

Article

The Influence of Energy Consumption and the Environmental Impact of Electronic Components on the Structures of Mobile Robots Used in Logistics

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Abstract: Industrial development has implicitly led to the development of new systems that increase the ability to provide services and products in real time. Autonomous mobile robots are considered some of the most important tools that can help both industry and society. These robots offer a certain autonomy that makes them indispensable in industrial activities. However, some elements of these robots are not yet very well outlined, such as their construction, their lifetime and energy consumption, and the environmental impact of their activity. Within the context of European regulations (here, we focus on the Green Deal and the growth in greenhouse gas emissions), any industrial activity must be analyzed and optimized so that it is efficient and does not significantly impact the environment. The added value of this paper is its examination of the activities carried out by mobile robots and the impact of their electronic components on the environment. The proposed analysis employs, as a central point, an analysis of mobile robots from the point of view of their electronic components and the impact of their activity on the environment in terms of energy consumption, as evaluated by calculating the emission of greenhouse gases (GHGs). The way in which the activity of a robot impacts the environment was established throughout the economic flow, as well as by providing possible methods of reducing this impact by optimizing the robot's activity. The environmental impact of a mobile robot, in regard to its electronic components, will also be analyzed when the period of operation is completed.

Keywords: mobile robot; power consumption; electronic components; carbon footprint



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1. Introduction

The constantly changing industrial environment has become very competitive, and all industries are trying to identify increasingly complex automation solutions that boost productivity [1].

Mobile autonomous robots constitute a particular class of robotic systems that can perform a task that involves moving various products from one side of a warehouse or a store to another. Their work allows for an efficient, precise, and rationalized flow, making human work less complicated. In anticipation of the implementation of Industry 5.0, the research activity related to these robots is growing, its aim being that people and machines should coexist and work together. The aim is that the future mobile robots will use clean energy sources which are also cost-effective and meet environmental requirements. Commercially viable solutions for these robots have already been found due to the research carried out

regarding their mechanical design, perception, navigation, and control. However, currently, these solutions are not sufficiently widespread because of inadequate power systems in diverse and largely unknown/uncontrolled environments.

The use of mobile robots has seen a significant growth in recent years, reflecting the global trend towards automation and process optimization. Thus, there has been a considerable increase in the use of these robots in various economic contexts, such as the following:

- Storage and distribution centers—About 80% of mobile robots are deployed in warehouses and distribution centers. They are used to transport goods, sort products, and manage inventory.
- Retail and e-commerce—The use of mobile robots in the retail and e-commerce sector has seen a significant expansion due to the requirements for managing online orders quickly and efficiently. Mobile robots contribute to order picking and packaging, reducing delivery time and improving process accuracy.
- Industry and production—In manufacturing, mobile robots transport components between different factory sections, helping to minimize downtime and optimize workflow.

In logistics activities, mobile robots can help increase efficiency, reduce processing time, improve operation accuracy, and ensure a safer working environment for employees.

Current mobile robot power solutions involve high initial costs and require recharging or refueling. These stop/start processes are not profitable [2].

Due to their ability to move, mobile robots are robust; they can also complete tasks in more than one place, repositioning and reinstalling themselves in a different workplace with a minimum of physical changes. In addition to this, they have the ability to operate in inaccessible and/or unknown environments, and their mobility offers them the flexibility to perform complicated, tedious, and repetitive tasks that are otherwise difficult or impossible for humans. All these characteristics make autonomous mobile robots (AMRs) useful in various economic sectors, such as manufacturing, logistics, healthcare, retail, agriculture, and construction. The efficiency and productivity of AMRs are the main reasons behind their success and provide the motivation for the rapid development of these tools [3].

Since Shakey, the first mobile robot to meet navigation goals, was developed in the late 1960s at the Stanford Research Institute, investments in research have mainly aimed to increase the autonomous capacity of these robots. Thus, the research and development applied to this type of robot has become an essential part of Industry 4.0 [4].

In 2021, the European Commission presented its vision of Industry 5.0 as sustainable, human-centric, and resilient [5]. Therefore, within this context, the robot market is expected to grow from earning USD 19 billion in 2018 to bringing in USD 50 billion in 2025, mainly due to the sale of industrial robots [6].

Along with these changes, new challenges arise related to the supply of energy for this equipment, along with finding appropriate ways to recycle it. Even though industrial robots, including AMRs, are electronic equipment, they are not included in the specific six categories, as explained in Annex III of Directive 2012/19/EU [5]; at the same time, many of these robots are not considered industrial equipment. However, while some of their components may fall into the six categories, as a whole, the robots do not. Consequently, rigorous research is needed to improve the currently available solutions for these robots' energy consumption and recycling methods. Currently, batteries with limited lifespans are used as powering methods for AMR operation. This influences AMR energy consumption and, implicitly, the carbon footprint and the service life of the electronic equipment used in AMRs.

Based on this conceptual approach, this article intends to present the environmental impact of an AMR's activity from the perspective of energy consumption and, implicitly, to evaluate the carbon footprint of the electronic equipment used.

In order to calculate the carbon footprint, the GHG Protocol was used as the only stand-alone document in this respect. In our research, we focused on electricity consumption

because we believe that it significantly affects the activity of an AMR. Moreover, we focused on the optimization of the AMR operation process in order to reduce the adverse effects on the environment and to increase the operating time in optimal conditions.

This article also aims to assess the recyclability of electronic waste from an AMR by analyzing the added value of removing various types of electrical and electronic components from the structure of autonomous mobile robots after their removal from service. The primary sources of environmental pollution during the recycling process are electronic components, rechargeable batteries, infrastructure materials, and connection cables. These can determine the components' ecological impact and the predominant types of products resulting during their disposal.

2. Literature Review

Nowadays, due to climate change, the world of handling systems has been revolutionized. With the advent of logistics centers and their rapid development, warehouses have become highly automated facilities with complex processes. Thus, companies progressively tend to introduce autonomous systems for handling materials in most of their operations.

As commercial activities have a significant impact on the environment, both developed and developing countries have taken various measures meant to conserve natural resources, limit carbon emissions and accelerate the energy transition. Numerous countries have announced their energy transition strategies for counterbalancing the energy demand and reducing the environmental impact [7]. As a consequence, alongside economic growth, other objectives have gained importance, such as protecting ecological resources, reducing carbon emissions, and using green energy at a larger scale [8].

E-commerce is developing at a fast pace and pilot studies have been initiated for the delivery of products to consumers with the help of autonomous robots. In this situation, there is a twofold focus: the ability of the AMRs to perform this task and the need to reduce the energy used by these robots and implicitly their carbon emissions [9]. In order to diminish the carbon emissions by lowering the energy consumption, one should consider the distance covered, the battery lifespan, and the planning horizon, these being some of the most important factors affecting the competitiveness of AMRs [10].

Storage operations usually involve laborious tasks, with taking orders being considered the most expensive and burdensome operation of all. Autonomous mobile robots (AMRs) are a specific class of robotic systems that can perform specific tasks, including moving a payload from one location to another, making it possible to increase the efficiency, precision, and rationalization of the workflow, thus rendering human work less difficult. Within the context of Industry 5.0, AMRs will be used more extensively. As the energy sources are an essential element of future robots, they will have to be clean, cost-effective, and environmentally friendly.

Research regarding AMRs focuses on mechanical design, perception, navigation, and control, and it has resulted in numerous viable commercial solutions for mobile robots. However, they are not currently used on a large scale due to the fact that the power systems are not efficient or environmentally friendly [2].

On the one hand, the use of artificial intelligence contributes to an increase in productivity and to creating scale economies, thus saving the resources and the energy of entire societies [11]. On the other hand, an ever-higher number of practitioners and researchers are pointing out that the dramatic growth in the capabilities of AI is accompanied by an exponential increase in energy consumption [12]. Briefly, new technologies and especially AMRs influence the current energy system in different ways and through various channels, as described in Table 1.

A sustainable approach is needed to manage energy consumption smartly, which is relevant within the context of increasing electricity prices [13]. Greenhouse gas emissions and low operational costs are widely targeted elements for a such a sustainable approach when referring to AMRs [14]. Moreover, a sustainable approach is also necessary regarding the waste resulting from the use of AMRs.

Table 1. Influence of AMRs on the energy system.

Measure	Activity
Energy generation	Integrated solar panels Collecting energy from the environment
Optimizing energy consumption	Intelligent routes Battery management

Integrating the new technologies into different economic sectors presents a dilemma regarding the benefits offered [15]. These technologies already provide increased efficiency, reduced waste, and resource optimization, which reduces CO₂ emissions. On the other hand, their large-scale adoption can escalate energy demand, subsequently increasing carbon emissions, especially in large energy-consuming industries [16,17].

Even though, potentially, digital energy systems can increase efficiency, economic expansion and falling prices may trigger a rebound effect. This effect may eventually lead to a net increase in energy consumption and CO₂ emissions [18]. This approach has drawn the attention of researchers who tackle the relationship between CO₂ emissions and economic growth with a view to reaching emission reduction targets [19].

Nevertheless, including mobile robots in logistics requires consideration of not only the issue of reducing CO₂ emissions, but also of the quantity of electrical and electronic waste that results from the removal of such a robot or even of one of its components, which also has a significant impact on the environment.

In Europe, Directive 2012/19/EU clearly specifies the six categories of electrical equipment that are targeted [20]. The waste collection systems for electrical and electronic equipment in European countries vary significantly, but all countries must adhere to the above-mentioned EU Directive.

The electrical and electronic equipment sector (EEE) is a critical one, where progress towards a circular transition has been limited. In 2019, Europe was responsible for the second largest share of e-waste globally and the leader in generating e-waste per capita [21]. Less than 20% of the electronic waste produced is estimated to be appropriately managed in compliance with the environmental requirements [22].

The increasing use of electrical and electronic equipment leads to large quantities of electronic waste. If handled improperly, this electronic waste could pose severe risks to human health and the environment. On the other hand, in order to properly manage this waste, a solid strategy is necessary in terms of awareness, collection, recycling, and reuse.

Efficient recycling of this type of waste constitutes a significant challenge for society. However, if these waste categories are properly recycled, materials with a recognized economic value can be reintroduced into the economic circuit. A relevant example is that of printed circuit boards. Almost all electrical and electronic equipment contains printed circuit boards that form the basis of many electronic industries and which are rich in valuable heavy metals and toxic halogenated organic substances.

Transforming business practices can be technologically difficult. Specifically, improving the efficiency of the current processes could be hampered by the lack of availability of technical solutions (for example, technologies for recycling the materials present in small quantities in electronic products) [23].

As the industry is constantly developing, new types of electrical and electronic equipment are introduced on the market [24], one of which is AMRs. Placing such instruments on the market complies with all the stages that are specific to this type of activity.

The introduction of mobile robots in various economic activities raises the issue of their elimination after the end of the operating period, which becomes a topical issue. When eliminating each type of mobile robot, one must take into account the specificities of its design, the composition of the equipment, and the environmental risks in the case of the destruction of the robot's structure, which will lead to its fragments reaching the external environment. Even if mobile robots are not explicitly included in the six categories

mentioned above, the existing recycling techniques essentially pursue the same results, namely the recovery of economically valuable minerals such as gold, copper, iron, and aluminum and the removal of toxic waste [25]. These pollutants can be released into the soil, water, and air and directly threaten animal and plant species throughout the food chain, thus posing risks to human health [14]. Therefore, depending on the type and purpose of robots, their disposal and recycling have special characteristics. A sustainable approach to the intelligent management of these types of waste means a low impact on the workers' health, a reduction in greenhouse gas emissions, and low operational costs [26].

Hence, if the problems related to these mobile robots' energy consumption and operational longevity are solved, not only will future robots become sustainable, but they could also increase their trading range, leading to further industrial expansion [27].

In consequence, rigorous research is needed to improve the currently available solutions regarding the energy consumption and recycling methods for electronic equipment after its period of operation.

3. Materials and Methods

3.1. Description of the Proposed Methodology

The methodology proposed for this paper aims to set objectives, to identify limitations, and to analyze the carbon footprint before and after optimizing the route taken by the mobile robots integrated in a warehouse, as well as to track the degree to which electronic waste results after the removal and recycling of an AMR.

The GHG Protocol was used to calculate the carbon footprint, since it proposes a unified energy consumption approach. In addition, it was necessary to analyze the environmental impact of the components in the structures of mobile robots used in logistics applications after their decommissioning, since such waste resulting from industrial equipment represents a major issue.

The analysis was conducted on a prototype mobile robot developed by the authors that can be integrated into warehouses to support logistics activities. As these activities are rather complex, the proposed methodology focuses on the energy consumption of mobile robots, starting from the idea that their exploitation is not pre-established, but it may, nevertheless, be predictable depending on the processes within warehouses. Moreover, the environmental impact caused by the respective energy consumption of electrical and electronic waste within the command and control structures of robots, as well as by the operating time and the lifespan of the electrical and electronic components inside them, was analyzed.

Through this study, we aim to establish an algorithm to calculate the carbon footprint of the real conditions for mobile robots integrated with a warehouse based on the mobile robot prototype developed by the authors. In order to perform this calculation, two work scenarios were analyzed, one with an unoptimized route and another one with an optimized route. In each case, the energy consumption was analyzed.

The proposed steps for this methodology are as follows:

- Stage 1: Setting the objectives and limitations accepted within the proposed model (the mobile robot prototype and implicitly the logistics application in which more such robots are to be integrated);
- Stage 2: Determining the energy consumption specific to the electronic components within the robots;
- Stage 3: Calculating the carbon footprint according to the GHG Protocol for a regular operation (unoptimized);
- Stage 4: Making simulations regarding the optimization of the robot paths and proposing new configurations specific to the working environment of the robots (their routes) to reduce energy consumption and greenhouse gases in a context in which several robots are randomly involved in performing specific tasks;

Stage 5: Collecting and analyzing the consumption data according to the dynamics of the activities carried out for the unoptimized and optimized route variants;

Stage 6: Analyzing the environmental impact caused by the electronic waste from the moment an AMR is removed.

The objectives accepted under this model refer to reducing the energy consumption required to power mobile robots that can serve a warehouse in logistics activities.

One limitation of this study is that we only focused on the energy consumption of mobile robots based on the prototype designed by the authors in a warehouse context in which many more pieces of equipment have an environmental impact. Another limitation is the way of framing the electronic equipment as a component of an AMR in a context in which equipment from the new technologies is not specified in Annex III of Directive 2012/19/EU. A final limitation is that the analysis only takes into account the emission factors in Romania.

Detailing the electronic components in a mobile robot's command and control system structure is necessary in order to determine the energy consumption specific to each element and to optimize the robots' routes and actions. Moreover, configuring the route and the working space of the robots is essential to establish energy consumption and provide solutions for optimizing the paths of mobile robots.

Domain 1 was used to calculate the carbon footprint because the t emissions are directly generated by the sources owned or controlled by the logistics center.

To calculate the emissions, the following formula was used:

$$E_c = C \times F_e \quad (1)$$

where

E_c = Emissions obtained;

C = Fuel (quantity of fuel consumed or, in the present study, the quantity of energy consumed);

F_e = Emission factor (used in Romania).

3.2. Description of the Mobile Robot Prototype and the Application in Which It Is Integrated

For this case study, a mobile robot in modular construction was designed which can be used in logistics centers for specific activities related to the internal transportation of products. This AMR is equipped with eight wheels, of which four are omnidirectional, and a lift system that facilitates the robot's passing over small obstacles and reorientation in a smaller space. Thus, the proposed AMR structure allows the robot to be used in different applications, regardless of the possible flatness or unevenness of the surface it moves on.

The components in the robot's structure can be grouped according to the block scheme in Figure 1.

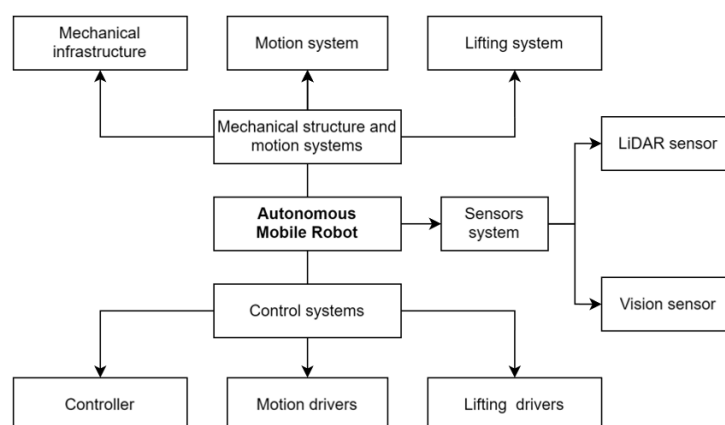


Figure 1. Block diagram with the main components of the designed mobile robot.

The previous scheme reflecting the components in the robot structure is detailed as follows:

- a. The mechanical structure and drive systems are represented in Figure 2 and have the following components:
 - A mechanical infrastructure, which supports all the other components. It is designed to ensure the easy and modular layout of the hardware components in the robot structure.
 - The robot displacement drive system, which includes four normal wheels and four omnidirectional wheels, each wheel being individually driven by a direct current motor equipped with an encoder for position control.
 - The drive system for reorienting the robot and passing over obstacles, which consists of two wheels each, and is driven by four motors and a coupling–decoupling subsystem of the action system required for elevators. The motors used for the reorientation subsystem are stepper motors equipped with a speed reducer and have the role of elevating the robot platform so that the standard or omnidirectional wheels remain on the ground for each system depending on the space in which it moves. This system is also used to allow passage over bumps and small obstacles.
- b. The command and control system (Figure 3) consists of the following components:
 - The central controller for the robot command represented by a mini-PC—Raspberry Pi 4.
 - Control drivers for direct current motors allowing the robot to move on the ground—BTS7960.
 - Control drivers for stepper motors that allow the robot to be lifted to reorient it and go over bumps and small-sized obstacles—TB67S.
 - Coupling–decoupling subsystem of the lift system—FEA 5.
 - Step-up Voltage converter—OKY3498-3.
 - Step-down Voltage converter—OKY3508.
- c. The sensor system (Figure 4) consists of the following components:
 - A vision sensor used to avoid obstacles.
 - LiDAR sensors used as an additional safety measure in exploitation.

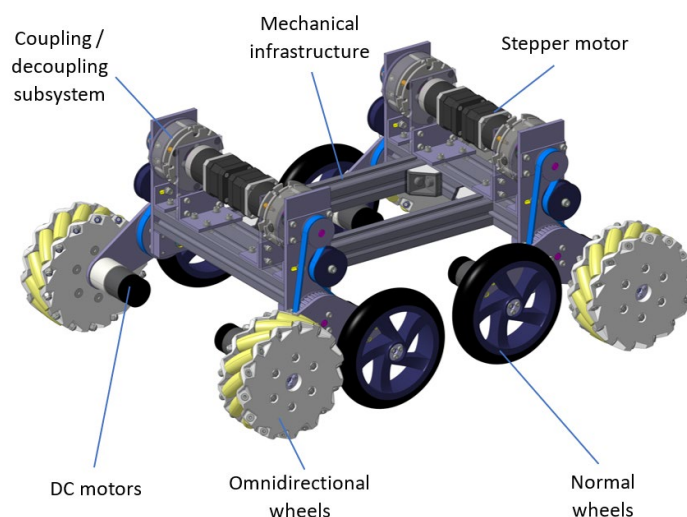


Figure 2. Robot-specific mechanical infrastructure and drive systems.

Table 2 shows the consumption characteristics and the number of specific electrical and electronic components in the designed mobile robot structure that were taken into account for calculating the energy consumption.

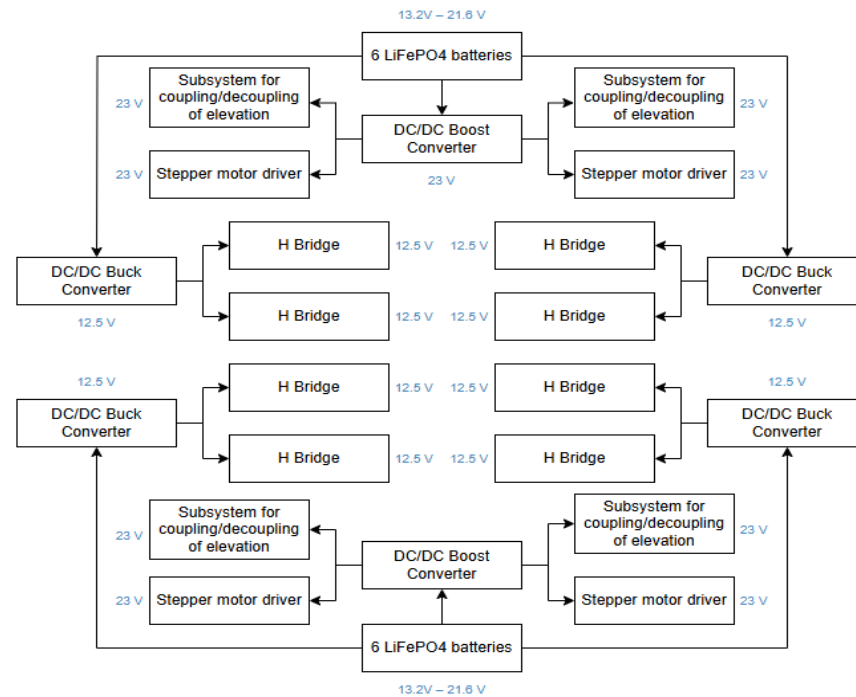


Figure 3. Electrical architecture specific to the command and control system of the designed mobile robot structure.

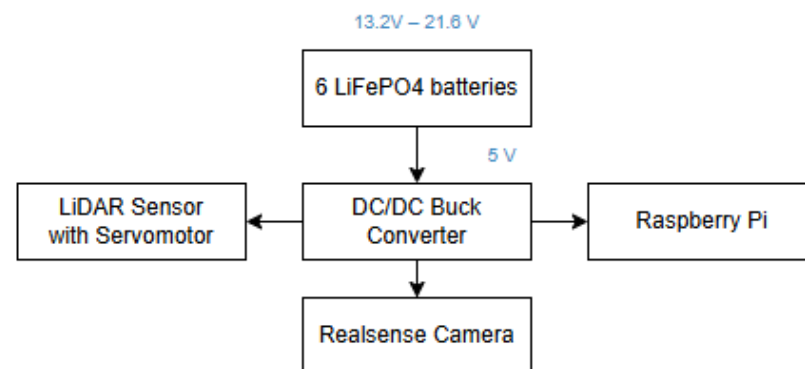


Figure 4. Electrical architecture specific to the sensor system in the designed mobile robot structure.

From the previous table, it can be noted that the power supply is represented by 12 LiFePO4-type accumulators, which have electrochemical robustness (low fire hazard in case of an accident). With regard to consumption, there are two main directions of consumption, namely, on the one hand, DC motors for moving the robotic platform, and on the other hand, the stepper accumulators and the coupling–decoupling systems for robot lift when reorienting and passing over obstacles. These two directions are essentially alternating, given that the robot wheel lifting is only performed when the robot is stationary.

Mobile robots can perform a multitude of tasks. Still, when they are used for warehouse-specific activities for cargo handling, they fall into 3 categories according to how they interact with the moved goods:

- Mobile robots with platforms that allow the transfer of relatively small goods directly on the structure of their platform;
- Mobile robots with forklifts that allow the handling of pallets with products;
- Mobile robots that allow the towing of racks or mobile loads.

Table 2. Electrical and electronic components in the designed mobile robot structure.

Name of Component	Name of the Manufacturer, Location	Description	Number	Picture	Maximum Power	Nominal Power	Type of Use
Accumulator LiFePO4	Headway, China	Cell of 3.2 V, 10 Ah, 3 C	12		$12 \times 90 \text{ W}$	$12 \times 40 \text{ W}$	Continuous (generation)
DC motor	Pololu, USA	DC 12 V motor with reducer and encoder	8		$8 \times 60 \text{ W}$	$8 \times 40 \text{ W}$	Continuous (consumption)
DC motor driver	Infineon NovalithIC, USA	H-Bridge, BTS7960	8		$8 \times 2.4 \text{ W}$ (96% efficiency)	$8 \times 1.6 \text{ W}$ (96% efficiency)	Continuous (consumption)
Step-down voltage converter OKY3508	Okystar, China	Intermediates between batteries and DC motor drivers	4		$4 \times 12 \text{ W}$ (efficiency 90%)	$4 \times 8 \text{ W}$ (efficiency 90%)	Continuous (consumption)
Stepper motor	Stepperonline, China	Used to lift the robot to climb steps	4		$4 \times 60 \text{ W}$	$4 \times 60 \text{ W}$	Period predetermined by conditions (consumption)

Table 2. Cont.

Name of Component	Name of the Manufacturer, Location	Description	Number	Picture	Maximum Power	Nominal Power	Type of Use
Stepper motor driver	Toshiba, Japan	Driver with step reduction, TB67S	4		4 × 3.6 W (94% efficiency)	4 × 3.6 W (94% efficiency)	Period predetermined by conditions (consumption)
Electromagnetic brake	Stepperonline, China	Keeps the system suspended	4		4 × 7 W	4 × 7 W	Period predetermined by conditions (consumption)
Step-up voltage converter OKY3498-3	Okystar, China	Intermediates between batteries and stepper motors drivers, as well as the coupling system	2		2 × 8 W (90% efficiency)	2 × 8 W (90% efficiency)	Period predetermined by conditions (consumption)
Depth camera Realsense D455	Intel, USA	To avoid obstacles	1		15 W	15 W	Continuous (consumption)
LiDAR sensor	Garmin, USA	For safety	2		2 W	2 W	Continuous (consumption)
Raspberry pi 4	Raspberry Pi Foundation in association with Broadcom, UK	For the logic of the system	1		15 W	15 W	Continuous (consumption)
Accumulator charger	E-Shine, China	Charger for the 12 LiFePO4 cells	1		210 W	210 W	6 h

The mobile robot designed and used for research in this paper is part of the first category: mobile robots with platforms. It was designed to operate in small spaces and in applications where there are bumps/uneven surfaces.

Figures 5 and 6 present two models of applications in which this AMR can be integrated. Two work scenarios are highlighted: one with an unoptimized route and one with an optimized route; in each case, the consumption of the mobile robot was analyzed according to the specificity of the application.

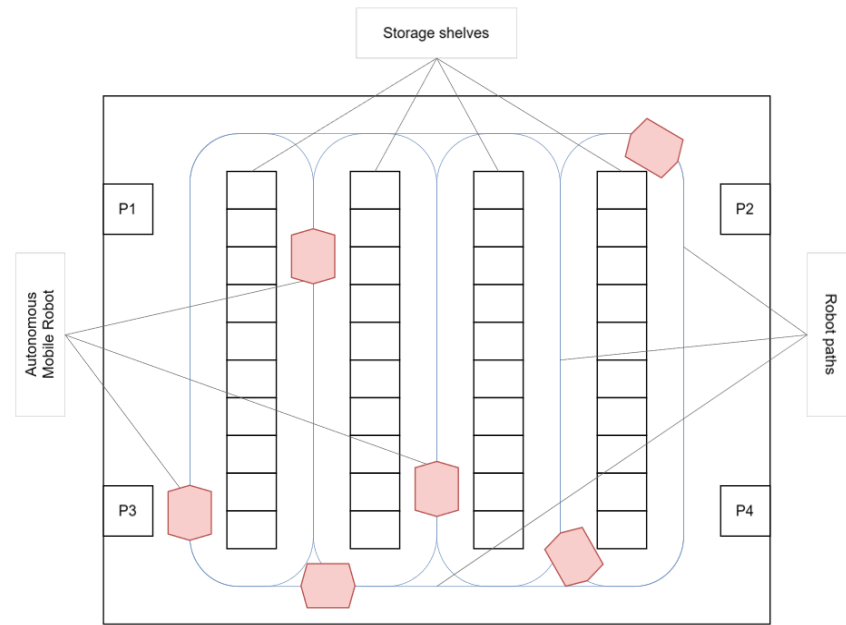


Figure 5. The application in which the designed AMR is integrated—initial route (unoptimized).

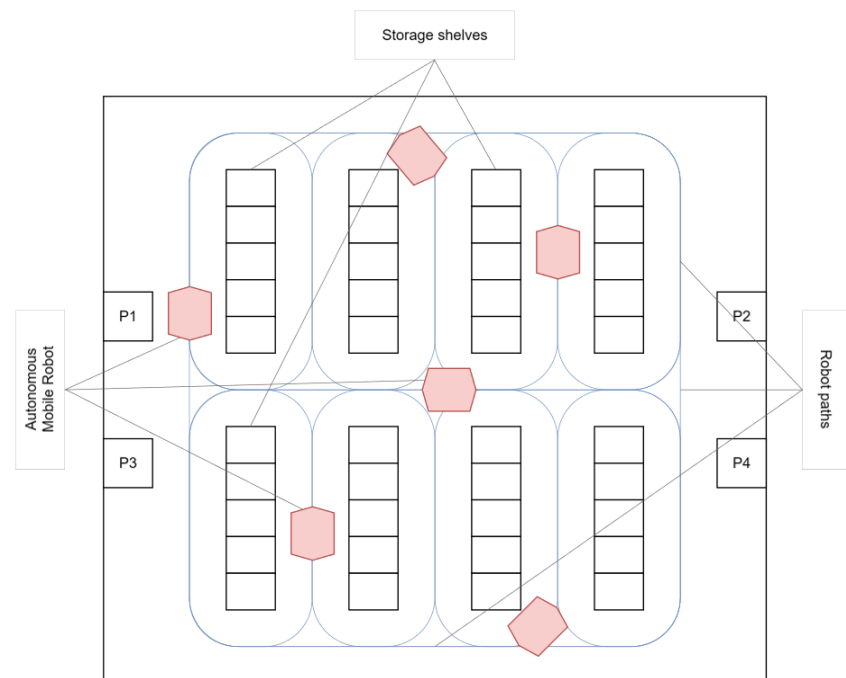


Figure 6. The application in which the designed AMR is integrated—with adapted route after reconfiguring the storage area (optimized).

The first scenario presented in Figure 5 includes 4 entry/exit posts—(P1, P2, P3, P4) for the products to go in and out of the storage place, consisting of 4 storage areas and

6 mobile robots that transport the products from the area of the entry/exit posts to the storage area and vice versa.

The second scenario presented in Figure 6 contains the same elements, with a similar storage capacity, but the layout of the entry/exit posts and of the storage structures is different. This results in another configuration of the route on which the mobile robots will be placed.

In both cases, the mobile robots can move between any workstation and the storage shelf.

In the second scenario (Figure 6), the aisle divides the storage area by length, adding another route. Due to this addition, the distance traveled between any storage shelf and the nearest entry/exit post is shorter than the distance traveled between any storage shelf and the nearest entry/exit post in the first scenario (Figure 6).

The main source of consumption of the designed mobile robot is the 8 DC motors, which have a maximum power consumption at start-up from the stationary position. In order to reduce consumption, it is necessary to reduce the number of complete robot stops. For this, algorithms for predicting the position of obstacles in time were chosen to start the bypass procedure while the wheels are still moving. There are two types of obstacles: fixed (objects) and mobile (people).

For the case study in this article, only the fixed obstacles represented by the static elements within the application were considered.

The technical details regarding the transfer of the products to the robot platform, the entry/exit posts and the storage shelves were not presented, as they were not the object of this research.

4. Results

4.1. Technical Information

Based on the two previously presented routes, the total energy consumption for the robot was determined based on the specific consumption of the electrical and electronic components in its structure.

Tables 3 and 4 show the data obtained by directly measuring the activity and inactivity times of each electronic component in the two scenarios with the micro-controller. These time values were then multiplied by the average energy consumption of each electronic component of the robot, determined separately by individual tests in various conditions. For example, the DC motors were tested by measuring the electricity and power when the robot was working at various speeds, while the DC/Cd converters were tested on a testbench when they were removed from the robot.

Table 3. Energy consumption of the robot in the unoptimized route.

Name of the Electrical/Electronic Component	Number of Components	Actions (Distance Traveled/Number of Lift-Time Liftings) per Hour	Energy Consumption per Hour	Energy Consumption per Day (16 Working Hours)
Accumulator LiFePO4	12		$12 \times 32 \text{ Wh} = 384 \text{ Wh}$ (generated)	Battery changed every 1 h 40 min
DC motor	8	5 km per hour, 80 km per day, 45 min work, 10 min station, 5 min lift	150 Wh	2400 Wh
DC motor driver	8	45 min per hour	6 Wh	96 Wh
Step-down voltage converter OKY3508	4	40 min per hour	15.6 Wh	249.6 Wh
Stepper motor	4	5 min per hour	17 Wh	272 Wh
Stepper motor driver	4	5 min per hour	1 Wh	16 Wh
Decoupling/coupling system	4	5 min per hour	2 Wh	32 Wh

Table 3. Cont.

Name of the Electrical/Electronic Component	Number of Components	Actions (Distance Traveled/Number of Lift-Time Liftings) per Hour	Energy Consumption per Hour	Energy Consumption per Day (16 Working Hours)
Step-up voltage converter OKY3498-3	2	5 min per hour	1 Wh	16 Wh
Depth camera Intel Realsense D455	1	Continuous usage	15 Wh	240 Wh
Raspberry pi 4	1	Continuous usage	15 Wh	240 Wh
Lidar sensor with servo motor	2	Continuous usage	2 Wh	32 Wh
TOTAL Consumption			224.6 Wh	3593.6 Wh

Table 4. Energy consumption of the robot for the optimized route.

Name of the Electrical/Electronic Component	Number of Components	Actions (Distance Traveled/Number of Lift-Time Liftings) per Hour	Energy Consumption per Hour	Energy Consumption per Day (16 Working Hours)
Accumulator LiFePO4	12		384 Wh (generated)	Battery change at 2 h 20 min
DC motor	8	4 km per hour, 64 km per day, 40 min work, 15 min station, 5 min lift	100 Wh	1600 Wh
DC motor driver	8	40 min per hour	4 Wh	64 Wh
Step-down voltage converter OKY3508	4	40 min per hour	10.5 Wh	168 Wh
Stepper motor	4	5 min per hour	17 Wh	272 Wh
Stepper motor driver	4	5 min per hour	1 Wh	16 Wh
Decoupling/coupling system	4	5 min per hour	2 Wh	32 Wh
Step-up voltage converter OKY3498-3	2	5 min per hour	1 Wh	16 Wh
Depth camera Intel Realsense D455	1	Continuous usage	15 Wh	240 Wh
Raspberry pi 4	1	Continuous usage	15 Wh	240 Wh
Lidar sensor with servo motor	2	Continuous usage	2 Wh	32 Wh
TOTAL Consumption			167.5 Wh	2680 Wh

Table 3 presents the consumption of each component in a non-optimized running regime in which an hourly consumption per day of 16 h was evaluated. The scenario shows the segmentation of activity times in an hour as follows: the system moves for 45 min, then it is stationary for 10 min, and 5 min are spent passing over small obstacles with the lift platform. As a result, it was necessary to replace the batteries every 1 h and 40 min during the day.

Using the robot designed and manufactured in the laboratory allowed us to obtain accurate results, as it was possible to change any part of the command system in order to measure all the necessary values, such as the electricity, the power, and the activity times, as well as to test the electronic components on a testbench in order to determine the values presented in Table 4.

Tests performed on several robots make it possible to increase the degree of generalization specific to this study, which is based on results obtained in the lab.

In Table 4, the optimization process is highlighted for each component. Thus, a consumption per hour per day of 16 h was evaluated. It was noted that the running time had decreased from 45 min to 40 min, and the robot platform's lifting time remained

at 5 min. However, the average power decreased because the number of stops/starts decreased as well. This led to the battery change interval changing from 1 h 40 min to 2 h 20 min.

4.2. Calculation of Carbon Footprint for an AMR

The 1-Scope 1 application was used to calculate the carbon footprint, since AMRs use direct emissions from resources controlled or owned by the logistics center. In other words, these are the emissions released into the atmosphere directly, resulting from the activities of a company.

The designed robot uses electric energy and the emissions were calculated according to Equation (1). The limitation accepted by the present article is that the emission factor used was the one for Romania. Table 5 shows the calculation of emission factors in the Scope 1 application domain.

Table 5. Calculation of the emission factors for Scope 1 for the unoptimized version.

Activity	Fuel Quantity	Standard Emission Factor	Total Emissions
AMR activity—1 working hour	224.6 Wh	0.701	157.445 kg CO _{2e}
AMR activity—1 working day	3593.6 Wh	0.701	2519.114 kg CO _{2e}

One can thus notice that for 1 working hour, the AMR had a total of 157.445 kg of CO_{2e} emissions. For a whole working day, the quantity of emissions was 2519.114 kg CO_{2e}. Because electric energy is a vital resource for the activities of an autonomous robot, it is necessary to optimize the activity of the AMR for an efficient management of energy consumption and the reduction of carbon emissions. This was achieved in the optimized variant presented in Table 6.

Table 6. Calculation of the emission factors for Scope 1 for the optimized version.

Activity	Fuel Quantity	Standard Emission Factor	Total Emissions
AMR activity—1 working hour	167.5 Wh	0.701	117.418 kg CO _{2e}
AMR activity—1 working day	2680 Wh	0.701	1878.68 kg CO _{2e}

By optimizing the route, it can be observed that the AMR showed a total of 117.418 kg of CO_{2e} emissions for one working hour and 1878.68 kg CO_{2e} for an entire working day.

From the previous comparison, we note that optimizing the route would have a considerable impact not only on the running time, but also on the number of starts and stops, and on the number of changes in direction on the spot. This is important because the instant power when starting a DC motor is 60 W, compared to less than 20 W when running. Specifically, in the scenario presented in the previous tables, we can notice a saving of 58 Wh, which is 20%.

4.3. Analysis of Electronic Waste Obtained after the End of the Period of Operation

As previously mentioned, the power supply for this particular AMR is represented by 12 LiFePO₄ rechargeable batteries. LiFePO₄ accumulators have a lifespan of about 5000 complete charge/discharge cycles, which means a lifespan of around 5 years.

LiFePO₄ battery waste cathode material is rich in iron, lithium, and other metals in smaller quantities. Physical pretreatment of LiFePO₄ accumulators leads to the extraction of iron and nickel, plastic, and other heavy metals.

The main energy-consuming parts are represented by DC motors, stepper motors, and coupling-decoupling systems for robot lifting when reorienting and passing over obstacles and reorientation.

The main motors are DC motors with permanent magnets and contact brushes, which have a lifespan limited to about a year but which can be extended if the brushes are changed annually.

Stepping motors have a longer lifespan than DC motors and the same is true about the power converters (such as switch mode power converters). The main result of the recycling process is copper, a material whose price has been steadily increasing yearly.

The mini-computer, the video camera, the Lidar system, and the other electronic boards have a very long life compared to the rest of the components. All circuits have electrolytic capacitors, which, even under harsh operating conditions, should last for at least 10 years.

Following the recycling process of mini-computers, one can obtain precious metals, including gold, silver, and copper from the processor and the motherboard. The circuit boards also contain a wide range of electronic components containing precious metals.

All the components of a mobile robot can be recycled, and the materials obtained that have economic value can be reintroduced into the economic circuit. Some materials negatively impact the environment and must be neutralized in the recycling process (for example, mercury).

5. Discussion

Through this paper, the authors wanted to bring forward the issue of the environmental impact of the new technologies used in logistics applications. The carbon emissions from this new equipment are mainly caused by the energy consumption.

In Industry 4.0, industrial equipment is widely used in logistics applications. Environmental impact analyses and eco-design guidelines are essential tools in the design phase because they have a decisive effect on the entire equipment life cycle [28].

The use of a mobile robot (AMR) can reduce logistics costs and implicitly the environmental impact due to lower greenhouse gas (GHG) emissions [29]. However, the development of optimization algorithms is essential because it leads to achieving the previously presented objectives.

Using the obtained results, we wanted to highlight the need for carrying out studies and analyses that would lead to a reduction in the energy consumed by an AMR.

Our study has limitations, but these can be remedied by identifying the sources which lead to an increase in energy consumption and implicitly of carbon emissions. The limitations of the methodology used to establish the energy consumption are caused by the manner in which the robots are configured, depending on the application specificity. That is why, in the proposed study, the average energy consumption was taken into consideration per robot, as if all robots were performing the same operations identically. In reality, such activities differ from one robot to another. These limitations can be dealt with by integrating counters for the electric consumption of the components, the consumption of which varies. In the case of our prototype, this is the case of the system which helps the robot move around and the system for changing direction and passing over obstacles. In this way, the specific consumption of each robot can be quantified irrespective of the types of operations to be performed.

Optimizing the energy consumption of mobile robots integrated into logistics applications can lead to a reduction in the operating costs, while the performance improves and the robot lifespan increases. Choosing energy-efficient components such as motors, drivers, and controllers can significantly decrease the energy consumption of autonomous mobile robots [30].

By optimizing the programs and reducing downtime in specific operations, the time can be reduced to minimize robot energy consumption.

Moreover, the use of energy-efficient motors and drives significantly impacts the amount of energy consumed. Another important approach in the context of the Green Deal is regular robot maintenance, which can reduce energy consumption by ensuring maximum efficiency of the robot components.

All the above are important within the context of rising energy prices and increasing environmental awareness, which have driven engineers and scientists to find new, innovative solutions in recent decades.

6. Conclusions

It is necessary to continuously optimize the specific activity of mobile robots in order to analyze and optimize their energy consumption and implicitly decrease the amount of greenhouse gases.

There are various ways in which this can be achieved, one of them being to reduce the inactive time of the robots during working hours to minimal levels. The process involves programming the robot to stop when not in use or reducing the time spent in standby mode. Energy consumption can be optimized by using a resting or energy-saving mode during robot inactivity, as well as by rethinking the space in which these robots operate.

Another way to optimize the energy consumption of mobile robots is to use energy-efficient components and technologies, such as LED lighting and high-efficiency motors and controllers. The materials used in the robot construction process can reduce the robot's weight, which influences the amount of energy required.

Another essential element is the increase in the robot's lifespan, better said of the equipment that forms the robot. This reduces the waste resulting from the electronic equipment that forms the robot.

The robot prototype used for the purpose of the present study is an average-sized one, with the capacity to adapt to various surfaces, which makes it equivalent to other platforms currently existing on the market, thus giving this study a sense of generalization. The robot is equipped with electric motors with average efficiency, but which can be controlled individually depending on the specificity of the application. The method used to establish the energy consumption was applied in the case of the robot prototype for two different situations, but it can be applied to any robot configuration for the electronic components of which the energy consumption is known.

It is our intention to continue the current study in our further research for a wider range of robots of various standardized sizes and which have the ability to perform different operations specific to the applications they are integrated in.

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