of robotic systems and AI technologies are mechanisms that have become crucial factors in boosting productivity and reducing operational costs in all parts of the sustainable SC. In a world where consumers increasingly expect fast and reliable delivery, these technologies play a vital role in meeting customer demands.

With advancements in robotics and AI, warehouses are evolving into intelligent hubs capable of optimizing every aspect of product management [1]. Warehouses represent a highly important part of a contemporary, prompt, and competitive market and a critical part of every SC. Companies have to ensure that goods can be carefully selected, appropriately packaged, accurately delivered, and efficiently delivered to customers, which coincides with the level at which warehouse operations are revolutionized by robots and AI systems [1, 4]. These technological innovations improve productivity, decrease human error, and optimize the delivery process, making SCs more resilient. To effectively manage warehouse operations, it is necessary to develop a WMS [5]. This sophisticated software system facilitates the management of warehouse and distribution operations. WMS typically tracks inventory, manages warehouse locations, maximizes warehouse space, handles ordering and receiving items, and monitors the flow of commodities through the warehouse [4]. WMS is frequently used in logistics operations to boost the accuracy of inventories, cut costs, and increase efficiency [5, 6]. Consequentially, WMS is a crucial element in today's SC management, as it enables companies to more effectively manage their warehouses, reduce internal processes, and improve the sustainability and reliability of deliveries. To effectively implement warehouse activities, a sustainable WMS has been strengthened with modern Industry 4.0 solutions [2, 5]. Among them, robotic solutions based on AI benefits dominate, which significantly increase the productivity of the warehouse as well as the complete SC, reduce the engagement of workers in difficult, repetitive, and tiring activities, and significantly contribute to environmental sustainability. The engagement of contemporary robotic technologies in logistics activities has a major positive impact on WMS efficiency, which serves as the foundation for resilient and intelligent SC's sustainable warehouse. Robots can swiftly and precisely select and arrange goods on shelves, and automated systems can boost warehouse productivity by 20% to 30% [1, 2]. The use of robotics lowers the error rate in product picking and placement, resulting in a 70% reduction in errors in warehouse operations [5]. Warehouses that are arranged vertically can have more available space by using robotic systems [6]. Up to 40% more storage capacity can be achieved with full automation. Because automation eliminates the need for manual labor, operating costs are reduced. Activities that can result in worker injuries can be taken over by robots, which can lower the hurt rate by at least 30% [2]. Robots' capacity to operate continuously around the clock, without a break, has been associated with a productivity increase [1, 5]. When compared to traditional technologies, warehouse productivity has increased by more than 50% with the implementation of contemporary robotic solutions [3, 4]. According to these and other advantages, it is considered that automation logistics operations in the warehouse are an important challenge since it raises a lot of issues regarding the necessity of using robotic technology solutions.

The warehouse is one of the critical elements in the SC because it represents the connection between the supplier and the producer and between the producer and the user, but often the largest part of the activity in the SC is realized because the users are served from the warehouse [1, 4]. Due to numerous activities and challenges, the efficiency of the warehouse relies on a sustainable WMS based on the automation of logistics activities. A wide range of robotic solutions are available on the market that enable the improvement of all aspects of the WMS sustainability to meet the needs of resilient SC. Robotic technologies are required for economically beneficial, ecologically sustainable, and socially acceptable logistics activities within an efficient WMS. Automated technologies for logistic activities in the WMS concept significantly reduce non-productive time, increase material turnover, reduce damage to goods, and reduce errors in logistics assignments [1, 4]. The engagement of AGVs, robotic arms, automated storage and retrieval systems (AS/RS), AMRs, and drones is becoming a critical element of sustainable logistics activities in the WMS [7]. These contemporary technology solutions are also based on the use of renewable energy sources; therefore, they are also environmentally sustainable. As they would be self-programmable, they could eliminate employee injury, which respects the pillar of social sustainability. Given the close connection between warehouse technologies and automation logistic processes, the essence of the WMS concept rests on robotization, material handling, and logistics activities (Figure 1) [3, 5]. Given the important environmental benefits provided by contemporary robotic and AI technologies, companies plan to use them to improve WMS sustainability [1, 4]. These technologies, which are primarily powered by electricity and tend to employ renewable energy sources, minimize carbon dioxide (CO_2) emissions while remaining environmentally friendly. Modern technology solutions in the warehouse are meant to substantially decrease human involvement in difficult, tiresome, and frequent activities and eliminate humans from dealing with dangerous substances [2, 4]. As a consequence, these contemporary robotic and AI technologies are regarded as socially sustainable, both in the warehouse and throughout the SC.

In evaluating robotic and AI technologies for warehousing, significant considerations to think about involve the kind and nature of warehousing activities, the size and structure of the warehouse, and the particular requirements of the company and its associated SC [8, 9]. The technology selection process commences with an examination of current warehouse procedures to determine which areas would benefit the most from automation.

The following phase is to assess the efficacy of existing and widely utilized technologies like AGVs, robotic arms, AS/RS, AMRs, and drones. The substantial initial costs are one of the most significant barriers to selecting and implementing these technologies [10, 11]. The costs of purchasing and deploying robotic systems can be high, necessitating careful and comprehensive economic analysis [2, 9]. Furthermore, integrating new technology with current systems can be complicated, necessitating employee adaptation and training. A further challenge is maintaining and servicing new technologies, which necessitates technical knowledge and more resources [12]. As a result, one of the primary objectives is to guide the selection of automated and AI-based technologies to increase

WMS sustainability.

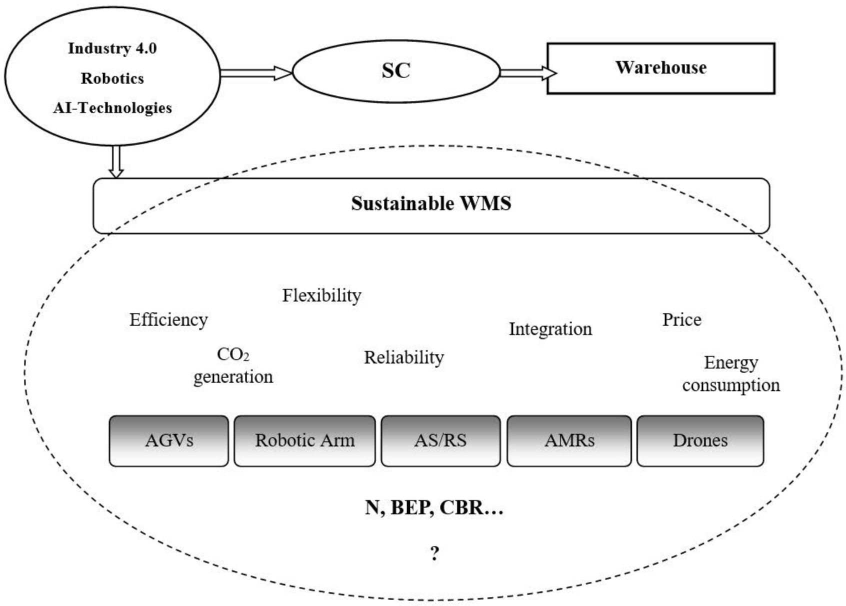

Figure 1. Components of a sustainable WMS

Following the introduction, the second chapter of this study briefly examines advanced technologies in the context of activities for achieving requirements in a sustainable WMS, as well as their advantages and limitations. The third chapter offers a comparative study of the investigated technologies, focusing on the economic viability of their implementation for the requirements of a sustainable WMS. The fourth chapter provides a discussion of the analysis of the researched technologies, along with practical guidelines for choosing the appropriate one. The final discussion provides an overview of the research, limitations, and directions for future analysis.

2 Some Types of Robotic and AI-Based Systems for a Sustainable WMS

Industry 4.0 has generated many technologies that enable more economical handling of materials in the warehouse to increase SC resilience. These modern robots and AI technologies are environmentally friendly as they reduce harmful emissions and resource depletion [1, 6]. They are also socially sustainable because they minimize the involvement of employees in difficult, repetitive, and tiring activities, freeing them from working with hazardous materials harmful to their health [5, 7]. Although AMRs and drones are the most common innovative technologies for a sustainable WMS, this study also explores AGVs, robotic arms, and AS/RS as alternatives for sustainable warehouse material handling, which is critical in sorting, order picking, and packing goods as crucial customer service activities in resilient SC [11, 13]. Therefore, the technologies mentioned above were considered in further detail in this section, with a focus on their applications, benefits, and limitations, as well as potential implementation challenges for a sustainable WMS.

2.1 AGVs for Automation Transportation in the WMS

AGVs are an advanced AI-based technology utilized for various tasks in warehouses and are essential for creating a sustainable WMS, ultimately enhancing the resilience of SC. These devices play a crucial role in the transport of materials, such as moving raw materials, semi-finished products, and finished goods between different sections of a warehouse or production sites [5, 6]. AGVs are also employed for loading and unloading racks automatically, reducing the need for manual labor and accelerating the storage process. Additionally, AGVs can deliver parts and materials directly from warehouses to production lines, ensuring continuous operations. In the order-picking process, AGVs assist by collecting the necessary products, which speeds up the process and reduces errors, contributing to a more sustainable WMS [5, 7]. Furthermore, AGVs support waste management by transporting waste materials from warehouses and production sites to designated disposal or recycling areas, thereby enhancing the environmental sustainability of the WMS.

AGVs symbolize advanced AI-based autonomous technologies that can significantly contribute to a sustainable WMS in several ways [5, 7]:

• Increased efficiency: AGVs optimize the movement of materials within the warehouse, reducing unnecessary paths and time needed to transport goods, which leads to a reduction in energy and resource consumption;

• Warehouse space optimization: AGVs can accurately collect and retrieve goods, enabling better use of storage space, thus reducing the need for warehouse expansion and additional construction work, which has a positive impact on the environment;

• Error lowering: automated transportation reduces human errors in handling goods, resulting in less waste and product losses;

• Energy efficiency: tensioned AGVs are energy efficient and equipped with technologies such as regenerative braking and optimization of energy consumption, reducing the overall carbon footprint of the warehouse;

• Emission reduction: by using electric AGVs instead of fossil fuel vehicles, warehouses can reduce emissions and improve indoor air quality;

• Reduction of physical work: the automation of heavy, repetitive, and tiring jobs reduces the physical effort of employees, thus reducing the risk of injuries and increasing the social sustainability and health of employees;

• Increased productivity: AGVs enable warehouse operations 24/7 without the need for breaks, thereby increasing productivity and reducing cycle time, which can lead to a reduction in overall resource consumption.

The implementation of AGVs in the warehouse brings many advantages, but there are also certain disadvantages and challenges, among which are [6, 7]:

• High initial costs: the engagement of AGVs requires a significant initial investment for the acquisition of vehicles, software, and integration with current systems;

• Integration complexity: incorporating AGVs with the existing WMS and other software platforms can be complex and require significant time, cost, and other resources;

• Dependency on technology: warehouses that depend on AGVs become highly conditional on technology, and failures and software problems can lead to significant disruptions in warehouse processes;

• Maintenance and repairs: AGVs require regular maintenance and can be expensive to repair, while breakdowns can cause downtime in operations, which can be problematic for warehouses with high turnover;

• Additional training: AGVs require employee training to work with the new technology, which may require additional time and resources;

• Limitations in the transport of specific loads: some AGVs are limited in handling specific types of loads or materials, which may require additional adaptations or complementary systems;

• Insufficient flexibility: AGVs are useful for repetitive tasks but may have limited flexibility in adapting to changes in warehouse activities;

• Compatibility with the existing equipment: AGVs may not be compatible with all types of warehouse equipment or infrastructure, which may require additional investment to adapt or replace the existing equipment;

• Safety risks: AGVs improve safety by reducing the need for manual work, but there is the potential for new safety risks associated with automated equipment, such as technical failures or software issues.

Specific advanced AGVs are equipped with automatic inventory control technologies, which allow for accurate tracking of inventory levels in warehouses [2, 6]. By using AGVs in these and similar tasks, WMS can achieve significant time and cost savings, improve the accuracy of operations, and increase the overall productivity of resilient SC [8].

2.2 Robotic Arms for Automation of Handling and Disposal of Goods in the WMS

The use of robotic arms in logistics activities within warehouses in industry processes can significantly enhance the efficiency and sustainability of the WMS by performing various tasks. Robotic arms can handle material by loading and unloading goods, removing them from shelves, and placing them in designated positions in the warehouse, or unloading goods from transport vehicles and arranging them in specific locations [2, 7]. These advanced components also play a crucial role in sorting and packing goods, using visual recognition and sensor technology to automate logistics, process customer orders efficiently, and improve both processing speed and accuracy. By integrating with the WMS, robotic arms can contribute to inventory control by managing the input, output, placement, and tracking of items [6, 7]. They also assist in material handling and SC management by transferring materials between workstations on production lines or managing materials within the warehouse. Additionally, robotic arms are skilled in assembling and packaging products in the warehouse, performing tasks such as assembling parts into finished goods and preparing products for transportation and storage.

Robotic arms, often named industrial robots, provide considerable advantages to operating in warehouses, and some of them are as follows [6, 8]:

• Increased efficiency: robotic arms can work 24/7 without the need for breaks or rest, which significantly increases productivity and reduces productive time;

• Improved accuracy and precision: robotic arms are precise and can repeat tasks with a high level of accuracy, reducing product handling errors and improving work quality;

• Flexibility in tasks: advanced robotic technologies are highly flexible and programmable to perform a variety of tasks, ranging from packaging and picking to material handling and transportation;

• Reduction of labor costs: regardless of the potentially significant initial investment in robotic arms, long-term labor costs are reduced as robots replace manual labor and reduce the need for large numbers of employees;

• Increased safety: robotic arms carry out dangerous, difficult, and repetitive tasks, reducing the risk of worker injuries and improving the safety of the work environment, thereby affecting the social sustainability of the WMS;

• Waste reduction: accurate handling of goods reduces damage and waste, thereby increasing efficiency and reducing damages and losses, which has a positive impact on the economic and environmental components of the WMS sustainability;

• Integration with the WMS and other systems: robotic arms can be combined with the WMS and other software platforms, enabling better coordination and optimization of operations;

• Space optimization: robotic arms can work in compact and optimized spaces, enabling better use of storage space and reducing the required workspace;

• Reduced physical effort for employees: by performing physically demanding tasks, robotic arms reduce physical stress for workers, allowing them to focus on more complex and innovative activities.

Analogous to all modern robotic technologies, robotic arms have certain disadvantages that generate numerous challenges as follows when they are involved in practical assignments [7, 9]:

• High initial costs: procurement, installation and integration of robotic arms into the existing WMS require a significant initial investment, which can be a barrier for smaller warehouses or companies with limited budgets;

• Maintenance and repair costs: robotic arms require regular maintenance and can be expensive to repair, and failures generate delays in the implementation of logistics activities in the warehouse due to a lack of parts;

• Employee training required: implementing robotic arms requires training employees to work with the new technology, which may require additional time and resources;

• Limited flexibility: although robotic arms are flexible in many tasks, rapid and unpredictable changes in warehouse operations may require additional reprogramming or adaptation of the robot;

• Technological dependence: warehouses that rely on robotic arms become highly dependent on technologies as software problems can lead to significant disruptions to warehouse operations;

• Safety risks: although robotic arms can reduce the risk of injury to workers, there is the potential for new safety risks associated with automated equipment, such as technical malfunctions or software problems;

• Limitations in handling specific and non-standard loads: some robotic systems may have limitations in handling certain types of loads or materials, which may require additional adaptations or specialized complements.

Furthermore, robots can quickly modify operations to meet changing demands for production or warehousing, allowing for a prompt response to deviations in customer demand [9, 12]. These modern approaches ensure the effectiveness of the logistics activities performed in the warehouse. Robotic arms speed up production and warehouse operations overall by completing tasks faster and more correctly than human workers, which implies that user requests get processed faster [8].

2.3 AS/RS for Optimizing Warehouse Space in the WMS

AS/RS are advanced systems developed for storing and retrieving goods in warehouses and production facilities, aimed at optimizing operations and improving efficiency. They are widely used in the WMS for various logistics, manufacturing, and other tasks. In high-bay warehouses, AS/RS are employed to automatically store and retrieve pallets or individual items from high shelves, maximizing the vertical space available in the warehouse [4, 10]. They are also suitable for storing and retrieving small parts or components, particularly in industries such as electronics and automotive. These systems play a crucial role in inventory control by providing accurate tracking and reducing errors, which improve the reliability of warehouse data and contribute to the economic sustainability of the WMS. Additionally, AS/RS facilitate the fast rotation of high-turnover products, enhancing inventory management efficiency and reducing cycle times, thereby increasing the overall WMS sustainability [11, 12]. Furthermore, AS/RS are used for handling special materials, such as storing products that require specific conditions, such as refrigerated items in the food or pharmaceutical industries, thus promoting the social sustainability of the WMS.

AS/RS are assessed as an advanced AI technology that provides the warehouse with many advantages as follows [11, 13]:

• Increasing storage capacity: AS/RS enable dense packing and optimized use of storage space, increasing warehouse capacity without the need for additional space;

• Increasing picking efficiency: AS/RS allow quicker and more accurate picking of orders, reducing the time needed to find and pick up items;

• Employee decrease: automated warehouse operations reduce the need for manual labor, thereby reducing labor costs and increasing worker safety;

• Increasing warehouse safety: AS/RS reduce the risk of damage to goods and improve warehouse safety, as the need for manual handling of heavy and bulky items is lowered;

• Integration with the WMS: AS/RS can be effectively integrated with the current and advanced WMS, enabling automatic coordination and optimization of warehouse operations.

Although AS/RS provide many advantages, the following disadvantages and challenges should be considered before implementing them in the warehouse [12, 13]:

• High initial costs: AS/RS installation requires a significant initial investment, including equipment, software, and building costs, which can be challenging for smaller company warehouses with limited budgets;

• Insufficient flexibility: AS/RS are often designed for specific tasks or product types, which can limit their flexibility in the event of changes in storage requirements initiated by the end user;

• Implementation complexity: integrating AS/RS into existing warehouse operations can be complex and time-consuming, requiring careful planning and coordination, as well as significant changes to the WMS;

• Maintenance and servicing: AS/RS require regular maintenance and can be expensive to repair, while breakdowns generate significant downtime in warehouse activities, affecting the WMS viability, especially when spare parts are not available;

• Limited interoperability: some AS/RS may be less compatible with existing technologies or software platforms in the warehouse, which may require the deployment of other technologies and additional costs.

The quickness at which systems are being adopted at various warehouses has increased significantly as a result of the rapid development of AS/RS technology and the availability of new options that provide a wide range of sizes, speed, affordability, and flexibility [10, 13]. AS/RS technologies are among the most widely used and advantageous investment solutions, particularly for requirements in warehouse systems, since the majority of enterprises can now afford them [1, 12]. A series of computer-controlled systems known as AS/RS are used to automatically deposit and retrieve products from designated locations to hold new shipments and fulfill orders, which makes them more flexible for integration with current technologies in a sustainable WMS.

2.4 AMRs as a Full Autonomous Technology for Sustainable WMS Activities

AMRs are vital for a sustainable WMS due to their ability to perform numerous operations. These robots autonomously navigate the warehouse, performing various logistics tasks such as order picking, sorting, inventory management, and goods transfer. One of their main functions is to transport goods between different areas of the warehouse, such as receiving, storage, and delivery zones, significantly reducing the need for manual labor [2, 12]. They also assist in warehouse and sorting tasks by automatically storing goods in designated locations using predefined algorithms and quickly retrieving them when needed. In addition, AMRs can sort products based on criteria like size, weight, or delivery destination and aid in the packing process by bringing required items to packing stations [11, 13]. The technology enables efficient order picking by following predefined instructions. When working alongside human employees, AMRs optimize the process, reducing time and increasing accuracy, contributing to sustainable logistics activities. Furthermore, AMRs automate loading and unloading of trucks, shortening the time required for these tasks by automatically picking up goods from the entrance and transferring them to the appropriate locations in the warehouse.

By engaging AGVs, all aspects of the WMS sustainability are not only improved, but numerous advantages are also realized as follows [11, 12]:

• Increased efficiency: AMRs can work continuously 24/7, without the need for breaks, which increases overall productivity and reduces the time required to complete tasks;

• Reduced labor costs: automation reduces the need for manual labor, which can reduce operating costs and the risk of occupational injuries;

• Decreased energy consumption: AMRs use optimized routes and algorithms to reduce unnecessary movement, resulting in lower energy consumption compared to traditional technologies that are associated with forklifts;

• Optimizing the use of space: AMRs can operate in narrow and hard-to-reach spaces, which allows for efficient utilization of warehouse space;

• Environmental efficiency: more efficient resource management and a reduction in the need for physical transportation can contribute to a reduction in overall CO_2 emissions.

Despite the significant advantages in the engagement of AMRs for the purposes of improving the WMS sustainability, this technology also has certain disadvantages as follows [2, 11]:

• Significant initial costs: investment in AMR technology can be high, including costs for robots, software and infrastructure;

• Integration complexity: integration of AMRs into an existing WMS can be technically demanding and may require adaptation of existing processes and systems;

• Maintenance and servicing: due to the innovative technology, AMRs require regular maintenance and occasional repairs, which can represent additional costs and complexity due to the lack of authorized service centers, parts and experts;

• Security challenges: robotic technology can pose security risks if not properly configured and monitored, especially in environments with human workers;

• Limitations in flexibility: although AMRs are highly adaptable, there may be limitations in terms of adapting to specific needs or contingencies of the warehouse environment.

Incorporating AMR technology in a WMS can considerably improve operational sustainability and efficiency, but it is critical to thoroughly consider the costs, technical needs, and potential issues before making an investment decision [12, 13]. As a result, before investing in AMRs, a company needs to evaluate its own economic potential in order to ensure that it can fully realize the benefits of this ecologically beneficial and socially sustainable technology.

2.5 Drones for Response Efficiency in Sustainable WMS Activities

Drones describe the cutting-edge, AI-based technology increasingly used in the WMS to enhance the efficiency, accuracy, and safety of logistics operations. Their primary function is to transport small quantities of goods over short distances, but they also provide significant benefits in various aspects of warehouse management. One of the key applications of drones is inventory tracking, where they continuously scan barcodes and Radio-Frequency Identification (RFID) tags, allowing for real-time tracking of product quantities and helping identify shortages or overstock circumstances [3, 5]. In addition, drones play a crucial role in supervision and security, as they can quickly inspect large warehouse areas, identifying potential security threats such as theft or vandalism, thereby enhancing the overall safety of the facility. Drones are also utilized for inspecting hard-to-reach or hazardous areas within the warehouse, such as high racks, ventilation systems, or storage areas that would typically require specialized equipment for human access. This not only improves safety but also streamlines maintenance processes. Moreover, drones are used for transporting small packages within the warehouse, reducing the need for manual labor and speeding up the delivery process, especially in large or multi-level facilities [2, 12]. In emergencies, drones can quickly deliver tools or materials needed for repairs or interventions, using their ability to navigate through the plant's vertical space effectively.

The use of drones in warehouses provides numerous advantages from the perspective of a sustainable WMS as follows [5, 12]:

• Increased efficiency: drones make it possible to quickly search and find products in large warehouses, reducing the time needed for searching and picking;

• Inventory management automation: equipped with sensors and cameras, drones automatically scan barcodes and RFID tags, reducing the need for manual inventory counting and checking;

• Improved safety: drones can carry out inspections of hard-to-reach areas of the warehouse, reducing the risk for workers, especially when working with hazardous goods;

• Increased accuracy: precise tracking of inventory and product positions reduces the possibility of human error;

• Cost reduction: process automation using drones can reduce labor costs and storage errors, which can contribute to the economic viability of the WMS in the long run.

Although suitable for increasing the WMS sustainability, drones have certain disadvantages and limitations in implementation for the realization of warehouse activities as follows [2, 5]:

• Significant initial costs: purchasing drones and implementing the necessary technology can be expensive, representing a significant initial investment;

• Maintenance and updates: drones require regular maintenance, software updates and staff training to use them, which can add additional costs and complexity;

• Technology limitations: the current drone technology may have limitations in terms of payload, battery life, and accuracy of indoor navigation;

• Security and regulatory challenges: the requirement to update existing legislation and the need to comply with regulations and safety standards related to the use of drones can be complex, costly, and time-consuming;

• Integration with existing systems: implementing drones requires integration with the existing WMS, which can be technically challenging and require customization.

Drones in the warehouse provide flexibility and efficiency, contributing to better inventory management and increased safety [11, 12]. At the same time, the use of drones reduces the costs and time required to carry out warehouse operations, which contributes to the economic viability of the WMS.

3 Comparative Analysis of Various Robotic and AI Technologies for the Needs of a Sustainable WMS

The selection of appropriate robotics and AI technology is not simple and generally signifies a key challenge in the context of increasing the WMS sustainability. To realize the user's requests, a quick response, reliability in the realization of the order, accuracy, and flexibility in delivery are required, all at acceptable costs [1, 13]. The conflicting requirements of users and service providers further question the selection of technologies that should satisfy all the requirements of a sustainable WMS [2, 3]. Therefore, it is necessary to provide insights into the comparative analysis of robotic and AI technologies that contribute to increasing the resilience of SCs through a sustainable WMS (Table 1).

Table 1. General comparative analysis of robotic and AI technologies for the needs of a sustainable WMS

Comparison Attributes	AGVs	Robotic Arms	AS/RS	AMRs	Drones
Efficiency	High	Medium to high	High	High	Medium
Flexibility	Medium	High	Low to medium	High	High
Reliability	High	High	High	High	Medium to high
Price	Medium to high	Medium to high	High	Medium to high	Medium
Integration	Medium	High	Medium to high	High	Medium
Energy consumption	Medium	High	Medium to high	Low to medium	High
Environmental friendliness	Medium	Medium	High	Medium	High
Convenience for employees	High	High	High	High	High
Complexity of the training	Medium	Medium	Medium	Medium	High
Adaptation period	Medium	High	High	Low to medium	Medium

AMRs are robots that move around the warehouse autonomously, using sensors and advanced algorithms for navigation. They are highly flexible and can be used for various tasks, such as transporting goods or filling shelves. AGVs are vehicles that move along predetermined paths, often using magnetic strips or laser guides. Although less flexible than AMRs, AGVs are very reliable and can significantly increase efficiency in warehouses [11, 12]. Robotic arms are designed to work close to humans [4, 13]. They can perform tasks such as packing, sorting, and assembly. Flexibility and safety make them suitable for various warehouse applications. AS/RS are sophisticated systems for automatic storage and retrieval of goods. They are very effective but can be expensive and less flexible compared to other technologies [12, 13]. Drones are used for inventory and inspection of warehouses. They enable quick and efficient inspection of high shelves and hard-to-reach places [2, 5]. Energy consumption is a significant challenge when implementing robotic and AI-based technologies for the needs of a sustainable WMS. AGVs have a lengthy working life because of the batteries they use, but because they have to start and navigate the warehouse frequently, their energy consumption can be categorized as medium [2, 6]. The robotic arm uses a lot of energy during startup, accurate positioning, and stability maintenance [3, 5]. Energy is used by AS/RS to move storage units both horizontally and vertically. Their size and complexity determine how much is consumed, but it typically ranges from modest to high [6, 10]. Because AMRs use sophisticated algorithms to optimize routes and reduce energy consumption, they are energy-efficient devices that can operate over extended periods while using less energy [2, 14]. Drones require a lot of energy to power their rotors and keep them stable in the air, especially the more capable models that fly for extended periods or accomplish challenging tasks [5, 15]. Although employee convenience is high for all systems, environmental friendliness, and training complexity vary [11, 12]. While robotic arms and drones are more ecologically friendly, their utilization of the warehouse's height necessitates more difficult training due to understanding both the technologies and the warehouse's layout [8, 9]. In contrast, AGVs and AMRs require less training [6, 7]. Although they require considerable training, AS/RS offer high levels of employee convenience and environmental friendliness [4, 14].

During the implementation of contemporary technologies in the WMS, the time required for the adaptation of the preferred technology to the existing ones is of significant importance to the company. Thus, AGVs require a certain amount of time to map the warehouse, set up routes, and integrate with the existing WMS because they need additional time for adding markers and tapes and so on [9, 11]. Implementing robotic arms often requires significant changes to the physical layout of the warehouse, programming of specific tasks, and adjustments of software integration with the WMS, which can be a complex and time-consuming process [11, 14]. AS/RS require significant infrastructural changes, including setting up storage units, modifying existing layouts, and thorough integration with the WMS, all of which require considerable time [13, 14]. In contrast, highly flexible AMRs are designed to be easily integrated with existing systems. The process includes storage mapping and software configuration but often does not require significant physical changes, which reduces adaptation time [8, 15]. The integration of drones may require the adaptation of inventory management software and procedures. Although it does not require significant physical changes, it takes time to reprogram routes and train employees, as well as adopt legal regulations when using drones [14, 15].

Table 1 provides a preliminary insight into the analyzed technologies that, when choosing the optimal one, indicates to companies the level of efficiency, flexibility, reliability, price, and the possibility of integration with existing systems in the warehouse. A comparative analysis is also provided for the aspects of energy consumption, environmental friendliness, employee benefits, training requirements, and the time of adaptation to the existing WMS. Based on this comparison, the company can have a basis for further analysis, which narrows its choice according to its requirements.

The prioritization of technologies for a sustainable WMS implies the engagement of environmentally friendly alternatives that can reduce environmental pollution and energy consumption and are based on sustainable energy sources. These technologies must be socially sustainable, reducing labor involvement in processes that involve handling heavy and bulky materials. Both of these aspects mandate the elimination of employees working directly with hazardous materials [13, 14]. As these pillars of the WMS sustainability are met by the development of robotics and AI technologies, companies face cost challenges. Accordingly, to rank robotic warehouse technologies with a budget, it is necessary to include cost estimates (including initial costs, maintenance costs, and operational costs) and their overall value for warehouses of different sizes and types. The operating costs of robotic technologies in warehouses include not only energy consumption but also maintenance costs, parts replacement, staff training, software upgrades, and other relevant costs [14, 16]. The energy efficiency of robotic technologies in warehouses is an important aspect of optimizing operating costs and reducing carbon footprints. Constantly improving technology and managing energy use can lead to significant savings and increased environmental sustainability. Energy consumption of different robotic technologies in warehouses varies depending on specific tasks, frequency of use, load, management method, and other factors [5, 13]. The environmental expenses of robotic technologies significantly depend on the way they are used, the type of batteries, resources required for production, and disposal procedures, while CO_2 emissions in production, use, and disposal are important for the WMS sustainability [16, 17]. Labor costs for deploying robotic technologies in warehouses can vary significantly depending on the complexity of the technologies, the training required to operate the technologies, and the additional personnel required for supervision and maintenance. Accordingly, some critical guidelines for a comparative analysis of the researched AI technologies from the aspect of the economic benefit of their implementation are given in Table 2.

Table 2. Comparative analysis of the profitability of implementing robotic and AI technologies [18–22]

Comparison Criteria	AGVs	Robotic Arms	AS/RS	AMRs	Drones
Acquisition costs (cca $ / vehicle) [1] in .000 $ / year	50-200	25-100	500-1,000 Most expensive	100-500	10-50 Cheapest
Maintenance costs (% of aq. costs per year) [2] in .000 $ year	5 2.5-10	5 1.5-5	7 35-70 Most expensive	5 7.5-35	10 1-5 Cheapest
Energy consumption (kWh/day)	2-5	0.5-2.5 Cheapest	5-10 Most expensive	3-6	1-2.5 Cheapest
Software upgrades and licenses (cca $ / year) [3]	2,000	3,000	5,000 Most expensive	3,000	1,500 Cheapest
Annual CO_2 generation in kg	300-500	150-250 Favorable	500-800 Unfavorable	350-600	150-300 Favorable
Labor Costs (in . 000 $/year) [1]					
Operators Technicians Training course total [4]	25-40 35-50 5-10 65-100	30-45 40-55 5-10 75-110	33-55 45-55 7-15 85-125 Most expensive	25-45 35-55 5-10 65-110	23-37 32-48 5-10 60-95 Cheapest
N refund period (year per 1 device) [5]	1.78	0.85	5	3.38	0.49
Break-even point (in units) [6]	1.040	727	4.000	2.160	505
CBR cost-benefit analysis [7]	1.33	1.47	0.51	1.31	1.35

Source: [1,2] commercial websites of companies: Walmart, Amazon, FedEx, DHL, etc. [3,4,5,6,7] references [18–22]

Considering that all technologies minimize resource depletion and reduce pollution of the environment, it is evident that they respect environmental sustainability. Furthermore, robotic and AI technologies are also socially sustainable because they were initially developed to minimize employee engagement in tough and exhausting tasks while also eliminating the need for workers to handle hazardous chemicals. Nevertheless, one of the first issues to consider when a company is considering a certain technology is the possibility that it can provide an economic return on investment due to engaging financially demanding advanced technologies for a sustainable WMS.

To calculate how many years the investment can pay off, the formula for the investment return period (payback period) was used in this study. This formula determines the time required to recover the initial investment costs. The formula for investment payback period is as follows [17, 19, 20]:

$$N = \frac{I}{P - C}$$

where, N is the number of years required for the investment to pay off; I represents the investment costs; P is the annual income from investment; and C represents the annual costs.

Assuming that the annual return on investment (P) is not specified by the company's data protection policy, the annual costs for maintenance, software and labor are used to calculate the minimum savings or income required to cover these costs. In this case, the formula can be simplified as follows [19, 21]:

$$N = \frac{I}{C}$$

Based on the total annual costs and investment in Table 1, the payback period for AGVs is less than two years, whereas for drones, it is less than half a year. Conversely, the investment in AS/RS exhibits the longest payback period, which aligns with their high initial costs and substantial maintenance, labor, and periodic software upgrade expenses. In addition to calculating how long it takes to return the investment, a company that invests in new robotic and AI technologies for a sustainable WMS attempts to determine at what point it starts to make a profit. This indicates that the Break-Even Point (BEP) estimates the point at which total revenues and total costs equal one another, or the point at which a company produces a profit [17, 19, 20]:

$$BEP = \frac{\text{fixed costs}}{\text{price per unit} \; - \; \text{variable costs per unit}}$$

where, fixed costs incorporate acquisition costs of maintenance, software, and labor. Given that the cost prices and costs of logistics activities in the warehouse are variable and mainly depend on the type of product for which the calculation is carried out for analysis, the following values are hypothetically assumed:

- Price per product unit: 500
- Variable costs per product unit: 200

Cost Benefit Analysis (CBA) is considered one of the most beneficial analyses for a company looking to invest in modern robotics and AI technologies for a sustainable WMS. CBA is a methodological approach that is usually carried out for at least five years and is one of the key indicators of the relationship between income and investment. If the ratio is greater than 1, the benefits of the investment exceed the cost, which means that the investment is profitable. If the ratio is less than 1, the investment is not profitable [21, 22].

Given the sophistication of the analysis, which requires revenue estimates based on previous observations, market forecasts, and the experience and skills of the company's managers, it is obvious that the calculation must be repeated several times to obtain relevant results that support the implementation of a certain alternative. According to this estimate, investing \$1 yields \$1.47 when using robotic hands, making the investment profitable. The CBA for AS/RS implementation is less than one, hence it is not recommended to invest in this technology.

$$CBR = \frac{\text{total costs}}{\text{total benefits}}$$

$$\text{Total costs} \;=\; \frac{\text{aquisition costs}}{(\text{maintnenace costs+labor costs}) \times 5 + \text{software costs}}$$

4 Implementing Investigated Robotic and AI Technologies to Increase WMS Sustainability

In implementing particular robotic and AI-based technologies in the warehouse to increase the WMS sustainability, it is essential to comprehend the techno-exploitation parameters of the technology as well as the social and environmental advantages of their employment. However, the company primarily analyzes its economic possibilities, i.e., economic viability, when applying advanced technologies. For this purpose, Table 2 was created in this study, which provides an insight into certain economic indicators based on which the cost-effectiveness parameters of the implementation of each examined technology were calculated. Acquisition costs, maintenance fees, and software expenses, along with labor costs, enabled the calculation of the payback period and BEP of the CBA. These analyses indicate that AS/RS technology is economically the most unsustainable and that, for its implementation, companies must consider the need and the activities it would implement. In addition, this technology is also low in flexibility, which indicates that it is difficult and takes a long time to adapt to new changes in the layout of the storage facility (Table 1). Even if it is highly sophisticated, environmentally friendly, and socially sustainable, it still requires significant investments and high implementation costs. Unlike this technology, using drones requires less investment.

However, the company must look at other techno-operational characteristics of the technologies, their possibilities and requirements for the needs of a sustainable WMS [23, 24].

AS/RS multi-component advanced technology is designed to utilize the height of the warehouse to quickly take products from the shelves, and is a fully automated system that is socially sustainable because there is no requirement to hire workers. It increases the utilization of storage space by at least 50%; therefore, its application is justified in warehouses that have a challenge related to maximizing the utilization of storage space. The insufficiency of the flexibility of AS/RS can be compensated by integration with other technologies, such as drones, which are intended for handling smaller loads at short distances and hard-to-reach positions. Drones are also suitable for monitoring the warehouse, but due to their low battery capacity, they are not suitable for transporting goods in the warehouse. This shortcoming can be compensated by AGVs as a reliable technology for the transportation of heavy and bulky goods in the warehouse. Even though these devices go on predetermined routes, this technology offers higher flexibility than AS/RS. However, all the need to eliminate workers from tedious and repetitive activities as well as engagement in working with hazardous materials is replaced by robotic arms and AMRs. Robotic arms have a high level of precision and accuracy in performing tasks such as packing, moving, and assembly. They can work 24/7 without breaks, increasing overall productivity, which also applies to AMRs. Although these two technologies do not require changes to the infrastructure of the warehouse facility, they can be cost-challenging as they require additional training and appropriate software support.

AGVs are self-moving vehicles that were first intended to be a superstructure for forklifts. AGVs can handle hazardous materials, including explosives, which is one of its numerous advantages over forklifts [10]. Because of their additional electrical components and explosion-proof construction, those devices can function in high-risk areas. When being given instructions, AGVs can follow a predefined path and stop at a certain location in the warehouse. Robotic arms are specialized for precise handling and manipulation of goods, often in stationary workplaces. They can carry out packing, sorting, and order picking with high accuracy and repeatability. They are also used to reduce errors caused by employees who need to be replaced in difficult and repetitive activities in the WMS. Despite being designed to automate warehouse tasks, AS/RS serve as the foundation for lowering losses and boosting material handling productivity in industrial operations. This technology, however somewhat pricey, makes it possible to utilize storage space more effectively, opening up possibilities for increasing the area set up for industrial operations. Inadequately configured AS/RS at startup could drastically lower material handling efficiency [20, 23]. Thus, the primary drawback of AS/RS is the requirement for a more rational route design for the goods drop-off and pick-up system, which is required to improve material handling efficiency. As AS/RS are put into practice, they can assist logistics companies in increasing space utilization, preventing product damage, and reducing energy consumption, all of which are considered significant benefits. While some AMRs employ free navigation with lasers, other technologies use fixed features like beacons, magnetic strips, and magnets to locate themselves. These features imply that because of their dynamic and efficient employment allocation, AMRs are more effective when paired with other technologies in warehouses and collaborative work environments. Additionally, compared to AGVs supplemented by robotic arms, AMRs have far more sophisticated hardware and software that enable more effective applications for the requirements of a sustainable WMS. Their efficiency is confirmed by more than 200,000 AMRs engaged in Alibaba and Amazon. Drones are regarded as the most controversial autonomous material-handling technology. They have benefits such as eliminating the need for workers to touch materials, managing all industrial operations to save downtime, and the environmental benefits of using less electricity. However, the biggest barriers to their deployment are their restricted range and carrying capacity as well as the lack of adequate legal control. Since this technology may increase material handling volume up to four times, it is being employed more and more for sustainable material handling [1, 11]. The main reason it is used is that it can be easily integrated with other technologies, such as AGVs and AMRs.

5 Conclusions

Optimizing all current warehouse practices has a direct link to how agreeably Industry 4.0 works and the level of autonomy used to carry out vulnerable material handling tasks and challenging logistics assignments. Due to growing e-commerce, widespread digitalization, and urbanization, companies are trying to improve their operations by introducing new autonomous technologies, strengthening customer support, and expanding their distribution network. Consumers prefer companies that can deliver items more quickly and affordably than competitors while still providing them with all the advantages of online ordering without limitations for buying in retail stores. Due to transferring logistic activities from production to the warehouse, deploying autonomous material handling technology provides the basis for a sustainable WMS. However, the selection of the appropriate technology for a sustainable WMS is dependent on not only the specific needs and goals of the warehouse but also the user's requirements and the need for increasing SC resilience. Accordingly, AMRs and robotic arms are suitable for flexible and diverse tasks, while AGVs and AS/RS are extremely efficient for highly specialized operations. Drones also have specific advantages, predominantly in control activities, and can be used as part of an integrated system to maximize the

WMS sustainability.

In practice, there are numerous positive experiences regarding incorporating advanced Industry 4.0 technologies in the current WMS. Amazon has implemented a combination of Kiva robots, computer vision, and machine learning algorithms to optimize their fulfillment centers, significantly reducing the time from order placement to delivery. The British online supermarket Ocado uses sophisticated AS/RS and AI-driven logistics to ensure efficient and accurate order fulfillment. According to Deloitte, deploying robotic technologies can lower operational costs by 50%. Besides, Amazon Fulfillment Centers use AMRs to transfer goods between different parts of the warehouse. Toyota factories use AGVs to transfer parts between production lines. DHL uses robotic arms for packing and sorting tasks. Wal-Mart uses AS/RS to store and retrieve goods quickly and accurately. IKEA uses drones for inventory and warehouse inspections.

Regarding the examples of good practices, the technical characteristics of advanced technological solutions, and the requirements for improving the WMS sustainability, companies face numerous challenges in adopting robotic and AI alternatives in warehouses. Specifically, the warehouse is a critical part of the SC because it integrates the activities of production companies and those in service of users. As current geopolitical circumstances focus on e-commerce and online ordering, the warehouse requires a sustainable WMS to increase SC resilience. Consequently, companies often resist the benefits of advanced Industry 4.0 technologies due to the high costs of their implementation, demanding maintenance, the need for additional employee training, and so on. However, from the perspective of a sustainable WMS, these technologies are environmentally friendly because they use clean propulsion, reduce harmful emissions, and reduce energy consumption. They are also socially acceptable because they were developed to replace a person in difficult, tedious, and repetitive jobs, which encourages their creativity at work. Contrary to the mentioned benefits, there are certain limitations in the implementation of the analyzed technologies as follows:

- Electric drives are often replaced by those with fossil fuels;
- Among employees, there is a justified fear of losing their jobs, especially for the lower-qualified workforce;
- The implementation of advanced technologies brings numerous challenges in terms of economic sustainability.

Considering the numerous contradictions of the analyzed technologies, Tables 1 and 2 provide some basic guidelines for choosing a technology for the needs of a sustainable WMS. Thus, for drones and robotic arms, it is concluded that they are solutions that are not expensive to implement and maintain, are flexible with existing WMS technologies, and are environmentally friendly because they consume little energy, which is why they have low costs of exploitation. However, because such devices have limited carrying capacity and are not self-sufficient in completing storage tasks, they have the greatest potential for integration with existing technologies, as well as with AMRs, AGVs, and AS/RS, which are sophisticated advanced technologies that independently perform storage activities, increasing the WMS sustainability. However, AS/RS are expensive to implement and maintain and have high exploitation costs, but they are one of the most commonly used advanced technologies because they contribute the most to increasing the utilization of storage space. Given the growing importance of a sustainable WMS in resilient SCs, this technology is optimal for warehouses with a high turnover of goods. In contrast to these solutions, AMRs and AGVs are technologies that meet all the pillars of a sustainable WMS. The key difference is their primary activity, with AGVs for transport and AMRs primarily for material handling.

Data Availability

Not applicable.

Conflicts of Interest

The author declares no conflict of interest.

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