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Application of Autonomous Mobile Robot as a Substitute for Human Factor in Order to Increase Efficiency and Safety in a Company

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Abstract: In this paper, we will compare two solution options to determine whether the deployment of an autonomous mobile robot will be a beneficial investment for a company not only in terms of cost, time, and manpower savings, but also in terms of efficiency and reliability in the implementation of selected logistics processes to ensure the smooth running of production. In this paper, we would like to analyse the technology in terms of functions, carrying capacity, and interconnection within the infrastructure in the enterprise. The logistics processes from material order to export to the final customer will be analysed when an automatically controlled robot is deployed. One of the solutions discusses the use of personnel and material handling equipment (tractor with transport kit). The second solution discusses the deployment of the robot and selected logistics processes. The paper concludes with a summary of both options in terms of time, cost, and efficiency of the solution.

Keywords: autonomous mobile robot; logistics process; company; material handling; safety

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1. Introduction

Today, companies are increasingly focusing on implementing automation options to ensure that their logistics processes run efficiently, smoothly, safely, and reliably. One option is the use of robots, which are part of Industry 4.0 and can perform processes efficiently and autonomously. Based on a comparison of robots, the company in this study decided to deploy robots instead of older automatically driven vehicles or a human with a logistics train directly in the process. By introducing an automatically controlled robot to the company, we are contributing to better maintaining safety in the company due to the movement of multiple types of material handling equipment and human personnel. The aim is to characterise how processes are currently carried out and which processes can be replaced by robots. After describing this solution design, the time intensity of the employee's work is calculated, i.e., how much time it will take an employee with a logistics train to perform the selected logistics processes. Based on the employee's time intensity, it will be possible to determine how many employees and logistics trains will need to be deployed to provide the processes. The second variant will be oriented towards the design of a solution in the case of deploying a robot for the selected logistic processes. This variant will consist of a characterization of the robot and a description of its operation. Based on this, the working time of the robot will be calculated to determine in what time the robot will be able to perform the logistic processes. The calculation of the robot's time requirement will help to determine how many robots the company will deploy for the selected logistics processes if this variant is deployed. A detailed characterisation of the two variants will be followed by a summary comparing the two variants in terms of cost, efficiency, smoothness, and reliability of the execution of a specific logistics process.

2. Literature Review

Over the past few years, the automation of internal logistics has spread to both large and small companies [1]. With material handling automation, organisations can optimise productivity and plan deliveries more efficiently [2]. Material handling technology has been developing rapidly in recent decades. The most significant advances in material handling technology have been the development of Automated Guided Vehicles (AGVs) and later the development of autonomous mobile robots (AMRs) [3].

With the technological level and experience with this automation technology available today, AGVs have found their way into almost all industries and production areas. The history of AGVs began in the USA in the mid-1950s [4]. An AGV is an unattended automatically guided vehicle equipped with contactless guidance with a microcontroller as the control core and a battery as the power source. The basic functions of an AGV are automatic driving, stopping point recognition, and load transfer [5].

Autonomous mobile robots are becoming increasingly important in a variety of fields; this is due to their ability to navigate different environments without the need for human intervention and electromechanical device guidance [6]. The automation of internal logistics and inventory-related tasks is one of the main challenges of modern manufacturing companies. Currently, the most advanced technology for such applications is autonomous mobile robots, which, due to their high adaptability in dynamic environments, are replacing more traditional solutions such as AGVs, which are relatively limited in terms of flexibility and require costly equipment upgrades for their installation [7,8]. Autonomous mobile robots that move inventory within a facility may transport goods, raw materials, or finished goods from one location to another. These autonomous mobile robots are equipped with LiDAR, cameras, and ultrasonic sensors that allow them to autonomously navigate within the facility. They follow pre-defined routes or use real-time mapping to determine the most efficient route to their destination. Examples of these types of autonomous mobile robots include self-propelled forklifts and specified warehouse robots [9–11]. Autonomous mobile robots that assist in picking can streamline the order fulfilment process in both warehouses and distribution centres. These robots work in conjunction with human operators and reduce the physical effort involved in repetitive tasks such as picking items from shelves or baskets. Not only that, but these autonomous mobile robots use advanced technologies such as machine vision, artificial intelligence algorithms, and collaborative robotic arms to accurately identify and select the right items [12,13]. Autonomous mobile robots have a wide range of small and energy-efficient sensing technologies such as integrated laser scanners, 3D cameras, accelerometers, gyroscopes, etc., that allow them to digitize the environment. Processing the sensing data using simultaneous positioning and mapping technology allows autonomous mobile robots to create a map of their environment and calculate their location [14].

However, conventional material handling equipment makes the production system inflexible to changes in process layout and routing. The availability of technologies using artificial intelligence for positioning and navigation can support the improvement of transportation in manufacturing systems by using intelligent vehicles such as autonomous mobile robots to obtain feasible solutions to increase the flexibility and productivity of manufacturing systems [15]. The techniques and knowledge developed have improved mobile robots at both the device and systems level. Artificial intelligence techniques have pushed mobile robot navigation towards autonomous driving and obstacle avoidance [16].

In general, the most used AGVs in industry are often bulky and require frequent human intervention to load and unload the equipment. Autonomous mobile robots' vehicles are often small and better manoeuvrable than AGVs. This means that autonomous mobile robots' vehicles can have access to a larger area and can be more widely integrated into the work area or workstations, allowing for production flexibility and to meet current production requirements [17,18]. Applications in the automotive industry suggest that autonomous mobile robots can also be used as an assistive system, as they can interact with humans in a variety of ways as robotic collaborators. These benefits mean that autonomous

mobile robots can be introduced into production networks, increasing the flexibility of production lines by creating connections between workstations. Autonomous mobile robots are particularly suited to intralogistics operations such as transporting and feeding parts inside production lines [19,20].

3. Material and Methods

Warehousing follows the receipt and recording of material, which is usually carried out by warehousemen using front-end forklifts.

The warehouse in the company is mainly made up of a racking system. These racks consist of upper and lower positions. The upper positions are storage positions where pallet units that are not needed yet are stored. When material is needed, an order is automatically issued to re-stack the pallet unit from the upper to the lower position. In the lower position, the material is then removed from the pallet unit for production.

All shelves in the warehouse are labelled. A group of racks is marked with a section (e.g., 1A), and each storage position is marked with a unique verification code so that the warehouseman cannot confirm the placement of the material in the system at the ramp before the pallet unit is placed in the required position. In this way, the company seeks to reduce misplacement of material in the warehouse.

The warehouse is also equipped with a mezzanine. This intermediate zone is located between ramps and racks. This area is used for short-term storage of empty packages and pallets that are returned to the supplier. All positions in the warehouse (racks, intermediate zones, and temporary locations) have precisely defined system locations so that unnecessary movements are avoided, and all activities are carried out efficiently, while at the same time ensuring the controllability of movements and inventory.

Warehouse handling is mainly performed by warehouse workers using forklifts of various types (front and side forklifts). Often, various low-lift trucks, hand trucks, or electrically driven trucks are also used in the warehouse. The individual operations are carried out by warehousemen using equipment adapted to the nature and type of work.

Handling in production is carried out with the help of transport trucks, which are used to distribute materials in the production part of the company between different entities. The trucks vary depending on the type of material to be transported and their packaging, i.e., they can have, for example, shelf/rack equipment or frame equipment.

The picking/collection is carried out in the warehouse using kanban technology. The production worker scans the barcode on the kanban card attached to the material and requests a replenishment of the material in case they run out of material. The kanban card is then printed in the warehouse in the material picking/receiving area. This is the position in the warehouse where warehouse workers prepare the material to be moved to the production line. There is also a printer in this zone that is used to print kanban cards based on requests from the individual production lines. The warehouseman takes the printed kanban card and scans the label, which directs the warehouseman to the necessary section where the material is located. The warehouseman then selects the required material in the required quantity from the predetermined picking positions located at the bottom position of the racking systems and brings them to the preparation area. They attach a kanban card to the material thus prepared, and then the warehouseman moves the material together with the kanban card to the production line, where they confirm the delivery in the system after the delivery of the material.

At this point, the material preparation process is carried out by human labour using material handling equipment. Due to the wide scope of tasks and their complexity, an automated solution in this step of the logistic operations would be too costly against real savings; for this reason, we have evaluated this process only as a potential option for future projects.

These transport frames are used to transport pallets stored on chassis. The pallets themselves can hold one type of material or several types in different quantities. The tractor

unit is driven by a human according to a predetermined route with defined stopping points for unloading the material.

Transport frames are distinguished into type B, C, and E, all of which have their typical characteristics:

- Type B frame—also allows the transport of three chassis with half the EURO pallet size;
- C-type frame—usable for high-weight material;
- Frame type E—used for standard EURO pallets.

The process itself is dependent on the human factor that drives the whole kit and is therefore a source of frequent problems and errors. From our analysis, it emerges as potentially the least complex task that could be replaced by the deployment of automation. Operations can be simplified and adapted to the extent that the process can also be automated.

Consumption/transformation is a process where, based on the issued kanban card, material is moved from the warehouse to the production line, which requires this material to transform into a sub-assembly to create the final product. These final products are then removed by a warehouse worker using a forklift truck and placed in a designated location in the warehouse. The process of creating the final product represents a financial value to the manufacturing enterprise.

Consumption/transformation activities are not part of logistics operations and are carried out mechanically by workers using equipment and production and assembly lines that are designed to create the final product.

Intra-company transport is carried out by workers who use forklifts to remove finished products from the production line and move and store them in a designated place in the warehouse. The stored products are then prepared for export.

Intra-company transport is also carried out by means of guided trains, which are used to move materials between individual company buildings (warehouses).

This operation is carried out mechanically by warehousemen who control the handling equipment. Intra-company transport of finished parts does not need improvement.

Export preparation means that the finished products to be shipped are moved to a location close to the loading bay, where an exit visual check is carried out to ensure that these products meet the criteria included in the customer's requirements. As part of the process, the correct type of material is verified at various steps and then shipping labels are printed and affixed to the individual pallet units.

In the next step, the dispatch from the warehouse is confirmed in the system and the debit from the stock (sale) is made at the same time. In the last step, the warehouseman loads the complete pallet units into the load compartment of a truck that has been identified at the concierge as a truck dedicated to the export of finished products to a specific customer.

The actual export and transport to the final customer is realized if all export preparation tasks have been correctly carried out and the goods have been inspected. The transport is carried out by the drivers for the customer for whom the goods are intended.

Communication between supply chain actors is electronic, through human input. There is no need for improvement options as the process is working satisfactorily.

3.1. Evaluating Processes for Possible Automation

Based on the previous analysis of the logistics processes, we can divide and evaluate the different operations according to the way in which they are carried out in the warehouse.

Operations can be carried out in the company in three ways:

1. Manual work—the work is carried out, directed, and controlled by the worker;
2. Mechanization—mechanisms replace the worker in heavy work, and the worker manages and controls their operation;
3. Automation—equipment replaces the worker.

In the table below (Table 1), we have categorised the different logistics processes according to the way in which they are carried out.

Table 1. Division of logistics processes according to the way they are carried out.

Name of the Process	Division of Operations	Activity
Incoming traffic	(1)	transport is carried out manually by the driver
Receipt and recording	(2)	reception and recording is carried out by authorised personnel using equipment (barcode scanner and printer)
Storage	(2)	the storage process is carried out by the warehouseman using handling equipment
Manipulation	(2)	handling is carried out by the warehouseman using handling equipment
Retrieved from	(2)	collection is carried out by the warehouseman on the basis of a kanban card issued by means of handling equipment
Supply	(2)	the supply is carried out using the SAP system, in which all information and movements and the current state of stock in the warehouse are stored
Intra-company transport	(1), (2)	can be carried out by a warehouseman with a hand truck or other handling equipment
Export preparation	(1), (2)	the warehouseman carries out the exit inspection, applies the shipping labels and moves the material using the material handling equipment to the place for export
The export itself	(1)	transport is carried out manually by the driver

(1) manual work; (2) mechanisation.

Based on the data in the Table 1, we can say that most of the logistics processes are mechanically secured in the current state.

Through analysis and evaluation, we were able to assess that the processes of handling, harvesting, and supply can be automated, as these processes are currently carried out mechanically, and in rare cases manually.

In these operations, the warehouseman must pick the goods based on the kanban card, prepare them, and move them to the production line. The form in which the various operations are carried out in the current state is less efficient, more flexible and, in addition, these processes are more time-consuming.

For the above reasons, it is therefore necessary to design a suitable solution to optimize these processes.

To improve and streamline these operations, the company plans to deploy autonomous robots (autonomous mobile robots) to increase its productivity and flexibility. The process of mechanically moving material from the warehouse to the production line by warehouse workers using material handling equipment will be eliminated. The deployment of autonomous robots will result in labour savings.

Another benefit might be time savings, as the warehouse worker will not be carrying out the activity of moving material from the warehouse to the production line. This activity will be moved by autonomous robots. The warehouseman's task will only be to pick the necessary material based on the issued kanban card and then load this material onto the robots. While the robot will move the material towards the production line, the warehouseman can pick more material in the meantime (Figure 1). We would eliminate the unnecessary mechanical movement of the person carrying the material to the production line.

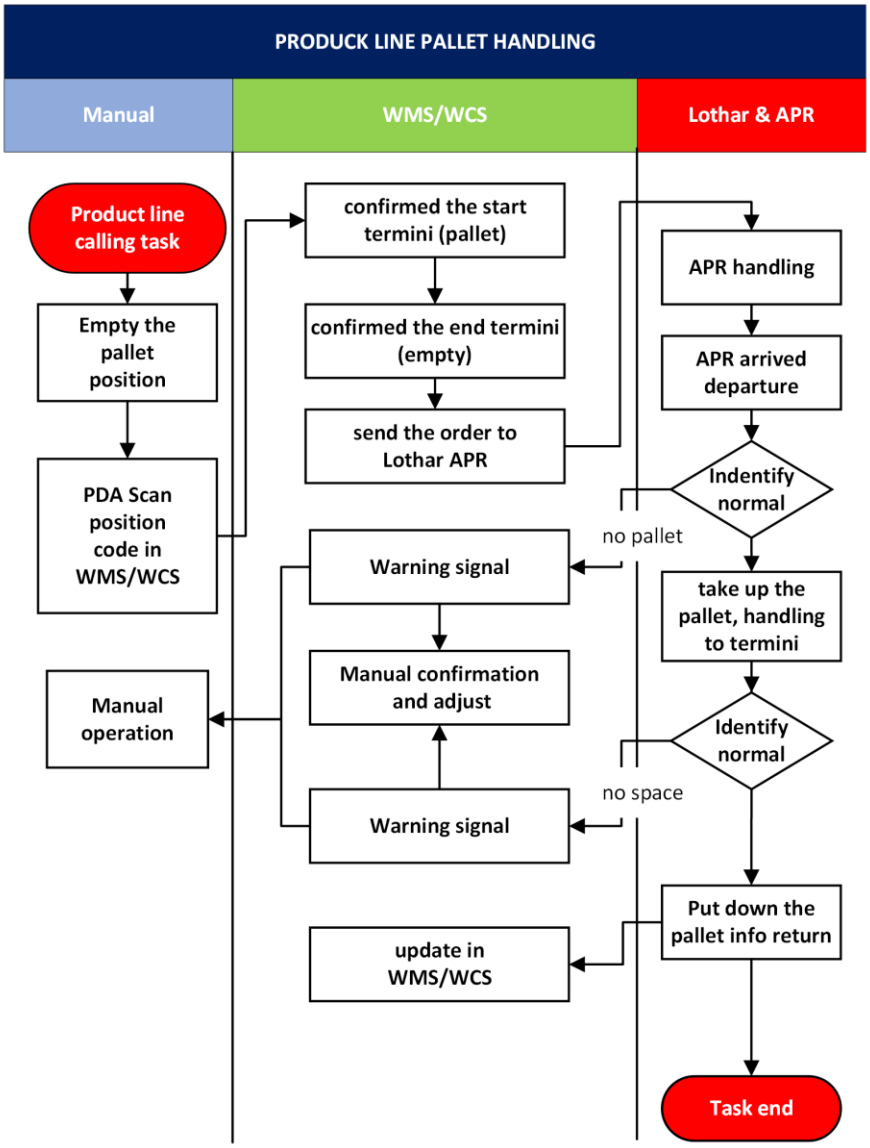

Figure 1. Product line pallet handling.

3.2. The Supply Process

Supply is an operation; we can transport the required material in the required time, type, quantity, and sequence to the destination in a predefined manner and by predefined equipment.

The supply can be divided as follows:

- Supplying directly to the assembly/production line—the warehouseman brings the material to the production and directly loads it onto the conveyor, which moves the material or boxes in front of the operator in a navigational way (transport of smaller number of boxes or pallets).
- Supermarket supply—a place that is designated as an intermediate warehouse is supplied; in this case the material is further stored in the supermarket and only then is it taken directly to the assembly/production line (transport of a larger number of boxes or pallets).
- inter-warehouse supply—transport of materials by truck between warehouses (transport of multiple pallet units).

3.3. Analysis of the Status of a Specific Action Carried Out by the Company's Employees

In the current state, the process starts from the moment a kanban card is printed in the material picking zone in the warehouse based on a material request from the production line. The warehouse picker scans the label on the kanban card, which directs them to the section where the required material is located.

The warehouseman then removes the material in the required quantity from the predetermined picking positions located on the lower position of the racking systems and brings them to the picking zone. The warehouseman attaches a kanban card to the material thus prepared.

After these operations, further operations from the warehouse to the production line are carried out by the worker who drives the tractor with the transport unit. The worker can load a maximum of 4 pallets of material on the tractor. Once loaded, he/she transports the pallets of material together with the kanban card to the production line along the route shown in Figure 2.

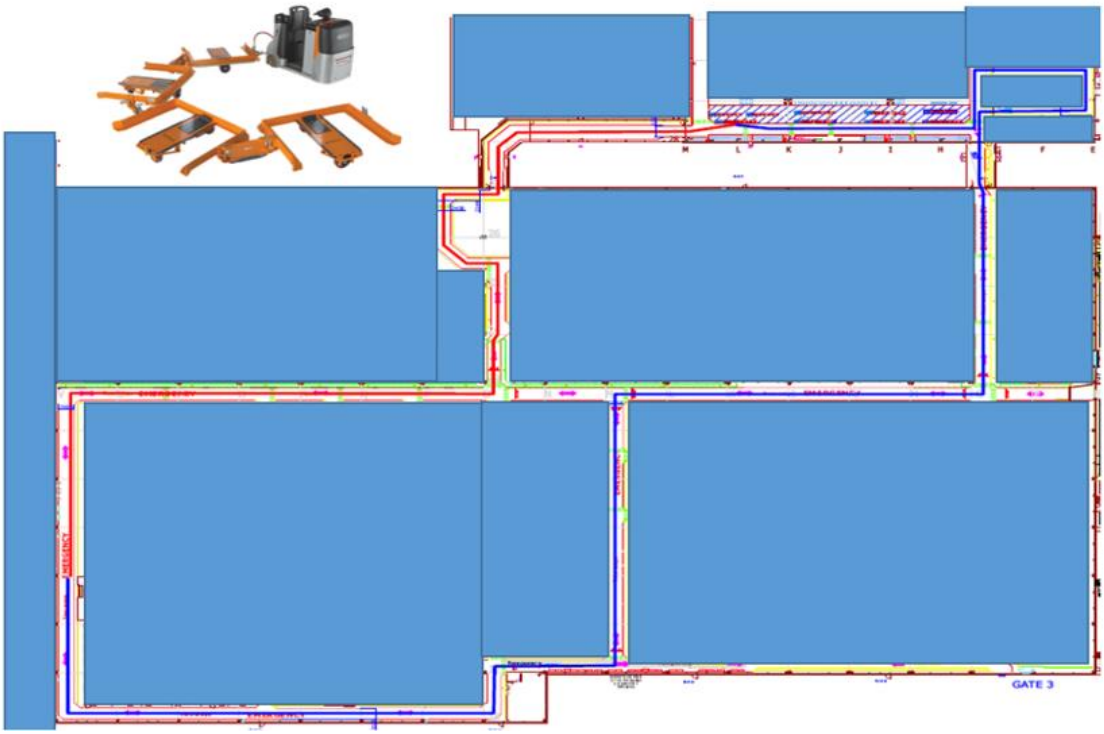

Figure 2. Layout—current status. Red line—transport route of tractor unit with loaded material. Blue line—transport route of tractor unit with empty pallets.

Upon arrival at the production line, the worker unloads the pallets, removes the material from the pallets and loads it onto the conveyor. They switch on the conveyor, which has a built-in system that blows the material to sufficiently clean the material of impurities. After this operation, the worker switches off the machine and moves the material to a clean room located next to the line for further processing of the material. They then return to the conveyor and load the empty pallets onto the tractor. Once loaded, the worker transports the empty pallets back to the warehouse to the intermediate area and then repeats the process.

The red colour shows the transport route, which is carried out by a worker with loaded material and an attached kanban card from the picking zone in the warehouse to the production line. The length of the route is 504 m.

The blue line shows the transport route carried out by a worker using a tractor unit with empty pallets. The length of the route is 321 m.

3.4. Calculation of the Amount of Time That Would Be Required for the Replacement of a Worker by a Robot

A worker with a tractor–trailer moves from the warehouse to the production line and back at an average speed of 4.5 km/h (Figure 3). The average speed is assumed because there may be downtime during transport (priority of entry and worker needs).



Figure 3. Tractor with loaded pallets [21].

It is necessary to transport 8 pallets per hour from the warehouse to the production line. A worker takes 4 pallets at a time, stored on a transport set. To find out how long the worker performs this process, we need to calculate the time consumption of the worker.

Upon arrival at the production line, the employee will unload the pallets, remove the material from the pallets, and load it onto a conveyor that provides a transfer from the dirty zone (the zone near the production line) to the white zone, provided the packaging is cleaned. After loading the empty packages, the employee will continue along a predefined route from the production line to the warehouse.

In the following Table 2, we need to calculate the employee's time commitment in order to determine whether an employee with material handling equipment would be able to meet the production line's requirement to deliver eight pallets per hour. By mutual agreement, the management employee deployed an employee who was supplying other production lines to determine how much time it would take to supply the production line in the clear zone and perform related activities (Table 2).

Based on the calculations from the Table 2, we found that the worker performs this process in approximately 50 min. Therefore, it was necessary to deploy two workers for this process to meet the clean room requirement of moving 8 pallets from the warehouse to the production line per hour. As this is a 4-shift operation, this process is carried out by eight workers.

Each worker is 85% utilised in the process. Increasing the workload is not an option in order not to overload the worker. Of course, we also must consider downtime (personal needs of the worker, etc.).

In our case, the current temporal analysis accepts the burden (84%).

We determined the employee's workload based on their work output, which is that they can deliver 8 pallets to the production line every 50 min. Therefore, out of a 60 min hour, this is 84% according to the calculation described below.

$$50 \text{ min} \times 100/60 \text{ min} = 83.33\% \doteq 84\%$$

Increasing the workload is not an option in order not to overburden the employee.

Table 2. Time intensity of worker's work—handling operations performed by the employee on a task-by-task basis.

Performing Warehouse Operation			
Location	**Name of Operation**		**Time (s)**
stock	unloading of empty pallets		76
stock	picking up components		76
		Total time	152 s
Transfer of Material from the Warehouse to the Line			
Route	**Route Length (m)**	**Speed Man. of Device (m/s)**	**Time (s)**
warehouse–line	591	1.39	425.18
		Total time	425.18 s
Performing Operations in a Clean Room			
Location	**Name of the Operation**		**Time (s)**
production line	unloading of pallets to the conveyor		687
production line	repacking of material + placing on conveyor		741
production line	processing of parts per subassembly		927
production line	barrels on pallet		14
production line	taking pallets from the storage location within the clean room		106
		Total time	2461 s
Transfer of Material from the Warehouse to the Line			
Route	**Route Length (m)**	**Speed Man. of the Device (m/s)**	**Time (s)**
Line–warehouse	321	1.39	230.94
		Total time	230.94 s
		Total Time	**3283.12 s**

Why automatization in a production factory with an automatized autonomous mobile robot is beneficial is as follows:

1. Introduction to infrastructure

Autonomous mobile robot—one of the main positives is that autonomous mobile robot vehicles do not require any infrastructure to make them able to move. For this reason, the implementation of the vehicles into the company is very simple and hassle-free. As with AGVs, autonomous mobile robots also need to maintain a clean infrastructure footprint. The impact of the use of this type of mobile vehicle can be evaluated very positively, due to the use of dynamic tasks [22].

2. Adding additional vehicles to the system

Autonomous mobile robot—when adding another autonomous mobile robot vehicle to an already operating system, it is minimally time-consuming as adding this type of vehicle can be achieved in less than a day. The rapid deployment is because the devices operate on a central controlled map that is simultaneously shared among the entire autonomous mobile robot fleet in the system. Compared to AGVs, the influencing element is the fact that there is no need for equipment planning, new staff training and, most importantly, infrastructure upgrades. In terms of investment, there is a saving that arises in maintaining the original infrastructure together with carrying out the necessary work to change the infrastructure [22].

3. Reusability

Autonomous mobile robot—In this case, an autonomous mobile robot is at a great advantage compared to AGVs because it can quickly adapt to new requirements when the production environment is constantly changing, materials are changing according to customer requirements, or entire contracts are changing. Should a transfer from one plant to another be necessary, this creates almost no problem and the actual integration into circulation is very quick and efficient. This advantage is provided by a central fleet manager and the time to upgrade the system is minimal [22].

4. Intelligence

Autonomous mobile robot—we can say after evaluating its features that it is an intelligent device. This specific characteristic makes it stand out through its adaptation to changing environments. Its internal system is based on the following essential elements: it can update the fleet map through specified (learned) parameters and it can collect key information for the company. By being intelligent devices, autonomous mobile robots can learn and find optimal routes [22].

Autonomous mobile robot—for these devices, the actual planning is much easier, because the implementation involves mapping the device using the robot itself and then superimposing the desired locations, zones, or single points on the map. Controlling the software in the autonomous mobile robot is easy because it is built on top of an interface where it directly outputs to the system what action to be taken by the authorized worker for the overlay [23].

An autonomous mobile robot can be used in any operation, regardless of its current use, infrastructure, modelling, and involvement. AMR machines have already established themselves in horizontal transport. Their strengths are particularly evident in confined spaces and in areas that have not yet been precisely defined. Conventional human-operated trolleys have long been seen as indispensable, but current market demands reveal their shortcomings, such as increased worker fatigue, lengthy transport times, and increased error rates, and not least the shortage of manpower itself. Research shows that manual trolleys lead to significantly lower efficiency, resulting in increased costs and a slower pace of work. The entry of autonomous mobile robots into production halls is revolutionizing material movement. AMRs are equipped with advanced sensors, artificial intelligence, and efficient navigation systems, allowing them to move quickly and accurately around the warehouse or production floor. As a result, efficiency is increased, and errors are kept to a minimum. Studies show that operating a warehouse with an AMR can reduce shipping times by 30% to 50%, increasing overall productivity. In addition, AMRs can operate continuously without the need for breaks, minimizing downtime. When it comes to safety, AMRs are equally impressive. With integrated safety systems that detect and react to obstacles, AMRs minimize the risk of accidents and injuries to workers. While manual trucks, with their limitations and inefficiencies, look rather outdated, AMR robots are becoming a key player in today's automated age. The advantage of AMRs lies not only in their ability to improve performance, but also in the fact that they represent an innovative step forward into the era of automation and technological efficiency [24].

In our case, a key factor is that we are introducing a new production line and new programming processes for the future. Since we cannot specify the route to the production line in advance, we choose autonomous mobile robots. The proposed solution is based on the production line already in use in the company and the supply setup according to the existing process. The degree of automation is based on the need to replace the workers performing these activities on the production line with a robot. The wage costs of the workers used are constantly increasing due to the acceptance of a minimum inflation level. In the company, a constant increase in wages is expected, so we see a reason to automate all supply processes on all production lines. In this paper, we will discuss the automation of only one newly planned production line. For this reason, we cannot specify exactly how this will affect other logistic processes in the production company.

4. Results

Autonomous mobile robots are among the most advanced transport robots that are designed for autonomous cargo movement in various industries.

An autonomous mobile robot is a type of robot that can understand its environment and move around independently.

These mobile robots work with warehouse workers, whether it is moving stock during picking, replenishing goods, or moving bulk goods. They transport batches to the next stage of processing and allow workers to move on to the next task.

They can move different types of materials and components on pallets or trolleys.

They use a sophisticated set of sensors, artificial intelligence, machine learning, and computation to plan the path. They do not need specialised infrastructure to operate. They operate seamlessly within the existing warehouse layout without major disruption to existing operations.

4.1. Autonomous Mobile Robot Design

The autonomous mobile robot consists of the following parts (Figure 4):

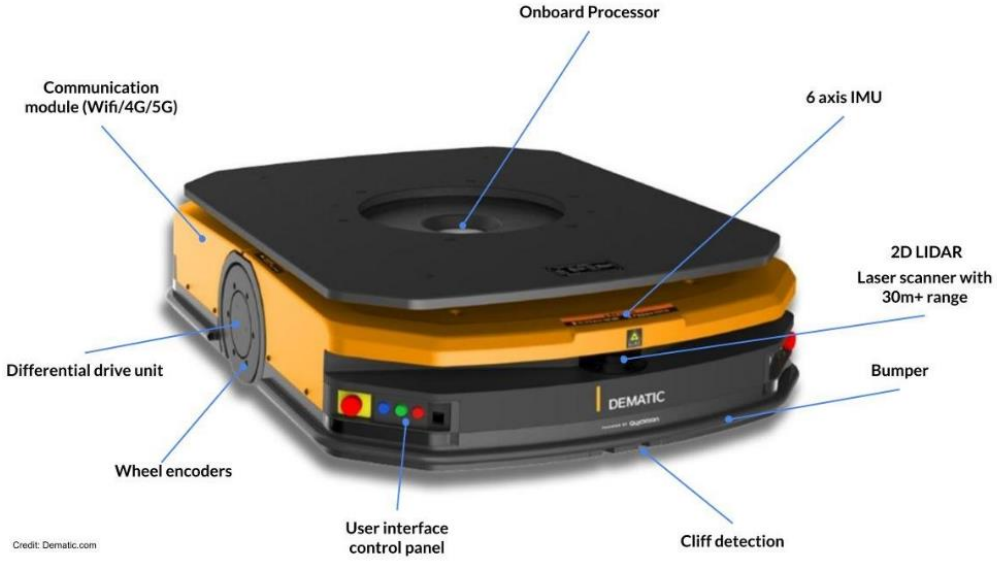

Figure 4. Autonomous mobile robot design.

Two-dimensional Light Detection and Ranging (LIDAR) illuminates the target with a laser and analyses the reflected light.

The computer processor is an integrated electronic circuit that performs the calculations that keep the robot running.

A wide-angle 3D depth vision system allows the robot to see and identify different objects. The system provides the robot with the ability to collect light reflected from objects, process an image from it, and then perform the desired action.

The laser sensor has a range of more than 20 m.

Gyroscope and accelerator data from these electromechanical devices inform the robot of its entire motion from the origin, current position, and next trajectory.

The user interface control panel allows remote monitoring and control of the robot, as well as the generation and configuration of new working environments.

The encoder provides accurate and precise feedback on angle, position, and speed.

The bumper protects the robot against collision and impact.

Three-dimensional cameras provide location information that allows autonomous mobile robots to locate themselves and respond to changing stimuli, and to stop when workers approach them.

Cliff detection is used to give the robot advance information that an obstacle is ahead and to allow it to avoid it in time to avoid impact.

A communication module is a communication component that provides wide-area radio connectivity (2G, 3G, 4G, and 5G) [25].

4.2. Advantages

The advantages of an autonomous mobile robot include:

- Flexibility;
- High efficiency;
- Higher accuracy;
- Takes up less space than self-driving cars.

4.3. Disadvantages

Among the disadvantages of an autonomous mobile robot we can include:

- Higher implementation costs;
- Software and algorithm development and maintenance costs;
- Training employees to work with robots.

4.4. Robot E10

These are E10-type robots that meet all the requirements of the company. This type of robot is used in industries such as automotive, electronics, and pharmaceuticals and their role is to streamline production processes and increase productivity (Figure 5).

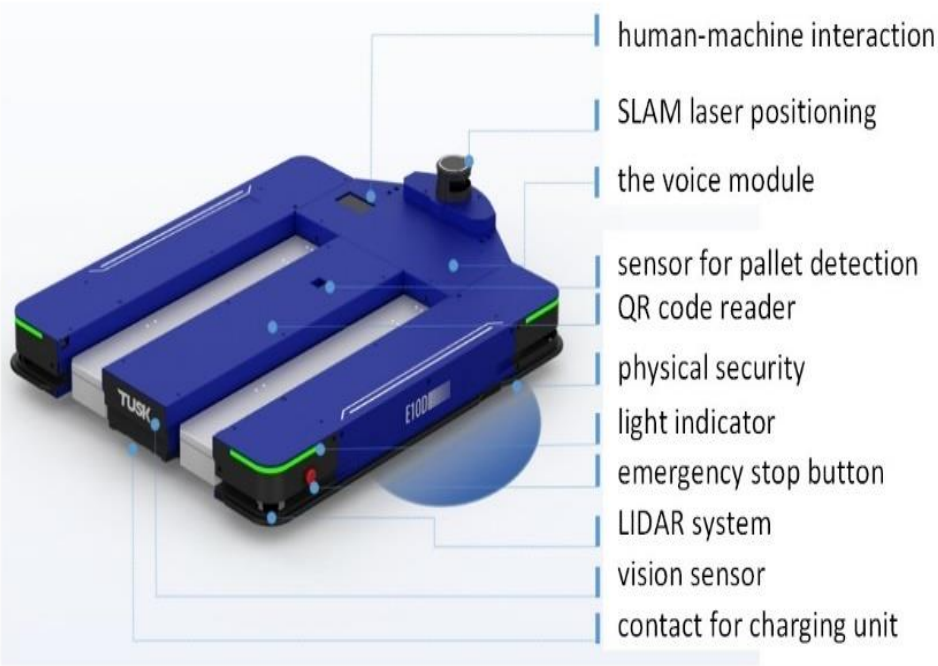

Figure 5. Robot E10 [26].

They are primarily designed to handle and move objects with high precision and speed, which can increase efficiency and reduce the risk of human error (Table 3).

Table 3. Basic parameters of the robot E10.

Dimensions (mm)	1283 × 983 × 170
kerb weight (kg)	300
maximum load (kg)	800
turning diameter (mm)	1555

These robots are adapted to international standards for internationally standardized pallets (Table 4).

Table 4. Basic parameters of the pallet.

dimensions (mm)	1200 × 800 × 915
pallet weight (kg)	25
maximum load (kg)	300

4.5. Description of Operation

Pallets will be retrieved from the storage positions in the same way as in the current state by the warehouseman. The warehouseman will prepare the necessary material to the dedicated loading area so that the area is always full of pallets of material.

Each position will be equipped with a pallet presence sensor, which will sense the presence of a pallet in the position from where the robot is to transport the pallet to the production area. This will eliminate the situation where the robot would arrive at the loading position and have nothing to do or move without a load. The sensor will have a special setting that will send a signal to the system about the presence of the pallet after continuously sensing the pallet in position for 20–30 s to avoid generating false information for the robot.

The robot itself is controlled by software from the manufacturer that can monitor the robot's work, evaluate its efficiency and display various data about its performance. In addition, it is the main control unit that processes the requests and generates the tasks sent to the individual robots. We can see the way to the production line (Figure 6 below).

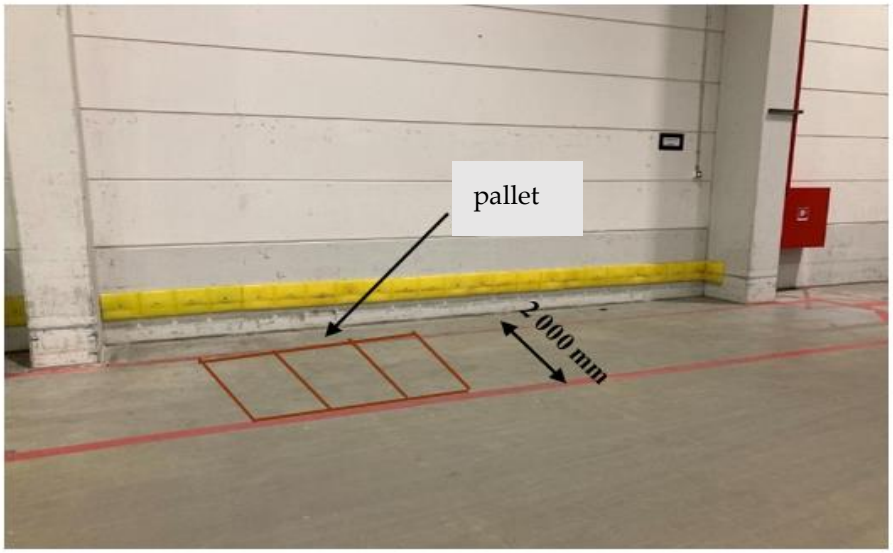

Figure 6. Loading position.

Once the pallets of material are loaded onto the trolleys, the robot starts moving the material to the production line. As the robot moves to the production line, there are

automatic rolling gates along the route through which the robot will pass. These gates have a built-in motion sensor, meaning that when the robot approaches the gate it will automatically stop and wait until the gate opens. Only when the gate is open will it start moving again.

The robot arrives at the production line, where it unloads the pallet brought in, moves to the loading point (loads the pallet with empty packaging) and heads back to the warehouse. In this concept, we are considering one warehouse operator who will have a workstation in the production area near the delivery point; their task will be to transport the brought material into the clean room while observing all the principles.

The worker loads the material onto a conveyor which blows the material and cleans it of impurities so that the cleaned material can enter the grey room (the material is stored there for a short time) and then the material is moved to the clean room for further processing. After these operations, the worker again waits for the robot to deliver pallets of material to them so that they can repeat the process (Figure 7).

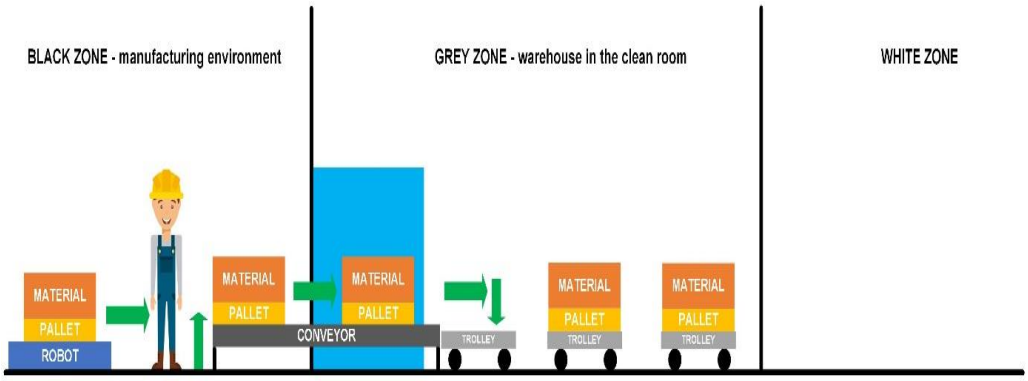

Figure 7. Delivery concept.

Upon arrival at the warehouse, the robot unloads the empty pallets in the unloading zone (Figure 8), where the warehouseman then takes the delivered empty pallets so that the dedicated pallet unloading area is always free when the robot arrives.

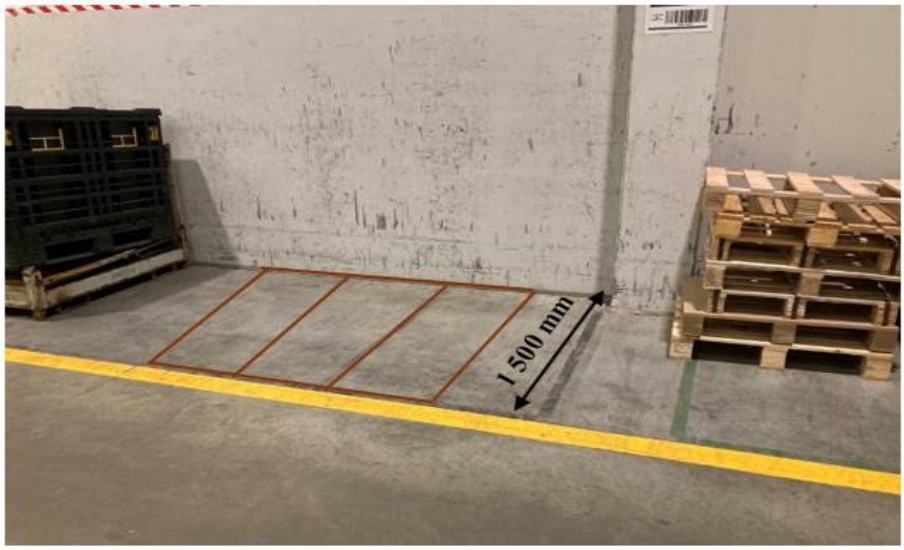

Figure 8. Position for unloading empty pallets.

The robot either repeats the process or, if necessary, moves to a charging station to recharge itself so that it can carry out the process again. These robots can automatically detect the charging station to charge. Once fully charged, they will again automatically

return to the position to start the handling process (Figure 9). Charging takes 12–15 min and the robot can be charged to 85% of the full capacity.

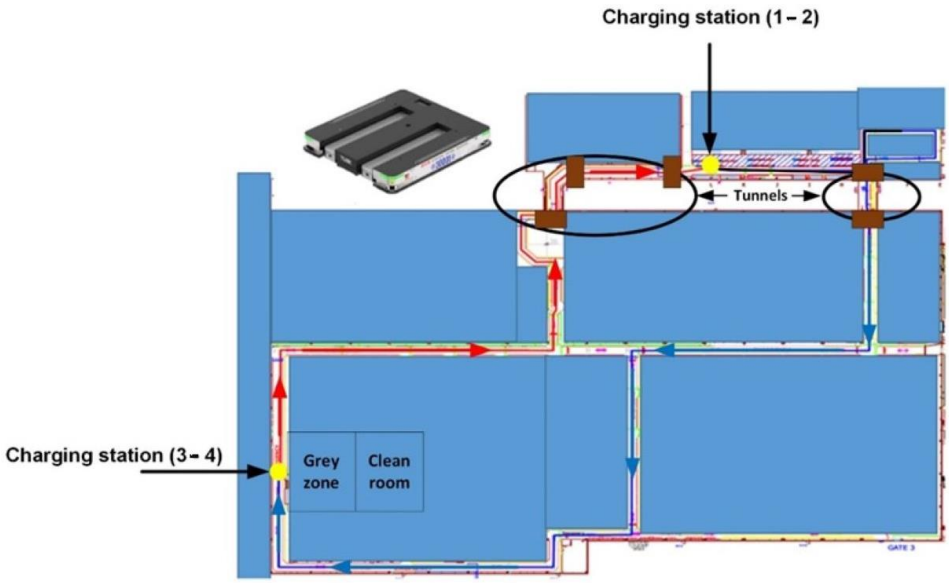

Figure 9. Layout—warehouse area without labels. Red line—transport route by robot with the loaded pallets; Blue line—transport route by robot with empty pallets.

The red colour shows the transport route, which is carried out by the robot with the loaded material and the attached kanban card from the picking zone in the warehouse to the production line. The length of the route is 504 m.

The blue line shows the transport route carried out by the robot with empty pallets. The length of the route is 321 m.

Thus, to determine how many times the robot repeats the process per hour, we need to calculate the robot's time consumption.

In the following Table 5, we give examples of automatic robot execution.

Table 5. Examples of automatic robot starts.

Pallet	Activities
Empty pallet	the system automatically causes the robot to refill an empty pallet/full pallet, e.g., refilling a pallet in a production line
Empty pallet → fully loaded pallet	the system automatically causes the robot to move the pallet, e.g., during storage
Fully loaded pallet → empty pallet	the system automatically causes the robot to transport the empty pallet to complete the return process e.g., picking and unpacking
Empty pallet → fully loaded pallet	the system automatically causes the robot to move a full pallet, e.g., when producing goods in a production line

Thanks to an application and the supporting sensors, the robot will be instructed by the system to perform the corresponding actions, thus providing automation for the handling and supply processes from the warehouse to the production line and back.

To be able to determine how long the robot will perform this process, we need to calculate the robot's working time.

4.6. Time-Consuming Work of Robots

In one hour, eight pallets need to be moved from the warehouse to the production line. The speed of the robot depends on the operation it performs. In the following Table 6, we calculate the amount of time the robot takes to perform the work it should perform in an hour.

Table 6. Time consumption of autonomous mobile robot work.

Loading Time				
Route	**Number of Pallets (pcs/h)**	**Route Length (m)**	**Speed (m/s)**	**Turnaround Time (s)**
Warehouse–line	8	504	0.8	630
Line–warehouse	8	327	0.8	408.8
				1038.8 s
Travel Time from the Empty Pallet Unloading Point to the Charging Station				
Route	**Number of Pallets (pcs/h)**	**Route Length (m)**	**Speed (m/s)**	**Turnaround time (s)**
Warehouse–warehouse	0	90	1.2	0
				0
Turnaround Time				
Route	**Number of Pallets (pcs/h)**	**Time (s)**	**Turning Speed (m/s)**	**Total Time (s)**
Warehouse–line	8	10	5	50
Warehouse–warehouse	0	4	6	24
Line–warehouse	8	12	5	60
				134 s
Time per Operation (Loading + Unloading)				
Route	**Amount of Jobs per 1 Pallet (s)**		**Loading and Unloading (s)**	**Time (s)**
warehouse–line	1		80	80
warehouse–warehouse	0		80	0
line–warehouse	1		80	80
				160 s
Other Operations				
Route	**Door Opening Speed (s)**		**Charging Time (s)**	**Total Time (s)**
warehouse–line	30		195.7	30
warehouse–warehouse	0		6	0
line–warehouse	45		148.4	45
				75 s
			Total Time	**1407.8 s ≒ 24 min**

One robot performs the entire process in 24 min, which implies that a robot can perform the process twice in an hour, for a total of 48 min. We have calculated this with an average robot speed of $0.8.m/s^{-1}$. For the remaining 12 min, the robot can perform half the process; that is, it can move the pallet from the warehouse to the production line and then move to a charging station near the production line to charge itself. What the half process achieves is that for every two hours it adds one more pallet. Since eight pallets need to be moved per hour, the company deploys four robots for this process.

We compared the work of workers and robots. We assumed a production line speed of 4.5 km/h for the workers and an average speed of 0.8 km/h for the robots. One handling route was 504 m long. And the other handling route was 321 m long. We needed to handle eight pallets every hour on the production line, and we have a four-shift operation and we need either eight employees or four robots to do this. Due to holidays, sickness, and shortages of skilled labour in the market, it is easier and more cost-effective to use automation options. Thus, robots not only bring economic returns and 100% uptime but also increase the level of safety on the production floor. This method/methodology for

calculating the needed quantity of robots is applicable to a variety of operations. It is based on the requirements of the availability of information on pallet requirements per production line that already exists in the company today.

4.7. Robot Work Scheduling

There are two variants of robot work scheduling (Tables 7 and 8). The first variant is that the company deploys one charging station in the warehouse and one near the production line; that is, the robots will charge for 1 h.

If a company deploys four charging stations, this means that two charging stations will be in the warehouse and two near the production line. The robots will charge simultaneously every hour for the remaining 12 min after the processes have been carried out for 48 min.

Table 7. Robot work scheduling in case of 2 charging stations—variant 1.

Start Time	Robot				Route	
	1	2	3	4	Warehouse–Line	Line–Warehouse
0:00:00	Charging	Charging			0	0
1:00:00	2.5	2.5	Charging	Charging	4	4
2:00:00	3	3	2.5	2.5	10	10
3:00:00	2.5	2.5	3	3	10	10
4:00:00	3	3	2.5	2.5	10	10
5:00:00	2.5	2.5	3	3	10	10
6:00:00	3	3	2.5	2.5	10	10
7:00:00	Charging	Charging	3	3	6	6
8:00:00	2.5	2.5	Charging	Charging	4	4
9:00:00	3	3	2.5	2.5	10	10
10:00:00	2.5	2.5	3	3	10	10
11:00:00	3	3	2.5	2.5	10	10
12:00:00	2.5	2.5	3	3	10	10
13:00:00	3	3	2.5	2.5	10	10
14:00:00	2.5	2.5	3	3	10	10
15:00:00	3	3	Charging	Charging	6	6
16:00:00	Charging	Charging	2.5	2.5	4	4
17:00:00	2.5	2.5	3	3	10	10
18:00:00	3	3	2.5	2.5	10	10
19:00:00	2.5	2.5	3	3	10	10
20:00:00	3	3	2.5	2.5	10	10
21:00:00	2.5	2.5	3	3	10	10
22:00:00	3	3	2.5	2.5	10	10
23:00:00	2.5	2.5	Charging	Charging	4	4
00:00:00	Charging	Charging	2.5	2.5	4	4
					202 pallets	

If the company deploys two charging stations for four robots, these robots will be able to move up to 202 pallets/day, which is beyond the currently required pallet quantity per hour of 180 pallets/day. The recharging of autonomous mobile robots takes only 12–15 min to reach 85%. We also use this time when calculating and using the number of robots in Tables 7 and 8.

Table 7 shows that four robots move 192 pallets from the warehouse to the production line and back in 1 day. This option also satisfies the requirement for 180 pallets/day.

Both methods will satisfy the requirement for a daily standard of 180 pallets/day, but the first method is more cost-effective as the company only needs to procure two charging stations compared to the second method where the company would need to procure up to four charging stations.

Also, the advantage of the first method is that if the demand for the daily standard increases by approximately 20 pallets, the robots will be able to meet this demand.

Table 8. Robot work scheduling in case of 4 charging stations—variant 2.

Start Time	Robot				Route	
	1	2	3	4	Warehouse–Line	Line–Warehouse
0:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
1:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
2:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
3:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
4:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
5:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
6:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
7:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
8:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
9:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
10:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
11:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
12:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
13:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
14:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
15:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
16:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
17:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
18:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
19:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
20:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
21:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
22:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
23:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
00:00:00	2 + charg.	2 + charg.	2 + charg.	2 + charg.	8	8
					192 pallets	

Table 9 shows the costs that a company incurs for deploying robots, accessories, and service costs.

Table 9. Cost of the robot.

Circulation	Robot		
	Unit Cost [€]	Number [pcs]	Total Costs [€]
Charger	15,000	2	30,000
Wirelles box	5000	1	5000
Tablet	3000	1	3000
Robot	55,000	4	220,000
Service costs	10,000	-	10,000
	TOTAL		268,000

The table shows that the company will spend EUR 268,000 on the deployment of robots and related technology.

In Table 10 below, we have calculated the cost that the firm would have to spend on staff and associated equipment because, as things stand, four staff would not be able to meet the supply requirement of the line. Also, in the current state, the firm has only one tractor with transport frames, but this tractor is deployed in other processes, meaning that the firm would have to purchase two tractors with transport frames because this is a four-shift operation and there will be two employees working on this process in one operation.

Table 10. Cost per worker and associated equipment.

Circulation	Staff		
	Cost per Worker [€/Year]	**Number of Workers**	**Total Costs [€]**
wages	30,000	4	120,000
	TOTAL		120,000
	Related Technology		
Circulation	**Unit Cost [€]**	**Number [pcs]**	**Total Costs [€]**
Tow tractor	20,000	2	40,000
Frame	10,000	8	80,000
Service costs	-	-	6000
	TOTAL		126,000
	TOTAL SUM		246,000

The company will save EUR 120,000 per year in staff costs and will also save the cost of a one-off purchase of related equipment (tractors with transport frames) worth EUR 126,000.

$$268{,}000 - 246{,}000 = \text{EUR } 22{,}000,$$

the company must pay extra to deploy the robots and related technology. (22,000 ÷ 246,000) × 100 = 8.94%. The return on investment is 8.94%.

Return on investment: 268,000 ÷ 246,000 = 1.08 years (approximately 395 days). The return on investment is expected within 2 years.

5. Discussion

In this paper, we have discussed in detail the material supply of the production line, which is currently performed mechanically. This causes a lot of confusion, errors, and problems in the management of the company's production capacity. Therefore, in the paper, we discuss two variants of solutions for the automation of this process. The first proposal of the material flow control procedure to the production line deals with the deployment of an autonomous mobile robot with two charging stations and the ability to handle 202 pallets per hour. The second proposal also addresses the deployment of an autonomous mobile robot to supply the production line and remove empty pallets, but with four charging stations. This ultimately also results in an increase in handling quantity to 192 pallets per day, against a requirement of 180 pallets per day. The first option is justified in addressing the potential increase in the quantity handled to the production line. In the case of gaining new customers in the market, there is the possibility of increasing this flow only by counting the number of autonomous mobile robots.

Based on the analysed processes and the used options of deployment of a human and classical handling technology or robot E10, it is possible to evaluate the benefits of the proposed solution for the company in terms of cost, efficiency, and time consumption.

The first option was the deployment of an employee and handling equipment, consisting of a tractor and a transport rig. After a detailed description of the supply process from the warehouse to the production line and back, we followed with a calculation of the employee's labour time to determine how long it would take the employee to perform this process to satisfy the production line's requirement of delivering eight pallets per hour. The calculation determined that one employee would take approximately 50 min to perform the process, indicating that he or she would not be able to satisfy the production line's requirement to deliver eight pallets per hour. Therefore, the company would have to deploy up to two employees and two tractor–trailers with two transport rigs per shift. Since this is a four-shift operation, the company would have to deploy up to eight employees for this process. The current state of mechanically secured transport of goods to the production line is therefore insufficient and it is necessary to solve other possibilities of handling equipment,

if we calculate the average speed of the sweeper and transport platforms as 4.5 km/h. By detailed analysis, we found that the employee pulling the loaded pallets follows a 504 m long route to the production line (blue) and with empty pallets follows a red route with a distance of 321 m. The detailed activities of each employee on a four-shift production operation are described in Table 1. By deploying eight employees, the company would have to spend approximately EUR 120,000 per year, and by purchasing two tractors and eight transport frames, an additional EUR 120,000. The company is also counting on annual service costs of around EUR 6000. In total, the company would have to spend EUR 246,000 on the first option. This option appears to be less efficient, as well as costly and inflexible. The disadvantage is that in the event of illness, leave, or other employee absence, it would be difficult to meet the production line's requirement to deliver eight pallets per hour. Also, in the event of a breakdown of a tractor or transport unit, it would be difficult to deliver the required number of pallets to the production line, causing production downtime.

The second option would be to deploy autonomous mobile robots for the supply process from the warehouse to the production line and back. After describing the supply method in detail, we needed to determine how long it would take the robot to satisfy the production line's requirement to deliver eight pallets per hour. After calculating this, we found that one robot would perform the process in approximately 24 min, which implies that one robot could perform the process twice, or in 48 min. For the remaining 12 min, the robot could perform half the process, or it could charge for those remaining 12 min. If the robot worked for the remaining 12 min, it would be able to perform the half process; that is, it would move one more pallet from the warehouse to the production line. The advantage of performing the half process is that for every second hour, it would add one extra pallet to the production line. To meet the production line's demand, the company would deploy four robots for this process.

By deploying four robots, the company would have to spend approximately EUR 220,000 at a time. The cost would also include the purchase of a tablet of EUR 3000, two chargers of EUR 30,000, (EUR 60,000 in the case of four chargers) and a wireless box for approximately EUR 5000. The company is also counting on annual service costs of around EUR 10,000. In total, the company would have to spend EUR 268,000 (two charging stations) or EUR 298,000 (four charging stations) for the second option.

The second option appears to be more efficient, with high flexibility, as the robots can work continuously for 8 h. In the event of a failure of one of the robots, the remaining three robots would be able to meet the demand to deliver the required number of pallets to the production line. The cost of deploying the robots is higher than that of deploying employees and handling equipment, but if the company opts for two charging stations, the difference between the two options would be only EUR 22,000. If the company opts for four charging stations, it will have to spend approximately EUR 52,000 more. The company will also save approximately EUR 120,000 per year in personnel costs if it deploys robots for the process of supplying the production line.

Other benefits of deploying robots are that the process of mechanically moving material from the warehouse to the production line by warehouse employees using material handling equipment is eliminated. The deployment of robots will result in a saving in the number of direct employees involved in the creation of the final product and will ultimately lead to a possible reduction in the final price of the manufactured product.

There may also be a benefit in time savings, as the employee will not be performing the activity of moving material from the warehouse to the production line. This activity will be transferred to the robots. The role of the employee in the warehouse would only be picking the required material based on the generated kanban card. While the robot would be moving the material towards the production line, the employee could pick more material in that time. The company should automate this process of handling to the production line and removal of empty pallets by deploying robots, which will not only save employees and time, but also streamline operations and eliminate errors in the implementation of the handling and inventory process.

Our proposed procedure for implementing an autonomous mobile robot is unique in that it can be used in any manufacturing plant for any material supply process. Future work could address battery life and recharging capabilities. As the physical wear and tear of the new robots occurs, it will be necessary to address other charging options and the possibility of deploying spare robots if this is what happens in many plants when deploying automated guided vehicles. In this paper we only consider the deployment of new autonomous mobile robots, so how many and how they could be deployed in service and how we could replace them is not addressed. It is a question to be addressed in a future paper, where we would test the functionality of the autonomous mobile robot in a given operation and these new robots would age and through an application that is installed directly in the robots we could monitor the possible errors that the robot has in operation. The biggest problem is the batteries. Therefore, the disassembly and assembly of a new battery is a question for the production department. Otherwise, the only simple solution is still buying one extra robot for reserve. This technology is still too new and little used in the conditions of the Slovak Republic, so exploring this area is impossible for now. In the future, we will not avoiding this and will be happy to test older AMRs in operation or in the lab, to see possible failures of optics, navigation, sensors, battery.

6. Conclusions

In the paper, we have discussed autonomous mobile robot technology. In this paper, we have described the use of an AMR to supply the production line in the company instead of a human and we have calculated the possibilities of charging stations in the company to increase the number of pallets needed to supply the production line by 20%. We have compared the performance of a sweeper in supplying the production line with that of a mobile robot with the result of the possibility of automating the process and especially the error-free 100% supply of the production line. It is possible to use this approach in other production supply methodology designs.

The deployment of autonomous mobile robots in the company's operations has resulted in higher safety and higher truck performance perhaps at the expense of speed, but with minimal need for manoeuvrability due to route requirements. This approach of managing handling in the company's warehouse contributes to a sustainable level of safety.

To deploy automation for the company's supply chain process, we started with a general characterization of the logistics processes, from order to export to the final customer. We then analysed and evaluated these processes in terms of their execution in the company. The result of the analysis and evaluation was that the logistics processes in the company are provided only mechanically, sporadically manually, while the supply process can be automated with autonomous mobile robots.

By analysing the logistics processes for the first variation, we found that one employee with handling equipment would perform the process in approximately 50 min. Therefore, the company would have to deploy up to eight employees and two tractor-trailers with two transport sets of four for the process of supplying the production line, as it is a four-shift operation (12 h). We also found that the total cost of the staff and related equipment, including service costs, would amount to approximately EUR 246,000.

By analysing the logistics processes for the second variant, we found that the robot executes one process in 24 min; that is, it can execute a process twice or three times in an hour, depending on how the robot's work scheduling (charging method) is solved. Based on this knowledge, the company would have to purchase four robots to provide the supply process. In addition, we found that the company would have to spend EUR 286,000/EUR 298,000 to acquire the robots and accessories.

By comparing the two options, we found that the option of deploying robots appears to be better for the company. The first advantage of this option is that the firm would only have to spend EUR 22,000/EUR 56,000 more, which is expected to result in a quick return on investment.

Another advantage is that the process of mechanically moving material from the warehouse to the production line and back by employees and handling equipment would be eliminated. This would result in a saving in the number of direct workers who would otherwise have to be involved in the creation of the final product, which would also ultimately lead to a reduction in the price of the product produced and a saving in the cost of four employees (EUR 120,000/year).

For the above reasons, the company should therefore decide to automate the supply of a particular line directly by deploying robots.

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