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Benefits and Challenges of Implementing Autonomous Technology for Sustainable Material Handling in Industrial Processes

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Abstract: The transition from traditional production activities to a manufacturing-dominated economy has been a hallmark of industrial evolution, culminating in the advent of the fourth industrial revolution. This phase is characterized by the seamless integration of digital advancements across all sectors of global industry, heralding significant strides in meeting the evolving demands of markets and consumers. The concept of the smart factory stands at the forefront of this transformation, embedding sustainability, which is defined as economic viability, environmental stewardship, and social responsibility, into its core principles. This research focuses on the critical role of autonomous material handling technologies within these smart manufacturing environments, emphasizing their contribution to enhancing industrial productivity. The automation of material handling, propelled by the exigencies of reducing material damage, minimizing human intervention in repetitive tasks, and mitigating errors and service delays, is increasingly viewed as indispensable for achieving sustainable industrial operations. The employment of artificial intelligence (AI) in material handling not only offers substantial benefits in terms of operational efficiency and sustainability but also introduces specific challenges that must be navigated to align with the smart factory paradigm. By examining the integration of autonomous material handling solutions, traditionally epitomized by the utilization of forklifts in industrial settings, this study delineates the essential benchmarks for their implementation, ensuring compatibility with the overarching objectives of smart manufacturing systems. Through this lens, the paper articulates the dual imperative of aligning material handling technologies with environmental and social sustainability criteria, while also ensuring their economic feasibility.

Keywords: Industrial processes; Autonomous technologies; Material handling; Benefits

1 Introduction

Since the first industrial revolution, numerous inventions, concepts, and methods have emerged to improve industrial production and adapt to user demands, including strict competitive market conditions. Since steam engines symbolized the transition from manual to machine production, technology has evolved. Activities in production technologies and material handling have become mostly digitalized, so employees manage more and more complex technological processes in every industry more easily and efficiently. Recently, technology has been developing, modifying, and improving very quickly, so that business keeps pace with new technological solutions following the characteristics of the third and fourth industrial revolutions. Industrial production is faced with a high frequency of changes at all levels, which is associated with unpredictable customer requirements. The emphasis is on making the product as simple to use, functional, and high-quality as possible to meet the user's requirements [1]. The user requires not only a product but also information, energy, and services. By employing contemporary technologies, i.e., the so-called smart devices of Industry 4.0 supported by the Internet, products and services are practically always and everywhere easily available [2]. Automation at all business levels has caused revolutionary changes in industrial processes and created an opportunity to improve all production and logistics activities in customer service [3].

The advancement of e-commerce and the fulfillment of stochastic customer demands, as well as high efficiency, reliability, and accuracy of transportation, have become critical components for the realization of smart logistics activities in sustainable industrial processes. One of the key creations is the smart factory concept, which is synonymous with the integration of modern production technologies and material handling activities. Furthermore, every modern factory is based on that concept, which is otherwise under the strict requirements of the circular economy (CE) based on the elimination of damages and the increase of renewability [2]. In addition to the application of modern technologies in production activities, material handling in industrial processes requires a comprehensive investigation of the benefits of automation. The fact that about 80% of material handling is still done manually and only 20% with the help of forklifts and possibly automated guided vehicles (AGVs) is a sufficient indicator that an increase in autonomy is required for these activities [1, 3].

Industrial processes have always been available for evolution, particularly now since environmentally friendly operations are the cornerstone of every logistics company's competitiveness. The concept of mass production as the basis of smart factories, which aim to increase output while cutting costs, gave rise to the idea of industrial automation [2]. Because automated solutions improve user relations, increase production process flexibility, and produce higher-quality products, they represent a new level of automation. Material handling accounts for more than 50% of the total operating costs of industrial processes [4], which requires the use of technologies based on Industry 4.0 that reduce costs and processing time. The efficiency of logistics activities in production is equally important as the efficiency of production technologies. It can be achieved by shortening transport routes, increasing the density of the network, optimizing the use of available time for handling materials, reducing the involvement of employees in difficult, repetitive, and tiring jobs, etc. Automated technologies for material handling in the smart factory concept would significantly reduce non-productive time, increase material turnover, reduce damage to goods, and reduce errors in logistics activities [1, 4]. These contemporary technology solutions are also based on the use of renewable energy sources, so they are also environmentally sustainable. As they are self-programmable, they are able to eliminate employee injuries, which respects the pillar of social sustainability. Nonetheless, social sustainability has attracted significant attention recently due to its close connection to employee safety concerns as well as mistakes during processes made by humans. To reduce handling material risks and improve the safety of employees, products, and industrial process technology, the automation of material handling procedures in industrial processes was initially implemented [3, 4]. Given the close connection between production technologies and material handling activities, the essence of the smart factory concept rests on automation at all production levels (Figure 1).

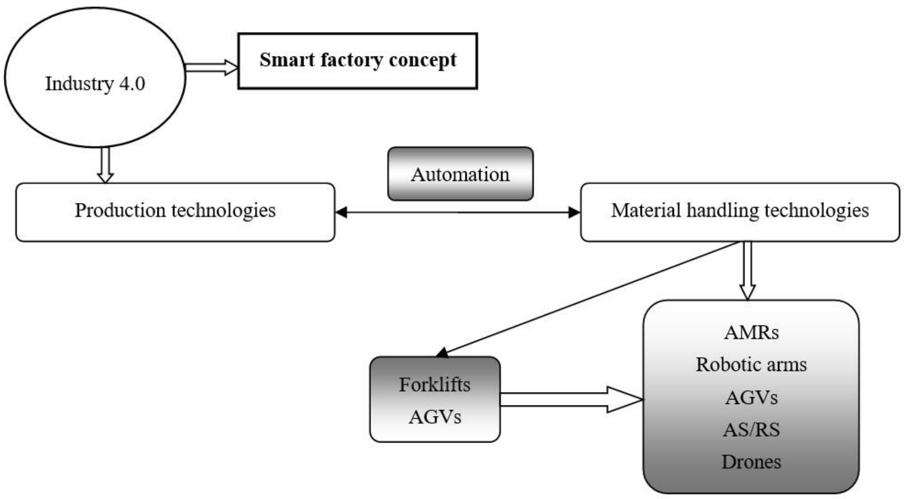

Figure 1. Development of automation technologies for handling materials

Comprehensive integration of the smart factory concept in industrial processes leads to changes in the economy, such as more flexible production, new products and services, new knowledge and skills, a reduction in human factor participation, the elimination of production errors, a reduction in production costs, etc. [1, 3]. The practice has indicated that material handling processes in a smart factory concept are often the "weak link" because they are oriented towards product development following user requirements. For this reason, the goal of the paper is to show the importance of certain autonomous technologies in Industry 4.0 from the perspective of their place and role in the continuity of material handling with respect to CE requirements [1, 2]. After the introduction, in the second chapter of the work, forklifts for handling materials in traditional industrial processes are briefly analyzed. Concerning partial automation as a result of the third industrial revolution, the method of handling materials using AGVs, including their advantages and disadvantages, was analyzed. In the third chapter of the paper, the most implemented automated technologies for handling materials for the needs of sustainable industrial processes in the smart factory are analyzed in detail. The sixth chapter discusses practical guidelines for the implementation of the analyzed autonomous material handling alternatives, while the conclusion provides a recapitulation of the work and directions for future research.

2 Material Handling in Traditional Industrial Processes

Before the implementation of forklifts and later AGVs, material handling was done manually. Employees loaded and unloaded the vehicles manually. This type of job was not an issue while dealing with lightweight goods. However, handling larger items resulted in injuries at work and damaged goods. The introduction of forklifts to the market first and foremost simplifies the movement and handling of goods at all stages of the manufacturing process [1, 3]. Forklifts are also used to lift and lower pallets from tremendous heights. However, despite the application of current technologies in Industry 4.0, the forklift has a limited carrying capacity, which is noticed as a critical obstacle that generated the need for the introduction of contemporary technological solutions. As a result, forklifts are being replaced by AGVs, which have been developed specifically for transporting large loads. AGVs were largely employed as an alternative to driverless transportation [5, 6]. The total annual expenses for performing responsibilities carried out by two forklifts with operators who can replace five AGVs are displayed in Figure 2, which illustrates the financial advantages of adopting AGVs [7]. This chart compares the average and total costs over a five-year period, where the average yearly cost of five AGVs is approximately 1/3 of two forklifts. As a result, AGVs constitute one of the most significant advances in the automation of material handling and transportation.

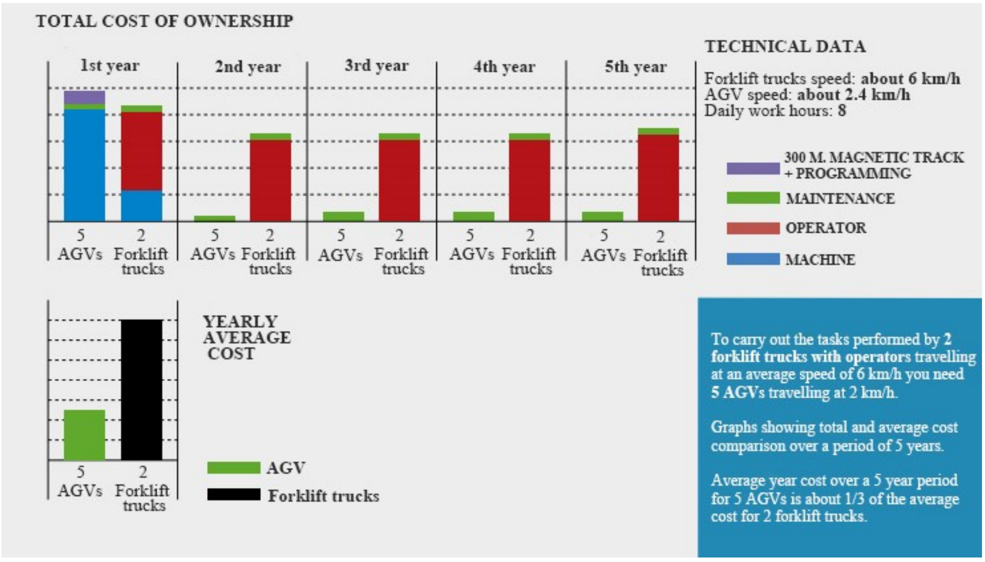

Figure 2. Comparison of the costs of employing forklifts and AGVs [7]

Figure 2 indicates engaging AGVs for material handling requirements in the automotive industry. There is an entire engine assembly on the vehicle that is installed in the vehicle. AGVs move along a predetermined and pre-marked route on the floor. The yellow part where the vehicles move must be perfectly clean and without damage so that the vehicles can move without stopping [6, 7]. This enables complete vehicle autonomy when moving. Compared to forklifts, AGVs can transport an entire body assembly or even a vehicle. AGVs are intended for the transport of heavy objects, and their construction, which has a flat surface for placing objects, enables them to do so. However, each transition from old to new equipment has its advantages and disadvantages. Nevertheless, the advantages must always outweigh the disadvantages for the implementation and application of new systems to be justified and profitable. Some of the typical advantages of AGV implementation are [8]:

- integration of such systems necessitates minimal additional infrastructure;
- augmentation in transport capacity;
- improvements in workplace safety;
- reduction of goods damage;
- possible handling of hazardous materials;
- reduction of workforce requirements;
- minimization of workplace injuries;
- reduction in labor costs;
- increased productivity (possibility of working 24/7);
- operational efficiency is not constrained by conventional working hours, etc.

AGVs have substantial advantages, but they also have certain challenges. Undoubtedly, AGVs are contemporary but expensive material handling equipment. Engaging these vehicles necessitates additional training for the employees who operate them, resulting in increased costs for the company. Similar to forklifts, AGVs are susceptible to frequent breakdowns, which can result in material handling losses. Furthermore, AGVs are more appropriate for defined routes with a predetermined, reiterating aim, so they may be limited to repetitive tasks [2, 7]. To enable AGVs to drive along the established fixed pathways, specific sensors must be installed on the floor, which causes additional costs. The benefits of forklifts are that they can move another pallet quickly after handling the previous one because they are managed by humans. On the other hand, AGVs receive an order to perform one request, after which they wait for the next tasks. Due to these and other material handling challenges, the introduction of autonomous material handling technologies is essential to address all pillars of sustainable industrial operations.

AGVs can be used in combination with industrial robots (robotic arms) for the most effective use in the smart factory concept [1, 4]. This generates more opportunities in line with Industry 4.0 standards. For instance, as seen in Figure 3, an AGV incorporates a robotic arm that enables it to carry out several tasks at once. Additionally, after moving one kind of cargo and holding it, one may grab another, load it onto a vehicle, and proceed to move the cargo to its location. AGVs can be used in activities where it's required to load one set of items onto an AGV right away after transportation and then unload it immediately. The so-called robotic arm, which may be used to actively seize and dispose of goods, can be the AGV's superstructure to boost both the efficiency and applicability of this equipment for sustainable material handling [2, 7].

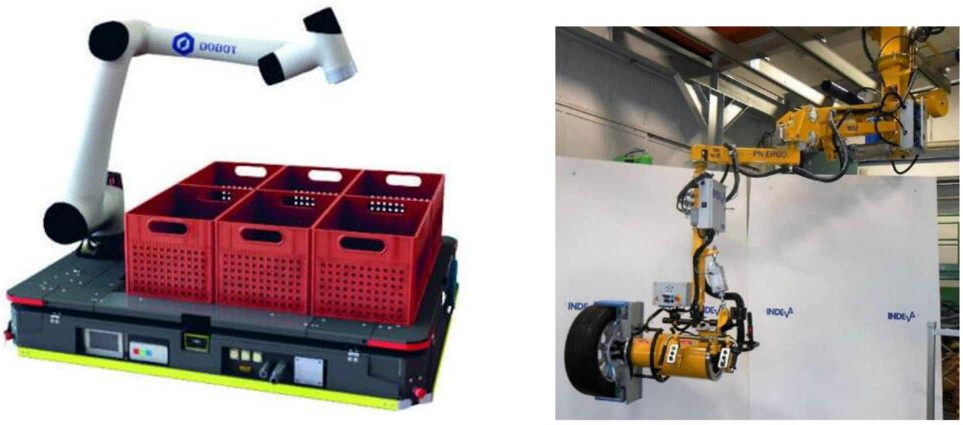

Figure 3. Some robotic arm solutions [7]

When it proved economically feasible, AGVs were used instead of forklifts in typical industrial operations, resulting in a dramatic shift in material handling. However, these technologies are not long-term sustainable because AGVs are autonomous in their movement and require robotic arms to automate material handling. Consequently, the next chapter analyzes contemporary autonomous Industry 4.0 solutions that were developed primarily to meet the material handling requirements of sustainable industrial processes.

3 Automated Material Handling in Industrial Processes

The requirement for products is increasing in concert with global population development, resulting in a rise in the volume and intensity of items flowing through supply chains (SC). Given that more than 80% of people live in urban areas, it is obvious that industrial systems in these situations are responsible for efficiently serving all consumer needs. As nations grow in size, the limited time available to meet changing demands from customers is becoming more of a challenge in manufacturing processes under CE requirements [1, 5]. This results in employee overburdening, a rise in the volume of laborious tasks, material damage, and a substantial number of customer service errors [5, 7]. As a consequence, automation in material handling comes as a solution to improving the efficiency of logistical activities in manufacturing processes. The need to reduce damage to goods, as well as human involvement in manual work and unhealthy conditions, are just two of the most important reasons to automate material handling [5, 6]. Furthermore, one of the needs of the CE is the elimination of losses and waste in industrial operations, which necessitates maximizing product turnover and avoiding errors in material handling to satisfy customer requirements efficiently [1, 3].

Picking and putting items together, order-picking, loading, unloading, palletizing, and packaging are a few of the most frequent logistical tasks involved in the handling of goods in industrial facilities [8, 9]. For unpredictable logistics activities to be completed while preserving continuity in the realization of goods flows that demand real-time automatic identification, the availability of manufacturing technology information, and the availability of solutions that support Industry 4.0, a smart and sustainable industrial process is required. In addition to AGVs, additional automation equipment utilized for this type of activity includes autonomous mobile robots (AMRs), drones, and automated storage and retrieval systems (AS/RSs). They are discussed in more detail below.

3.1 AMRs for Material Handling Requirements

AMRs are estimated to be an innovative material handling system that operates entirely on its own without the assistance of employees in logistic activities. Autonomous navigation is facilitated by a multitude of compact, inexpensive, but energy-efficient sensor technologies that are commonly installed on AMRs. AI approaches are being used to support AMR in navigation and service provision, made possible by technological advancements [10]. In uncertain and dynamic environmental conditions, AMRs function independently [11, 12]. Barriers can be recognized and classified using AI techniques like machine learning and vision systems. Large volumes of data about the AMR's immediate environment are collected and transmitted employing a LiDAR scanner, 3D cameras, accelerometers, gyroscopes, and wheel encoders that provide positional information to determine the distance the robot has moved or turned. Figure 4 shows the AMR in an industrial plant.

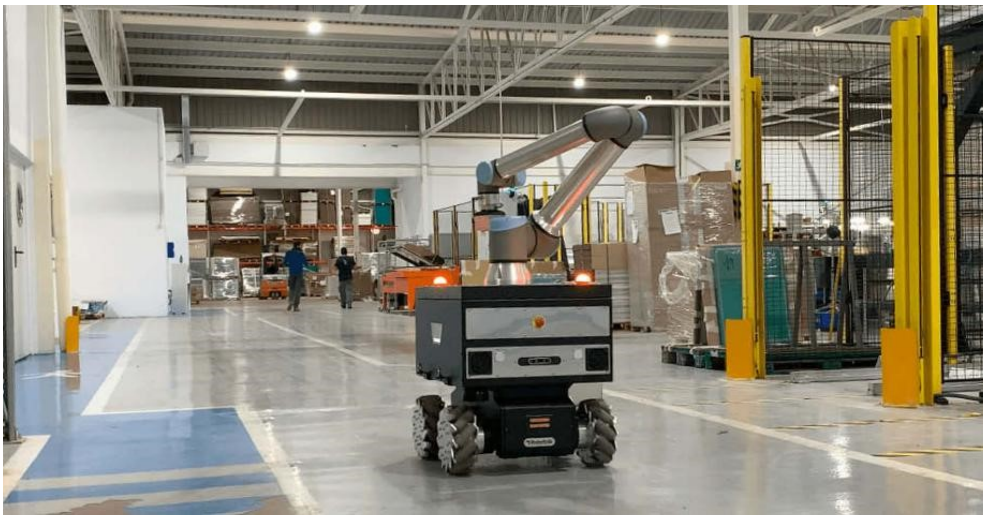

Figure 4. AMR in an industrial plant [12]

Logistics operation optimization in material handling is completely possible with contemporary AMR technology. AMRs enable workers to concentrate on completing primary tasks, such as operating manufacturing lines without requiring the transportation of materials, since they perform material handling and transportation duties. The following are the benefits of using AMR [1, 12, 13]:

• AMRs are equipped with software that autonomously generates movement paths in response to environmental conditions and operational demands;

• a high level of flexibility implies the realization of various requirements. Due to a change in the environment or the expansion of the existing system, AMRs quickly adapt to the new system and tasks;

• the safety of goods and employees has been increased by the introduction of AMRs because this technology independently detects and overcomes obstacles;

• a high degree of intelligence and relief in the workforce allows AMRs to realize activities instead of employees;

• an environmentally acceptable electric drive with rechargeable batteries improves not only the sustainability of material handling processes but the entire SC;

• fast implementation means that the process of adapting production technologies to circumstances is relatively straightforward;

• humanization of work means relieving the employee of handling materials. AMRs handle difficult positions and operate in dangerous environments where they are exposed to various risks (handling dangerous goods, hot pieces of metal and sharp objects) without the risk of injuring employees.

There are numerous advantages to using AMRs for material handling in industrial operations, but many weaknesses exist. A few of them rely heavily on the company's financial resources. Several major challenges stand in the way of the practical application of AMRs, such as high investment costs, the requirement for suitable information support, and compatibility with current material handling systems.

3.2 AS/RS for Material Handling in Industry Processes

AS/RSs were previously considered out of reach by many smaller order fulfillment operations and retail warehouses of industrial companies, which did not have the funding to invest in advanced autonomous technology. Nevertheless, as AS/RS technology has developed quickly over time, new choices offering a broad range of sizes, speed, affordability, and flexibility have led to a sharp increase in the pace of system adoption at primarily different distribution centers. Since most companies can now afford them, AS/RS technologies are among the most popular and beneficial options for investment, especially for requirements in warehouse systems [1, 13]. AS/RSs are made up of a succession of computer-controlled systems for autonomously depositing and collecting goods from predetermined places for holding fresh shipments and picking orders [14]. By retrieving items for use or shipping and putting them back in the proper places within the production facility, these advanced technologies automate the handling of materials (Figure 5). Cranes that remove primarily pallets from racks and shuttles that travel between racks are the foundation of AS/RS systems. Industrial processes where large amounts of inventory enter and exit production or distribution processes are suitable for AS/RS. In that way, upgrading to an automated warehouse creates more secure, ergonomic working conditions while enhancing throughput and productivity with dependable, secure storage that prevents damage to goods and equipment [13, 14].

Figure 5. AS/RS in an automated warehouse [13]

Although AS/RS is primarily developed to increase warehouse productivity, it is regarded as a technology that substantially automates material handling in sustainable industrial processes. Among the main benefits that AS/RS has achieved are [13, 14]:

- increased use of storage space;
- improved inventory management and tracking;
- decreased expenses associated with hiring labor;
- maximized workplace safety;
- minimized damage to items;
- increased productive time;
- operational accuracy.

Although using AS/RS to automate material handling, particularly in warehouses, as carriers of logistical activities in sustainable industrial processes has many advantages, there are challenges. High investment costs, limited adaptability when switching production and storage technologies, and reliance on manufacturers for maintenance are a few of the more significant ones [14, 15].

3.3 Drones in Industrial Activities

Unmanned aerial vehicles, also known as drones, were primarily developed for military purposes. However, those devices have found use in a variety of industrial activities because of their capacity to handle and manage material handling operations as well as their ability to transfer material flows “from the ground to the air”. The construction and agricultural sectors are where drones are most frequently utilized. However, there are other industries, like automotive, electronics, and pharmaceuticals [16]. Drones are fully automated technology for both transport and material handling. With low energy consumption and high productivity, they belong to contemporary sustainable technologies.

Drones can be used by automobile companies at large-scale facilities to find vehicles on-site swiftly and efficiently. This is already in place at Audi’s Neckarsulm facility [17]. The distinctive radio frequency identification (RFID) chips that are paired with each automobile’s ID number form the basis of this automated procedure. Drones with specialized equipment can fly over the manufacturing surface, using an RFID scanner to pinpoint and save each vehicle’s precise location. This way allows monitoring of complete material handling processes and identifying manufacturing potential gaps. Drones are an efficient, automated technology for quickly shipping light items and goods by air. Drones can get around the traffic that is typically on the roadways in this way. For this reason, they make optimal options for distribution systems; however, assembly line activities in car manufacturers and warehouses can make smaller use of them (Figure 6). As such, drones are a feasible solution for transferring particular light components from one production line to another if they need to be moved [16, 18].

Figure 6. Drones in Audi car manufacturing [18]

As contemporary automated technologies, drones are characterized by numerous advantages for material handling in sustainable industrial processes. Some of them are:

• low price;
• high flexibility and the possibility of integration with existing technologies;
• fast transport of small quantities of material to the place where it is used;
• low energy consumption, etc.

Drone adoption challenges can be a hindrance to their engagement in sustainable industrial operations for material handling needs. A few of the challenges are restricted payload and range, inadequate information support, and the high implementation costs of drone systems. The absence of suitable legislative regulations for their use creates a critical limitation for industrial-purpose implementation.

The following chapter provides a comparative analysis of autonomous technologies, considering the numerous challenges involved in deploying those contemporary solutions for material handling requirements. A comprehension of both the advantages and disadvantages that might serve as practical guidelines for the automation of material handling in sustainable industrial processes is given through the discussion of their benefits, drawbacks, and implementation difficulties.

4 Comparative Analysis of Autonomous Technologies from Sustainable Material Handling Aspects

Employing forklifts in industrial processes has significantly improved material handling activities. The primary reason for their development was to minimize the need for employees to perform tedious and repeated manual labor, especially for positions characterized by manual handling with positions over 20 kilograms [5]. Utilization of forklifts in material handling can reduce manual activities by almost 60% and reduce goods damage by more than 80% if they are managed properly [19]. However, AI, as a core of contemporary Industry 4.0 technology, seeks to automate material handling in industrial operations for smart factory concept requirements. One of the key motivators for the automation of material handling is the stability of the forklift, which is considered a challenge in its use and can threaten the safety of goods and employees [20]. Initially developed as a superstructure for forklifts, AGVs have autonomy when moving. AGVs also have many benefits over forklifts, including the capacity to handle hazardous goods, particularly explosive materials [10]. Those devices are capable of operating in high-risk regions because of their additional electrical components and explosion-proof structure. AGV technology can follow commands by adhering to a predetermined route and coming to a stop at a defined location.

Although there are some similarities, an AGV is not an AMR. Namely, AGVs have been around since the 1950s, are usually used for transporting heavy loads, and run along a specific lane or conveyor belt and a predetermined route [11, 13]. Advanced AGVs notice barriers, but they do not redirect routes; they stop when they encounter an obstacle. The flexibility of AMR to work in different locations means working without changing the schedule, resulting in easier scalability in terms of the number of units and work zones [9, 14]. AMRs use free navigation using lasers, while others are located by fixed elements: magnetic strips, magnets, beacons, etc. This indicates that in industrial processes, warehouses, and places where the work environment is shared with people, AMRs in integration with other technologies become more effective due to their dynamics and efficiency in the partition of material handling activities. In addition, AMRs have much more advanced software and hardware that provide more efficient applications compared to AGVs reinforced by robotic arms. The complete autonomy of material handling and transportation, which enables them to operate around the clock without the need for employees' involvement, constitutes one of the main advantages of using AMRs. Reduced employee engagement results in economic benefits (i.e., salaries are eliminated) and environmental benefits (i.e., hydrogen and other renewable energy resources can be used) [19, 21]. In this way, including staff members in enjoyable tasks, giving those opportunities for advancement and education, and teaching them ways to use materials as sustainably as possible significantly contribute to social sustainability. Due to these and other advantages, two of the biggest customer services companies in the world, Alibaba and Amazon, have engaged a significant number of AMRs to increase the effectiveness of material handling operations in response to rising urbanization and e-commerce needs, of which Amazon has more than 200,000 units [11, 21].

Because the emphasis is on the humanization of labor, autonomy in industrial mobility, and material handling, AS/RS is seen as the sustainable solution in the smart factory concept. Using AS/RS, which complies with CE requirements, decreases cycle times and energy use. The implementation of AS/RS is becoming increasingly connected to high-bay warehouses, where material handling logistics operations are essentially equivalent to transportation. Cycle times and energy consumption are decreased by using AS/RS by about 30% in comparison to using forklifts [18, 19]. Although AS/RS are originally intended to automate warehouse activities, they are the starting point for reducing time losses and increasing the efficiency of material handling in industrial processes. Although relatively expensive, this technology enables more efficient use of storage space, which creates opportunities for expanding the space designated for industrial activities [20]. However, the improper initial configuration of the AS/RS might significantly reduce the effectiveness of material handling by more than 5%, which generates significant financial challenges for the whole SC [17, 22]. Therefore, the main limitation of AS/RS is the need for a more sensible route design for the goods drop-off and pick-up system, which is necessary to increase the effectiveness of material handling. For practical implementation in the logistics company, AS/RS would help maximize space use, minimize product damage, and cut energy usage, which are considered the meaningful benefits of this contemporary autonomous technology, particularly in warehouse requirements.

The most controversial autonomous material handling technology is thought to be drones. On the one hand, they offer advantages like eliminating the need for personnel to handle materials, controlling every aspect of industrial processes to minimize downtime, and the environmental advantages of using less electricity. Drones are still considered a socially challenging alternative due to the possibility of complicated acceptance by employees. However, their limited carrying capacity and range, along with insufficient legal regulations, pose the main obstacles to their deployment. This technology is being used more and more for sustainable material handling since it can improve the volume of material handling up to four times [12, 23]. It is utilized mostly because it can be combined simply with other technologies like AGVs and AMRs.

5 Practical Guidelines for Selecting Sustainable Material Handling Technology

There are substantial benefits and challenges to choosing the right material handling technology. It is necessary to adhere to all sustainable industrial process criteria and the latest advancements in automated production technology under rigorous CE requirements. The methodology is based on Apple's (1977) equation, which has been modified by various researchers to consider the application of contemporary material handling technology in real-world scenarios (Table 1) [24]. This approach is predicated on the characteristics that material handling systems need to have to satisfy the requirements of sustainable industrial processes.

Prioritizing technology to handle materials for sustainable industrial processes is a complex procedure that requires decision-makers to determine the most appropriate material handling methods that can handle a variety of materials safely and effectively, following the responsibilities they have been given [23, 25]. Many tools are available for this purpose to help identify cost-effective and suitable material handling technologies. This process becomes more challenging since autonomous material handling is favored. Nonetheless, in the selection of sustainable material handling solutions, engineers frequently employ the sources, components, and practical guidelines listed below in professional circumstances [21, 26]:

- material handling technology manufacturer catalogs and manuals;
- the personal experiences of the designers and decision-makers;
- professional consultation from practitioners in related fields;
- expert engagement;

• employee perspectives in material handling technology decision-making;
• scientific research findings.

Table 1. Selection of material handling technology based on Apple's equation [24]

Material Features		**Handling**		**Method**	
Question	Answer	Question	Answer	Question	Answer
Appearance form	Pieces, bulk materials, liquid, gaseous	Source and destination	Area (workplace, department, within the facility, between two facilities), movement path (transport tracks, transport lines, overhead transport routes)	Handling unit	Type, kind, dimension, weight, number
Quantity	< 1000 kg, < 2000 kg, < 3500 kg, or more	Material flow features	Distance, frequency (number of movements/time per unit of goods), the environment	Equipment	Function: storage/retrieval, order picking, positioning, transportation, auxiliary devices Handling type: manual, mechanical, automated Features: required capacity, loading time, number of loadings per hour Price: hourly labour costs, annual costs
Features	Shape, dimensions, temperature, perishability, way of handling, etc.	Type	Cycle transport, continuous transport, transshipment (handling), vertical movement positioning, transfer	Workforce employees	Time per activity, price per hour, annual costs
				Physical limitations	Working aisle width, object height, door dimensions, bearing capacity of the floor, working surface, load capacity of the object, ramp slope, lift capacity, the infrastructure, material handling requests, buffer zone, etc.

Although every strategy on this list has advantages, it also comes with certain challenges. Designers frequently select technology that most effectively meets their goals when making technique decisions based solely on experience, rather than focusing on what is most cost-effective for industrial processes that are socially and environmentally appropriate. Material handling technology vendors may have an edge in their recommendations because it is in their financial best interests to sell their equipment. On the other hand, consultants usually demand high fees for the time they spend providing education and referrals. As a result, a cost-effective solution is not always guaranteed by these possibilities. Reliance on scientific research is questionable since the attributes and traits of the investigation's task may differ from the characteristics of the actual assignment.

Consequently, the requirements of the sustainable industrial process of the examined company have to be taken into account while selecting material handling technology. To prioritize autonomous technologies that are considered, the decision-making criteria are usually specified. Selection of appropriate criteria based on research experience and the requirements of the investigating case study. As a result, this issue is increasingly becoming the subject of academic study to satisfy the requirements of engineering practice, which provides guidelines for the implementation of advanced autonomous material handling technologies in sustainable industrial practice. One of the analyses of the type and characteristics of the material may indicate that it is necessary to handle the pallets. Further analysis may reveal that it is essential to lift the load to a height of six meters, the transport distance is 50 meters, and certain maneuvering is also required during the transport of the material. This suggests that a forklift would be an adequate material handling technology. Additional analysis of the methods can tell more about the specific characteristics of the forklift. For example, a forklift is needed to work in narrow aisles with a floor capacity of 1/2 ton. In this phase, a detailed financial analysis is carried out, which includes various parameters such as payback period, benefit-cost ratio, etc. A financial analysis can provide guidance on which forklift manufacturer to select [25, 27]. However, given the requirements for sustainable material handling, it is clear that the forklift requires replacement by certain autonomous technologies. Therefore, Apple's equation is used as a basis for selecting sustainable material handling technology, which is simply modified by the characteristics of contemporary technologies in the Industry 4.0 era.

Given that the research has practical implications, Figure 7 shows the share of material handling methods in the analyzed literature. According to studies reviewed here and discussed in academic research, forklifts have been the subject of analysis in up to 70% of publications about material handling technologies [1, 14, 25]. This is supported by the fact that forklifts may be widely employed for a variety of activities due to their features and multifunctionality, but also because of their limitations, which is why autonomous technologies for material handling are being implemented. The least discussed technologies are AMRs and robotic arms because of their significant challenges and unknown benefits of their implementation for the requirements of sustainable industrial activities [13, 25, 28]. The need and importance of automated material handling to satisfy CE regulations and ensure the sustainability of industrial processes necessitate increased research and practical emphasis on the benefits of AI technologies as well as the challenges associated with their implementation. As a result, investigations of material handling automation research trends can serve as recommendations for preferring the proper material handling automation technology. Integration of the fundamental practical supports for the selection of material handling technology with the advantages and difficulties of automated solutions provides the basis for a more efficient choice of the most suitable automated alternative, following the requirements of empirical analysis. According to previous studies, these useful research suggestions combined with contemporary autonomous solutions can be seen as an appropriate foundation for selecting a sustainable substitute that satisfies the needs of empirical analyses to handle materials in industrial processes.

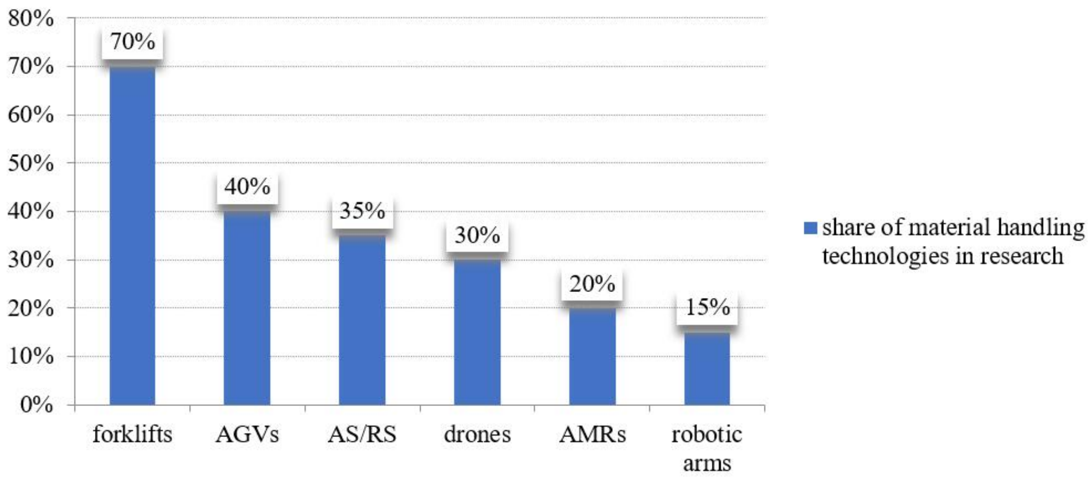

Figure 7. Proportions of materials handling technologies in scientific research

6 Discussion

Rationalizing industry processes has a direct connection to the efficacy of Industry 4.0 technologies and the level of autonomy utilized when conducting vulnerable material handling activities. 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 [1, 5]. 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 [5, 8]. As a result, deploying autonomous material handling technology provides the basis of the smart factory concept, which is essential to sustainable SC under CE requirements [9, 14].

Implementing autonomous technology in industrial processes is a reasonable approach to managing numerous environmental issues by lowering energy consumption and emissions of pollutants while performing material handling activities. As employee safety is questionable when handling materials with forklifts, automation would also improve social sustainability as it would provide a healthier working environment and reduce employee harm. In this way, errors in material handling would be minimized and damage to goods, facilities, and equipment would be reduced. Automation can also be viewed as a crucial phase in the development of a smart factory concept as a critical part of effective SC. Nevertheless, some challenges remain in the way of the widespread implementation of new autonomous material handling systems based on cutting-edge Industry 4.0 technologies [12, 22, 28]. The main obstacles to complete autonomy in material handling and all industrial operations are considered to be inadequate infrastructure, inadequate employee training, and a deficiency of awareness of the advantages of contemporary AI technologies. An empirical analysis that would respect the criteria for the needs of a particular company would significantly contribute to this, which simultaneously would raise the question of the justification of the application for the need for automation of material handling based on data from other real case studies. However, from the perspective of efficiency in SC, comprehensive automation might be critical in terms of increasing operational expenses and maintenance costs, the possibility of job loss, and mistakes in material handling in the absence of humans [9, 10, 29]. The potential risks connected with employees communicating "with the device" while handling materials constitute another threat to the social pillar of sustainable SC. For this purpose, there are a significant number of Industry 4.0 innovations and applications on the market that are used to track goods and vehicles and quickly implement modern technologies that are equally effective for industrial processes and users. These tools also support employees in easily overcoming barriers to the efficient adoption of autonomous material handling technologies, favoring AI benefits at the expense of overcoming potential challenges of their implementation.

By eliminating the salaries of material handling employees as a major expense of using forklifts, industrial activities achieve a large economic advantage. Furthermore, employees can acquire retraining to avoid activities that are monotonous, exhausting, and inhuman. Future research ought to concentrate on finding ways to get around social constraints related to workers' perceptions of using autonomous technologies for material handling because, despite their high cost, these technologies reduce errors caused by human error and are environmentally friendly [5, 28]. The most popular and quickly adopted autonomous technology for material handling that can be fully utilized in conjunction with a robotic arm is AGVs. AS/RS are autonomous technologies initially developed to automate material handling in warehouses, increase the utilization of warehouse capacities, and reduce errors caused by the human factor. Although this advanced technology is designed for warehouse activities, its automation represents the starting point of sustainable industrial activities and complete SC. Drones are considered the future of material handling automation [29, 30]. Although limited in payload, range, and regulatory challenges, this autonomous technology is highly flexible and easily combined with other existing and advanced technologies.

The implementation of autonomous material handling technologies has undoubtedly provided numerous benefits for the sustainability of SC. Based on the discussion of advantages, limitations, and implementation challenges, it can be concluded that AMRs represent a technology that ensures autonomy at all levels. This can be explained by one of the numerous examples of good practices for the company Yanfeng and the distribution center Ariat International that successfully implemented AMRs [20, 29, 30]:

- improved efficiency, accuracy, and throughput;
- the number of employee steps was reduced by over 95%. In the Yanfeng Company, the number of employee steps was reduced from 70,000 steps to 4,000 steps because AMRs deliver goods to employees;
- increased worker productivity: the focus is on the core activity, production;
- more preeminent safety of the working environment;
- the electric drive of AMR provides environmental sustainability.

7 Conclusions

Material handling activities are known to have a substantial impact on all pillars of SC sustainability and customer service effectiveness, necessitating the use of advanced autonomous technologies in Industry 4.0. Using autonomous smart technologies is an opportunity to get over the main challenges associated with handling materials in traditional production processes. More specifically, although the usage of AGVs is increasing, forklifts still handle the majority of materials in industrial processes. The use of autonomous technologies in material handling is essential for sustainable manufacturing processes, even in light of the high costs and knowledge gaps regarding these technologies. Research and an increasing amount of implementation in practice indicate that the use of AMRs for this purpose is sustainable, provided that it respects the potential and requirements of industrial processes and defines appropriate criteria for evaluating autonomous technologies. AS/RS and drones have also been investigated, although these technologies are most suited for improving material handling efficiency when combined with other autonomous alternatives.

In the context of stringent CE regulations, this study offers fundamental recommendations for selecting suitable autonomous technology to handle materials in sustainable industrial processes. It also addresses the effective application of contemporary technological advancements that can be used as frameworks for these answerable decisions. Consequently, highlighting research trends about material handling automation and providing helpful advice for selecting the right technology is one of this work's fundamental responsibilities. This research's primary contribution is the unification of the first practical supports for the selection of material handling technology with the advantages and difficulties of automated solutions, which would ensure a more effective selection of the most suitable option in compliance with the demands of empirical analysis.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The author declares no conflict of interest.

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