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Selecting Optimal Alternatives for Sustainable Intralogistics in Automotive Industry Warehouse Supply Chains

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Abstract: Intralogistics activities within automotive industry warehouses play a critical role in the efficient management of materials, components, and finished goods throughout production and distribution processes. These activities contribute significantly to the optimization of warehouse space, reduction of delivery lead times, and minimization of storage costs. Furthermore, effectively implemented intralogistics processes are essential for ensuring continuous production and the timely delivery of high-quality products to customers. This study focuses on the enhancement of sustainability in intralogistics operations within warehouses by adopting innovative technologies, optimizing resource utilization, and minimizing environmental impact. The automotive industry's supply chain was examined, with particular emphasis on the challenges associated with intralogistics and sustainability. The study explores the optimization of warehouse intralogistics processes, which directly affect operational efficiency, cost reduction, and overall productivity. Based on the identified challenges, three potential solutions—mini-load (ML) Automated Storage and Retrieval System (AS/RS), AutoStore systems (ASSs), and Autonomous Mobile Robots (AMRs)—were analyzed through a sustainability lens. The evaluation of these technologies was conducted with respect to various sustainability criteria, such as energy consumption, space efficiency, cost-effectiveness, and environmental impact. The primary objective is to identify the most suitable solution for improving the sustainability and operational efficiency of intralogistics processes within the automotive industry. By investigating the potential of these innovative technologies, the research aims to provide a comprehensive understanding of how they can address contemporary intralogistics challenges, enhance operational performance, and align with the broader objectives of environmental sustainability and cost optimization.

Keywords: Supply chains; Automotive industry; Robotic technologies; Sustainability

1 Introduction

The supply chain in the automotive industry represents a complex system encompassing all stages, from the procurement of raw materials to the delivery of finished products and spare parts to end customers. This supply chain involves a global network of suppliers providing all necessary components for production, where the efficiency of its operation has a direct impact on the competitiveness and success of companies in the market [1]. With growing demands for greater flexibility, faster responses to changes in demand, and reduced environmental impact, sustainability is becoming an increasingly important factor in optimizing supply chains and intralogistics. The automotive supply chain operates in a highly dynamic and competitive environment, where the ability to adapt and implement sustainable practices is critical for maintaining market relevance and meeting regulatory requirements. Intralogistics plays a key role in the efficient management of materials and information within the supply chain, acting as the backbone for the seamless flow of goods and resources. The sustainability of intralogistics activities has an essential effect on the sustainability of the entire supply chain. This includes not only environmental considerations, such as reducing carbon emissions, but also operational efficiency, waste minimization, resource optimization, and long-term cost reduction [2]. By incorporating sustainable intralogistics practices, companies can achieve significant improvements in productivity and cost-effectiveness while addressing global challenges such as climate change and resource scarcity. These practices might include the adoption of advanced technologies, such as AS/RS, robotics, and real-time data tracking, all of which contribute to more sustainable operations by enhancing precision, reducing energy consumption, and minimizing waste. In this context, sustainability is no longer viewed solely as an environmental imperative but also as a strategic approach to improving resilience, fostering innovation, and ensuring long-term business success in the automotive sector. Thus, the integration of sustainable intralogistics activities is vital for achieving a balance between economic goals, environmental stewardship, and social responsibility.

The automation of manufacturing and intralogistics processes plays a crucial role in enhancing sustainability by enabling more efficient resource utilization, reducing errors and waste, improving the accuracy and speed of operations, and directly addressing challenges such as delays, product damage, and incorrectly picked goods. Automation not only streamlines operations but also contributes to the broader goals of sustainability, efficiency, and cost reduction, which are essential for long-term business viability [3]. This study analyzes a problem faced by a logistics company supplying automotive parts through its distribution warehouse. Issues such as delays in order preparation, product damage, and incorrectly picked items for shipment negatively impact operational efficiency and increase costs, posing a threat to the long-term sustainability of the business. From a sustainability perspective, these problems lead to unnecessary resource consumption, reduced efficiency, and an increased environmental footprint due to the need for repeated deliveries or reprocessing of damaged products [1, 3]. The proposed solutions to these challenges focus on improving the sustainability of intralogistics activities within the distribution warehouse by implementing automation technologies. The key solutions under this research consideration include:

a) ML AS/RS enables the automated storage and retrieval of smaller loads, optimizing space utilization and reducing human intervention. This advanced technology minimizes errors, enhances efficiency, and reduces energy consumption, contributing to both operational and environmental sustainability [4].

b) ASS is a highly efficient storage system that uses robots to retrieve and deliver goods. This solution drastically reduces the space required for storage, increases picking speed, and minimizes the risk of product damage, all while consuming less energy than traditional warehouse systems [5].

c) AMRs are widely used robotic solutions capable of navigating the warehouse independently. They streamline material handling processes, reduce the risk of errors, and enable faster order fulfillment. Additionally, their energy-efficient operation and adaptability make them ideal for addressing sustainability goals in modern warehouses [6].

By integrating these automation solutions, the company can address the identified problems effectively. Automation reduces delays in operations, minimizes the risk of product damage, and eliminates errors in order picking. From a sustainability perspective, these technologies ensure optimized resource usage, reduced waste, and a smaller carbon footprint. In addition to operational benefits, the adoption of these solutions enhances the company's ability to meet growing market demands for flexibility, speed, and eco-friendly practices [1, 4]. It also positions the company as a forward-thinking industry leader, aligning its intralogistics operations with global trends in sustainable development and innovation. Thus, automating intralogistics processes not only resolves immediate operational issues but also lays the foundation for long-term competitiveness, environmental responsibility, and long-term sustainability [6].

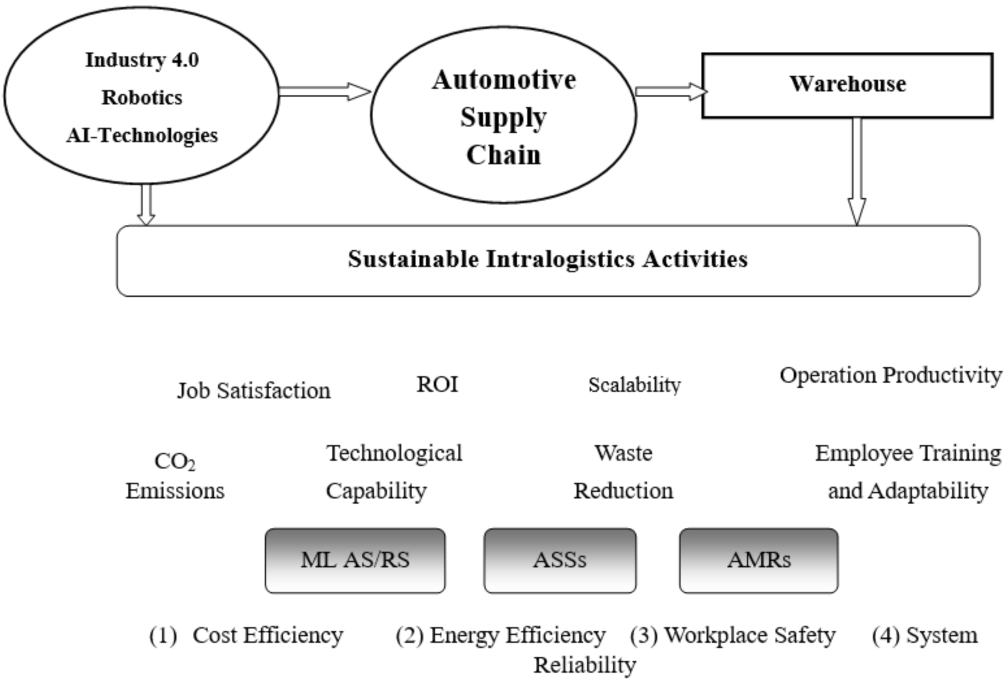

Figure 1. Components of a sustainable WMS

Following the introduction, the first chapter of this study provides a comprehensive investigation of the supply chain in the automotive industry, highlighting its key characteristics and the dominant challenges it faces. This chapter examines the complexities of global supply networks, the need for real-time adaptability, and the growing pressure to incorporate sustainability into all stages of the supply chain. Particular emphasis is placed on the interconnection between supply chain efficiency and sustainability, as well as the role of technological innovation in addressing these challenges [2, 3]. The second chapter delves into a detailed analysis of the specific problem encountered by the logistics company under study, which serves as a supplier of automotive parts. The issues examined include delays in order preparation, product damage, and errors in item picking, all of which disrupt operational efficiency, increase costs, and compromise the company's dedication to sustainability. These inefficiencies not only strain the company's ability to meet market demands but also contribute to increase waste, unnecessary energy consumption, and higher emissions due to remanufacturing and repeat shipments [7]. The chapter underscores the critical challenges for achieving operational excellence, environmental responsibility, and social sustainability. The third chapter analyzes and evaluates alternative solutions for addressing the identified problems, with a focus on enhancing the sustainability of intralogistics operations. The proposed alternatives include ML AS/RS, ASSs, and AMRs, each representing advanced automation technologies with significant potential to optimize warehouse operations. Within the same chapter, a robust framework of criteria was established to compare these alternatives. These criteria were conceived with an emphasis on sustainability, considering factors such as energy efficiency, resource optimization, reduction of waste, cost-effectiveness, scalability, and the environmental impact of implementation [3, 5]. Finally, the conclusion provides a comprehensive summary of the research, highlighting key findings and the implications of the proposed solutions for improving intralogistics sustainability. It also outlines directions for future research, emphasizing the need for continuous exploration of innovative technologies and their integration into supply chain and intralogistics operations. The conclusion argues that advancing sustainability in intralogistics requires a multidimensional approach, combining technological innovation, process optimization, and a commitment to reducing the environmental footprint. Accordingly, by structuring the analysis in this way, this study not only addresses practical industry challenges but also contributes to the broader discussion on sustainable supply chain management. This research demonstrates how targeted interventions in intralogistics can catalyze achieving sustainability across the entire supply chain, offering a valuable framework for both company practitioners and scientific researchers. Figure 1 shows the components of a sustainable Warehouse Management System (WMS).

2 Specificities of the Supply Chain in the Automotive Industry

Logistics in the automotive industry involves the detailed planning and implementation of processes involved in the production and transportation of automotive components, spare parts, and complete vehicles from raw material suppliers, subassemblies, and component manufacturers to end customers [5, 7]. The supply chain in the automotive industry can generally be conceptualized as a sequence of four key links: part suppliers, production, distributors, and customers. Within and between these links, various logistical systems play a critical role in configuring and ensuring the smooth operation of the supply chain. One of the most significant of these systems is the warehouse system, which serves as a central hub for collecting, storing, and distributing raw materials, subassemblies, and finished vehicles [8]. This system functions as the base that connects a series of operations and ensures the overall efficiency of the supply chain [9].

Within the warehouse systems of the automotive supply chain, numerous intralogistics activities are conducted to ensure the timely and correct movement of goods within the warehouse. These activities include material and part receipt, sorting, storage, relocation, order picking, and preparation for shipment to the next link in the supply chain. Each of these processes plays a crucial role in maintaining the uninterrupted flow of goods and information, which is essential for meeting the high demands and strict delivery schedules of the automotive industry. Given the complexity of operations and the increasing challenges faced by modern supply chains, these intralogistics activities must meet stringent criteria of environmental, economic, and social sustainability [6, 8]. Environmental sustainability requires minimizing energy consumption, reducing carbon emissions, and adopting practices that limit waste generation during warehouse operations. Advanced technologies such as energy-efficient automated systems and robotics can significantly contribute to achieving these goals. Economic sustainability involves optimizing resource utilization, reducing operational costs, and improving throughput while maintaining the quality and accuracy of processes [1, 9]. Efficient storage solutions, real-time inventory management systems, and data-driven optimization strategies are critical in this regard. Social sustainability emphasizes creating a safe, ergonomic, and inclusive working environment. Automated systems, such as collaborative robots, can reduce or eliminate physically demanding tasks, decreasing workplace injuries and improving employee well-being.

Furthermore, as the automotive supply chain often involves a global network of suppliers, manufacturers, and distributors, the scalability and adaptability of intralogistics systems become crucial [9]. Warehousing solutions must be capable of handling the increasing complexity of operations, such as managing a diverse inventory of components or adapting to fluctuations in demand. To meet these demands, engineers and logistics specialists are increasingly leveraging innovative technologies, such as AS/RS, ASSs, and AMRs, which are developed to address the specific challenges of intralogistics in the automotive industry. These technologies enable enhanced precision, speed, and flexibility while promoting sustainable practices throughout the supply chain. In summary, the warehouse systems and intralogistics activities within the automotive supply chain are pivotal to ensuring the efficient movement and management of goods. By integrating sustainability into these processes, companies can achieve not only operational excellence but also align with broader goals of environmental and social responsibility, ensuring the long-term viability and competitiveness of their operations.

2.1 Key Elements of the Supply Chain in the Automotive Industry

The automotive supply chain begins with raw material suppliers, and companies involved in the exploitation and processing of materials such as steel, aluminum, and other essential components needed for the production of complex, multi-component automotive products. These raw materials are required for the manufacturing of various automobile parts. Many raw material suppliers focus on innovation and sustainability, employing recycling methods and eco-friendly materials to minimize their environmental impact. These materials are then transported to component suppliers [1, 5]. Component suppliers produce specific parts required for vehicle assembly, such as engines, transmissions, advanced driver-assistance systems (ADAS), switches, etc. These suppliers often play a significant role in the development and design process, tailoring their products to meet the needs of automotive manufacturers. Effective communication between component suppliers and Original Equipment Manufacturers (OEMs) is essential to ensure seamless integration and process alignment [7]. Once manufactured, the components are shipped to assembly plants, where OEMs take over the next stages of production. OEMs are at the center of this complex supply chain, managing relationships with numerous raw materials and component suppliers while supervising the design and assembly of vehicles. Their role extends beyond assembly since OEMs are responsible for ensuring that stringent quality and safety standards are met throughout the production process, from raw materials to finished vehicles. OEMs must also adapt to evolving market trends, consumer demands, and technological advancements, requiring them to remain innovative, flexible, and proactive [8].

Once vehicles are assembled, they are distributed to dealerships for sale to end customers. However, the OEM's responsibilities do not end at the point of sale. They continue to manage customer relationships by providing support throughout the vehicle's lifecycle, including warranties, maintenance services, and technical support. These services are critical for maintaining customer loyalty and protecting the brand's reputation. The supply chain in the automotive industry does not stop with the initial sale. Customers may seek to upgrade or replace parts and accessories over the life of their vehicle, a process facilitated by the supply chain's after-sales services. At the end of the vehicle's lifecycle, the supply chain concludes with the recycling or environmentally responsible disposal of the vehicle. These end-of-life practices have become increasingly important in response to growing sustainability and environmental accountability demands [10].

The production of a vehicle is the result of the interaction among multiple stakeholders in the supply chain, including manufacturers and an extensive network of suppliers and logistics partners. While OEMs design and assemble the vehicle, they do so in collaboration with a network of suppliers who provide the necessary components and systems. Larger suppliers often participate not only in manufacturing but also in the design and development of the product and, in some cases, even the assembly of specialized vehicles. Suppliers are categorized into different tiers based on their roles in the production process (Figure 2).

This hierarchical structure highlights the interdependence of the supply chain, where OEMs rely on the first-level suppliers for critical components, which in turn depend on the second- and third-level suppliers for their inputs. Each tier plays a crucial role in the creation of the final product. Consequently, the automotive supply chain is a complex network of companies and processes that must function in harmony to produce a complete vehicle. Any failure or disruption at any point in this system can have a cascading effect on the entire industry, underscoring the importance of coordination, resilience, and efficiency across all levels of the supply chain [10, 11].

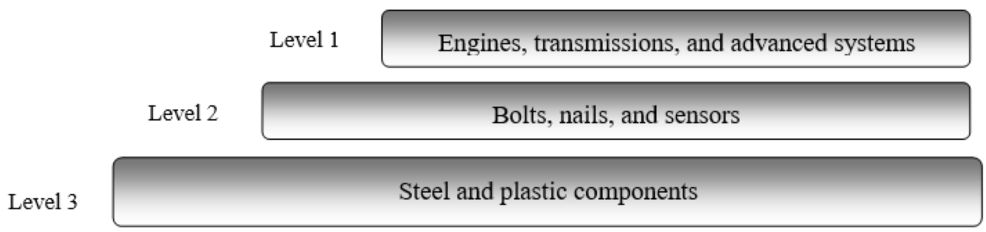

Figure 2. Suppliers at different levels

2.2 Highlighted Challenges in the Automotive Industry

A typical motor vehicle can contain over 20,000 parts, depending on its design, functionality, and performance. All these parts are assembled to produce the final product—a fully functional vehicle. Over time, global sourcing of parts has become standard practice, as OEMs and major suppliers seek components and materials from the global market that meet quality standards at the lowest possible costs. However, transportation distances, shipping costs, and warehouse requirements also present significant challenges in the automotive industry [10].

One of the key characteristics of supply chains in the automotive industry is the focus on minimizing inventory costs and improving process efficiency and communication between manufacturers and suppliers [12]. Transparency plays a critical role, but many suppliers fail to provide automakers with detailed information about their supply chain, particularly lower-tier suppliers [13]. Toyota pioneered an approach to address this issue with its "Just-in-Time" (JIT) strategy [11]. Namely, JIT in the automotive industry emphasizes minimizing inventory costs by ensuring that parts and materials are delivered precisely when needed for production, avoiding stockpiling and reducing warehouse and maintenance expenses [10, 12]. Beyond cost reduction, JIT offers several benefits, including reduced inventory levels, improved product quality, waste minimization, increased employee motivation, higher productivity, enhanced flexibility, reduced space requirements, and shorter delivery times. However, JIT also has vulnerabilities; a single missing component can halt an entire assembly line [12]. To mitigate such risks, companies can integrate technology into their operations, such as creating shared inventory management platforms [11].

An additional challenge is in the dependence of automakers on external companies for various aspects of their operations, despite attempts to control larger portions of the supply chain. This dependence makes supply chains vulnerable to disruptions in transportation, production, or material procurement. For example, the 2021 Suez Canal blockage delayed component deliveries to European automakers, while the ongoing semiconductor shortage has disrupted production despite raw material availability, as second-tier suppliers struggle to meet global demand [14].

The COVID-19 pandemic further exposed vulnerabilities in the automotive supply chain. Originating in China, a major supplier of automotive parts, the pandemic caused disruptions in the flow of raw materials and finished products due to factory shutdowns and logistical bottlenecks. As the pandemic spread, many manufacturers faced plant closures, labor shortages, and increased costs, leading to delays and inefficiencies across global supply networks. Strategies for mitigating such risks include developing localized supply sources and adopting advanced Industry 4.0 technologies [15].

The balance between technological advancements and consumer acceptance also remains an important challenge. While automakers introduce advanced automated features, many consumers resist these innovations due to safety concerns and a lack of understanding. Building consumer trust and awareness is crucial for the adoption of such technologies. However, consumers increasingly recognize the benefits of automation in intralogistics and vehicle functions, supporting the development of advanced automated features for improved safety and efficiency [16, 17].

These challenges highlight the critical importance of sustainability in intralogistics for the future of automotive supply chains. Sustainable intralogistics can optimize the use of human, material, and financial resources to maximize productivity while reducing costs. It also contributes to waste reduction, more efficient inventory management, and streamlined material flow. Accordingly, this focus on sustainability is not only a response to current challenges but also a vital opportunity for innovation and the enhancement of intralogistics processes.

2.3 AS/RS for Optimizing Warehouse Space in the WMS

Intralogistics is defined as the complex interaction of various logistical functions encompassing the organization, control, execution, and optimization of internal flows of materials and information [9]. It manages material flow throughout the entire supply chain, ensuring efficient movement of goods and resources within facilities—from production lines and warehouses to distribution centers. Intralogistics has become increasingly important in modern business, helping companies improve efficiency, reduce costs, and meet the growing demands of the market [15].

Within warehouse systems, numerous intralogistics activities are performed to enable the efficient management, storage, and distribution of materials and finished products along the supply chain. These activities include goods reception, storage, picking, packing, and preparation for dispatch. Effective management of these processes ensures the timely availability of necessary materials and products, directly impacting the speed and accuracy of order fulfillment. Warehouses play a critical role in intralogistics, as they centralize inventory, enable its control and optimization, and help reduce costs while avoiding production and distribution delays [16].

In the automotive industry, the integration of effective intralogistics processes within warehouses and distribution centers is essential due to the complexity of managing a vast number of components required for vehicle production. A typical automobile consists of thousands of individual parts sourced globally, making warehouses and distribution hubs central nodes for synchronizing supply and demand. These facilities not only store raw materials and components but also prepare them for JIT delivery to production lines or final distribution to customers and dealerships [4, 13].

Sustainability has become a critical element for companies aiming for long-term success, social responsibility, and competitiveness. The three main pillars of sustainability—environmental, social, and economic—play an essential role in intralogistics, particularly within warehouses and distribution centers. In the automotive supply chain, sustainable intralogistics supports the optimization of resources, waste reduction, and energy-efficient management, contributing to an environmentally friendly supply chain [14, 17].

Environmental sustainability in warehouses focuses on minimizing the ecological footprint by optimizing resource utilization, employing energy-efficient equipment, and reducing waste through recycling. For instance, adopting ML AS/RS and renewable energy solutions, such as solar panels or energy-efficient lighting, allows automotive warehouses to lower their carbon emissions. These practices are crucial in addressing the environmental challenges of global automotive supply chains, particularly as the industry transitions to electric vehicles and increased demand for sustainability compliance.

Social sustainability ensures the creation of safe and productive work environments for employees. Intralogistic technologies such as AMRs and automated picking systems reduce physical strain and the risk of workplace injuries. In the automotive sector, where large and heavy components are often handled, these technologies improve working conditions, enhance employee motivation, and align with the industry's commitment to worker welfare and safety.

Economic sustainability emphasizes cost reduction and operational efficiency. Sustainable practices in warehouses, such as real-time inventory management, predictive analytics, and process optimization, lead to lower operating costs and increased profitability. In the automotive industry, this directly impacts the overall supply chain, reducing lead times, preventing stockouts, and ensuring uninterrupted production lines. By optimizing warehouse and distribution processes, automakers can meet JIT requirements while minimizing inventory holding costs and transportation expenses [16].

In the context of automotive supply chains, sustainable intralogistics within warehouses and distribution centers are critical for competitive market survival. Warehouse facilities function as connections between raw material suppliers, component manufacturers, and OEMs, ensuring that parts and materials are stored, managed, and delivered efficiently [13, 15]. With the automotive industry's ongoing push toward sustainability and electrification, optimizing intralogistics not only addresses current challenges but also fosters innovation and resilience in supply chain operations.

3 Case Study: Optimizing Goods Preparation for Shipment in Auto Parts Supply Chains

Suppliers of auto parts play a critical role in the efficiency of OEMs, who rely heavily on them. Their importance to the supply chain can be noticed in various aspects that contribute to product efficiency and quality. First, the quality of auto parts provided by suppliers directly impacts the performance and quality of the final product. Additionally, supplier flexibility is crucial in the automotive industry, where demand is often unpredictable for varied reasons. Suppliers also play a key role in inventory management, reducing the risk of production interruptions. Their role is to ensure timely delivery, thereby eliminating delays and disruptions in the supply chain [8, 17].

The primary activity of a logistics company, whose name is protected by business policy, is the supply of auto parts such as sensors, switches, batteries, wires, connectors, and light-emitting diode (LED) lights. The company faces numerous challenges in its operations. It stores produced parts in its distribution warehouse, from where they are shipped to customers. These customers include automobile manufacturers, service centers, retailers, and other specialized automotive equipment shops. The demands of these customers vary; some may order goods in larger quantities (e.g., palletized shipments), but more often, goods are ordered by the box or as individual items. One of the fundamental problems in the distribution warehouse is the preparation of goods for shipment. This process is often time-consuming and prone to errors, including product damage and mistakes in separating goods for dispatch. As a result, delays occur in delivering goods to customers, and incomplete or incorrect deliveries are common.

An analysis of the company's operations reveals that the primary cause of failure in meeting customer demands lies in the way goods are handled, relying heavily on manual labor and outdated technology. In the company's warehouse, workers prepare goods for shipment manually, using various types of forklifts. This method poses numerous challenges, including financial losses, occasional customer attrition, reduced production efficiency, and difficulties in planning. These factors collectively harm the company's overall performance. Product damage during handling is a significant challenge for suppliers. The primary causes are often related to employee inexperience, which manifests in improper lifting techniques and incorrect positioning of goods. This issue is especially relevant for electronic auto parts, some of which are fragile or require specific orientations (e.g., batteries). Employee inexperience is also evident in the use of inappropriate equipment for handling these goods or using equipment, such as forklifts, for which they are not adequately trained. Tight deadlines often exacerbate the issue, as rushing to meet schedules can lead to damage during handling. Additionally, poor warehouse organization, narrow aisles for forklifts and lapses in quality control of goods being dispatched contribute to the problem. Since the supply chain is a series of interconnected links, this problem negatively affects not only the company in which it originates but also the entire supply chain [10]. Consequences include production delays, damage to the company's reputation, strained client relationships, reduced flexibility, increased costs, and delayed deliveries [11, 12].

Delivery delays are closely linked to product damage during shipment preparation. When goods are damaged, additional time is required to replace and reprepare them for shipment, often leading to delays and increased costs for the company. Low levels of process automation also contribute to delays. These issues, like other recurring problems, affect the rest of the supply chain, leading to similar consequences as product damage. Increased costs due to urgent shipments, production stoppages, and dissatisfaction among end users, planning difficulties, and reduced profits are just some of the downstream effects on the supply chain.

Various solutions, technologies, and strategies can be employed to address these problems. However, based on practical examples and existing research, automation is often the most commonly recommended approach by researchers and practitioners in such scenarios. The nature of the goods, characterized by demand for individual items, a wide product assortment, and frequent small shipments, necessitates modern solutions. Advanced technologies such as AMRs, ML AS/RS, and ASSs allow for the optimization and enhancement of warehouse processes through automation. The implementation of these technologies not only improves the efficiency and accuracy of warehouse operations but also promotes sustainability by reducing errors, waste, and unnecessary costs. By integrating sustainable practices, the company optimizes resource utilization, minimizes environmental impact, and strengthens the resilience of its supply chain.

4 Alternative Solutions for More Efficient Preparation of Goods for Distribution

In order to increase the sustainability of the intralogistics activities of the supply chain of the analyzed company, which is engaged in the production and storage of parts for the needs of the automotive industry, three automated technologies were analyzed that can contribute to the optimization of the preparation of goods for shipment. Each of these technologies has specific characteristics and advantages, enabling improvements in processing speed, order accuracy and warehouse space optimization. However, different applications of these solutions bring different challenges, as well as variations in the effects on the overall efficiency of the system.

4.1 ML AS/RS

AS/RS is designed to handle goods stored in small containers or boxes within the system. This system is particularly suitable for storing small quantities of various stock-keeping units (SKUs). One of the primary features of the ML AS/RS is its ability to maximize space utilization while simultaneously increasing throughput [17]. Implementing an ML AS/RS represents a solution that can significantly enhance the order preparation process in the observed company. This system enables automated storage and retrieval of smaller units of goods from the warehouse, eliminating some key limitations of manual labor and forklift usage. The primary advantage of an ML AS/RS lies in its ability to accelerate storage and retrieval operations, directly reducing delays that currently pose a major challenge for the company. Instead of relying on workers using forklifts to locate and transport items, the ML AS/RS automatically identifies the location of the requested products and retrieves them precisely and efficiently, with minimal waiting time. This accelerates the shipping process, increasing overall productivity and reducing costs associated with supply chain delays. In addition to speed, the ML AS/RS reduces the number of errors and product damage during retrieval. Automation minimizes direct human contact with goods, lowering the risk of damage caused by manual handling. The system also ensures high accuracy in item retrieval by using pre-programmed commands to precisely identify and retrieve the exact required goods, eliminating the possibility of incorrect retrieval. This improves order fulfillment accuracy, helping the company avoid additional costs related to product returns and subsequent reshipping of corrected orders [18, 19].

Furthermore, inventory management becomes more efficient due to the system's ability to automatically track and record the movement of each item in real-time, enabling faster responses to customer demands. Another notable advantage is the improved safety within the warehouse due to better organization, which is a critical aspect of operational efficiency. The automated system significantly reduces human labor requirements, easing the workload for employees, decreasing fatigue, and enhancing their ability to focus on other tasks. In the order consolidation process, ML AS/RS facilitates the automatic grouping of retrieved goods in a single location. This simplifies product assembly, as all necessary items are delivered in the correct sequence to the consolidation area within the warehouse. In addition, it reduces the time needed to prepare complete orders for shipment, thereby increasing overall delivery speed. Packaging and labeling processes are also streamlined with the ML AS/RS. When items are automatically delivered to the packing station, workers can complete final tasks more quickly and efficiently, as all required items are already grouped and ready. Additionally, the system can integrate with automated labeling systems, further accelerating the process and reducing errors in packaging and labeling goods for shipment [19].

Despite its numerous advantages, the implementation of an ML AS/RS comes with certain challenges and potential drawbacks. One of the main disadvantages is the high initial investment required for the procurement and implementation of the system. Companies considering this solution must be prepared for substantial upfront costs, including equipment acquisition, software implementation, and employee training for system operation. Additionally, the ML AS/RS requires regular maintenance and can be prone to technical malfunctions, necessitating the involvement of specialized personnel for repairs. Any system failure can result in operational downtime, leading to significant delays. Compared to manual operations, the ML AS/RS also has a limitation in terms of flexibility and adaptability to changes. These systems are best suited for predictable and repetitive operations, making them less versatile when faced with dynamic or irregular workflows [18].

4.2 ASS

ASS is an advanced solution that utilizes robots and bins/ML units to efficiently handle the picking of small and lightweight items. It provides better utilization of available space compared to any other automated system, thanks to its design that allows direct stacking of parts and the storage of multiple different products within the same bin. Over time, the system optimizes itself by identifying high-turnover products and storing them in the upper layers to ensure faster retrieval [20]. The implementation of the ASS represents a modern and flexible solution for improving order preparation processes. As an automated storage system based on robots managing storage units, ASS enables faster, more efficient, and more accurate order processing, addressing key challenges of the current manual processes. The primary advantage of ASS lies in its ability to optimize warehouse space utilization. The system employs a grid of robots that move along the top of the structure, retrieving bins containing goods and delivering them to workstations. This eliminates the need for forklifts and minimizes physical contact between workers and goods [21].

ASS ensures high accuracy in item retrieval through robotic automation, which minimizes errors and enables the precise collection of items according to customer orders, significantly enhancing efficiency in order preparation. Robots deliver the exact items required directly to the workplace, reducing waiting times and accelerating the flow of goods. This approach streamlines and accelerates the packaging process, as operators receive items in the correct sequence, thereby reducing process completion times and potential errors. The accelerated processing allows the company to respond more quickly to client demands and drastically reduce delays which is critical in industries reliant on timely deliveries. ASS also simplifies the labeling and marking of items. Automated item retrieval based on order requirements reduces the likelihood of labeling errors. The system can integrate with automatic labeling solutions, further speeding up the marking process before shipment while ensuring enhanced precision [19, 21].

A notable advantage of ASS is its energy efficiency. The robots used in the ASS consume significantly less energy compared to traditional material-handling equipment. Moreover, the robots are designed to handle bins carefully, reducing the risk of physical damage to goods, which is often associated with manual handling or forklift use. ASS improves warehouse organization and visibility, as each bin is precisely positioned and easily accessible, enabling optimal utilization of storage space. The system also simplifies the control and verification of order accuracy. Automated item handling based on predefined parameters allows faster checks of each shipment's accuracy. This enables precise verification of every product before it leaves the warehouse, reducing errors and potential customer complaints. Like other advanced automated solutions, ASS minimizes human involvement, further contributing to operational speed and accuracy [20]. One of the primary disadvantages of the ASS is the high initial investment required, including costs for equipment, robotic units, centralized software, and implementation. Additionally, it requires trained personnel to operate the system and address potential technical issues or malfunctions. Another potential limitation of the ASS is the risk of operational downtime in case of system failure. Furthermore, the system supports only bins specifically designed for ASS, which could pose challenges for storing some of the company's products. The system is primarily optimized for small-scale order picking, which may represent a significant limitation for larger-scale operations [21].

4.3 AMRs

AMRs are a type of robot capable of independent movement within a given environment. AMRs are equipped with advanced sensors, utilize artificial intelligence, and have the ability to plan navigation routes within their surroundings. With the aid of sensors and cameras, AMRs can easily overcome obstacles in their path. The implementation of AMRs represents an innovative solution for enhancing order preparation processes. This technology offers several key advantages but also presents specific challenges, particularly concerning the workplace dynamics that robots create for employees [4, 8].

One of the main advantages of using AMRs is improved efficiency and speed in order processing. AMRs can transport goods from storage locations to packing and shipping zones, significantly relieving employees and reducing the time required for order preparation. Their flexibility and ability to navigate freely allow them to optimize routes in real-time, meaning AMRs can bypass obstacles and find the shortest possible path to their destination. The implementation of AMRs also reduces the risk of product damage. Robots use high-precision sensors to handle and transport goods, minimizing the likelihood of accidental damage during transport within the warehouse during the order preparation process. Furthermore, AMRs enhance workplace safety for employees. Equipped with advanced obstacle detection systems, these robots reduce the possibility of accidents and injuries in the warehouse, resulting in a safer working environment. Another significant advantage of AMRs is their ability to improve the flexibility of warehouse operations. AMRs can easily adapt to changes in workload, seasonal variations, or unexpected customer demands, enabling quick responses to dynamic conditions. This is particularly important in industries such as automotive, where demand can fluctuate rapidly. AMRs also can automatically collect real-time inventory data, allowing for precise and fast updates. These automated solutions provide accurate inventory insights at all times, facilitating better decision-making regarding reordering and warehouse space optimization [7, 20].

As with other solutions, the implementation of AMR technology comes with certain challenges. One of the main drawbacks is the high initial investment cost. However, unlike some other automated systems, it is possible to purchase individual AMRs, allowing for a phased implementation based on budget constraints. This flexibility reduces the financial burden compared to systems that require an all-at-once investment. Another limitation of AMRs lies in their capacity to handle complex tasks. While AMRs excel at simple tasks like movement and transport, more intricate operations, such as careful handling of fragile items or storing irregularly shaped products, may exceed their capabilities. In such cases, human intervention is still necessary, which can limit the overall efficiency of automation and require additional resources. Moreover, since AMRs primarily assist workers rather than fully automate processes, the potential for errors is higher compared to fully automated solutions like ML AS/RS or ASSs [18, 21]. A unique challenge in introducing AMRs to a warehouse is the impact on workplace dynamics and employee reactions. Although AMRs improve operational efficiency, some employees may feel uneasy working alongside robots that move freely in their environment. This unease can stem from a sense of being monitored or concerns about job security due to automation, potentially affecting motivation and job satisfaction. To address this challenge, companies implementing AMRs must invest in employee education and training to familiarize staff with the robots' functionality and benefits. This approach can help alleviate feelings of insecurity and foster a positive attitude toward technology [17].

4.4 Criteria for Evaluating the Proposed Alternatives

This chapter outlines the criteria for evaluating proposed alternatives to enable the selection of the optimal technology for order preparation in a distribution center. The criteria were organized into three core dimensions of sustainability: environmental, economic, and social. The defined criteria are based on a comprehensive analysis of available literature and the specific characteristics of the company. They represent the most relevant and frequently used criteria in similar studies on the selection of technological concepts in warehousing. Moreover, these criteria ensure that all aspects of sustainability are thoroughly considered, reflecting the importance of achieving a balanced approach to environmental responsibility, economic efficiency, and social impact while respecting the technical features of analyzed alternatives. Below is a detailed description of each criterion (Table 1) [4, 8].

By evaluating these criteria, the proposed alternatives can be systematically analyzed to identify the most suitable solution that aligns with the goals of operational efficiency, cost-effectiveness, environmental sustainability, and employee well-being. This structured evaluation is particularly critical in the automotive industry, where supply chain demands are dynamic, and operational delays can have noteworthy unfavorable effects on production timelines and customer satisfaction. Selecting a technology that meets these criteria ensures that the distribution center can adapt to fluctuating demands while maintaining high standards of precision, speed, and sustainability, all of which are essential in a highly competitive and fast-paced sector like the automotive industry [12, 14].

Table 1. Criteria for selecting optimal alternatives for sustainable intralogistics activities

Group	Criteria	Description
Economic	Cost efficiency	Minimizing operational and maintenance costs.
	Return on Investment (ROI)	Measuring the profitability of the technology over time.
	Operational productivity	Maximizing throughput and reducing delays in workflows.
Environmental	Energy efficiency	Reducing energy consumption of automated systems.
	CO_2 emissions	Lowering the carbon footprint during operation.
	Waste reduction	Minimizing waste generated during warehouse operations.
Social	Workplace safety	Enhancing safety for employees by reducing exposure to risks.
	Employee training and adaptability	Ensuring that workers can easily adapt to new technologies through effective training programs.
	Job satisfaction	Improving employee engagement and satisfaction by reducing repetitive tasks and enhancing roles.
Technical	System reliability	Ensuring consistent performance with minimal disruptions.
	Scalability	Enabling the system to handle increased demands without major upgrades.
	Technological compatibility	Integrating seamlessly with existing infrastructure and software.

Given the requirements for the short-term implementation of advanced technological solutions to support sustainable intralogistics activities in automotive parts warehouses, and with a focus on the challenges of implementing such advanced solutions, companies often encounter significant difficulties in prioritizing key criteria. Based on a comprehensive analysis of available literature and insights from company management, one criterion was identified as the foundational and indispensable starting point for selecting the optimal alternative:

a) Economic criterion: cost efficiency

The primary focus is selecting technologies that minimize operational and maintenance costs while maintaining high performance. Automotive parts warehouses often handle large volumes and require cost-effective solutions to remain competitive in a highly dynamic supply chain. Cost efficiency ensures long-term financial sustainability and better resource allocation [1, 9].

b) Environmental criterion: energy efficiency

For ecological sustainability, the focus is on prioritizing systems that consume less energy while maintaining productivity levels. The automotive industry is under increasing pressure to reduce its carbon footprint. Energy-efficient technologies align with sustainability goals and help in achieving regulatory compliance and corporate environmental responsibility [4, 8].

c) Social criterion: workplace safety

Selecting systems that reduce physical strain on employees and minimize workplace hazards is desired in the social sustainability aspect. Automated solutions that improve safety protect employees and foster a positive work environment. In the automotive parts supply chain, where handling heavy or hazardous items is common, prioritizing safety is critical for both morale and compliance [17, 19].

d) Technical criterion: system reliability

Selecting technologies with proven reliability and low failure rates is the most desirable technical element in the implementation of advanced technical solutions. Reliable systems ensure uninterrupted operations, which is vital in a warehouse managing complex inventories like automotive parts. Consistency reduces downtime and avoids delays in meeting supply chain demands [2, 13].

5 Conclusions

Intralogistics represents a critical segment of the supply chain, directly impacting the speed, accuracy, and reliability of order fulfillment. In modern supply chains, particularly within warehousing systems, efficient intralogistics activities enable the optimization of material flow, the reduction of operational costs, and the minimization of errors, thereby enhancing productivity and ensuring business stability. At the same time, sustainability within intralogistics is becoming increasingly important as demands rise for reducing energy consumption, CO_2 emissions, and the overall environmental impact of warehousing operations. By implementing sustainable intralogistics solutions, companies not only optimize their processes but also achieve significant resource savings, aligning their operations with environmental and social standards.

This study addresses the challenges of intralogistics activities in the warehouse of a company specializing in automotive parts supply. The company faces persistent issues in the order preparation process, resulting in frequent delays and product damage. These challenges jeopardize customer satisfaction and the overall efficiency of the supply chain. To address this problem, the study focuses on analyzing three potential technological solutions that could improve processes in the distribution warehouse while ensuring a more sustainable approach to warehouse and supply chain management. The proposed solutions are ML AS/RS, ASSs, and AMRs. These technologies are presented as alternatives to traditional manual operations and forklift use, which cause slow and inefficient processes. The study evaluates each alternative solution in detail, applying sustainability criteria that encompass economic, environmental, and social dimensions.

Through the analysis of the defined criteria relevant for evaluating the alternatives, the advantages and disadvantages of the proposed solutions were identified for the outlined problem. The ML AS/RS stands out as the best solution in terms of operational costs and system lifespan, offering high efficiency and long-term cost reduction in material handling. However, its primary drawback lies in its high initial acquisition cost. ASS emerges as the most energy-efficient solution due to its compact design, which optimally utilizes space and reduces energy consumption. Nevertheless, this system has a longer return-on-investment (ROI) period, which may pose challenges in terms of capital recovery speed. AMRs excel in terms of ergonomics and employee safety by reducing physical strain and minimizing injury risks. However, their reliance on batteries results in higher CO_2 emissions compared to other automated solutions, making their environmental performance less favorable.

The key objective of future activities should focus on implementing decision-support systems to select the optimal alternative for the analyzed problem. While the focus of this study is on specific solutions, there is significant scope for further research not covered here. Beyond the discussed advanced technologies, other innovative options could be considered as potential solutions to the described challenges. Furthermore, the set of evaluation criteria could be expanded to encompass additional dimensions of sustainability. This would enable a more comprehensive analysis of each solution, ensuring the identification of the one that best meets the requirements and contributes to the sustainability of intralogistics processes. Expanding the criteria would provide a more holistic approach and ensure the selection of a solution that maximizes both efficiency and long-term business sustainability.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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