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# Ranking of Autonomous Alternatives for the Realization of Intralogistics Activities in Sustainable Warehouse Systems using the TOPSIS Method

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**ABSTRACT**

The requirement for intralogistics activities to be automated has been impacted by current trends based on the impact of Industry 4.0, the growth of e-commerce, the emergence of the consumer society, the rise in demand for logistics services, etc. Automatization of warehouse intralogistics is fundamental in aiming quickly responds to all user requests. The most common intralogistics equipment in warehouses is the forklift. However, its engagement results in a low level of automation. Consequently, it is useful to implement autonomous technology, such as automated guided vehicles (AGVs), automated mobile robots (AMRs), and drones, to have sustainable intralogistics activities. In addition to advantages and limitations, their application in practice increases performance, adaptability, system efficiency, customer satisfaction, and accuracy and contributes to the efficiency of the entire supply chain. The operating environment is more humane, environmental standards are respected, and certain economic advantages are achieved. These technologies are compared using eight criteria and the technique for order of preference by similarity to ideal solution (TOPSIS) method. AMR was selected as the most suitable option for implementing intralogistics activities. As the automation of intralogistics activities affects the entire supply chain, AMR is the solution that satisfies the social, environmental, and economic requirements of sustainable supply chain management.

## 1. Introduction

The development of contemporary technologies under the influence of Industry 4.0 has initiated improvements in all areas of supply chains. Logistics activities are a key factor in any supply chain and require a high level of productivity, flexibility, and autonomy [1]. Intralogistics activities are a critical subgroup of logistics activities that are focused on handling materials within warehouses, production, distribution, and other supply chain systems. Automating the movement of goods and enabling real-time material inventory control is an essential challenge in warehouses [2]. A warehouse management system (WMS) primarily assists in the management of material flows to meet deadlines

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for all customer requirements. Intralogistics activities are improved by integrating warehouse systems with advanced Industry 4.0 technologies. In this context, flexible intralogistics activities are required to meet contemporary challenges caused by the growth of e-commerce, changing customer needs (more frequent delivery of lesser amounts of items), and the development of current technologies [1, 3]. Contemporary Industry 4.0 technologies aim to increase the level of autonomy of intralogistics activities, improve productivity, respond to the increasing number of environmental challenges, reduce costs, humanize working conditions, etc. [2–3].

Automation of intralogistics systems reduces operational costs, makes more efficient use of resources, increases flexibility, and productivity, and contributes to all aspects of sustainable WMS [4]. This methodology is connected to the reduction of the number of engaged employees for the realization of manual intralogistics activities. Also, employees are engaged in the realization of primary activities (work on production lines), and thus labor costs in intralogistics are reduced by over 60 %, the productivity of production improves, and the utilization of storage space increases by over 30 % [1–2]. However, although automation is associated with an increase in investments in contemporary technologies based on Industry 4.0 technologies and information systems, globally it contributes to the reduction of total logistic costs by almost 20 % [2].

In modern business conditions, different technologies are employed to improve intralogistics activities and minimize manual handling [1]. The relevance of selecting an alternative for the successful completion of intralogistics duties is highlighted by the growing trend of automation [3]. Among numerous solutions, autonomous mobile robots (AMRs) are viewed as the collective name for a group of robotic technologies that are designed to autonomously realize most intralogistics tasks and provide a sustainable warehouse as part of the supply chain, while autonomous guided vehicles (AGVs) and drones are technologies that are currently in the implementation phase [1, 3]. Due to their high performance, these technologies can rapidly and easily adapt to their environment and carry out a variety of activities within the whole supply chain. For selecting the best solution for the realization of intralogistics activities, multi-criteria decision-making methods (MDCM) are recognized as relevant [3–4]. MDCM methods enable researchers to make appropriate decisions related to the choice of the most suitable solution, thus providing the basis for decision-making by managers in practice.

The goal of the research is the ranking and selection of the best autonomous alternative for the realization of intralogistics activities that affect the improvement of the performance of the warehouse system as part of the supply chain. The comparison of proposed autonomous alternatives was made using the technique for order of preference by similarity to ideal solution (TOPSIS) method, and for that purpose, eight criteria were defined for their evaluation. The study's other goal is to provide researchers and practitioners with a basis for decision-making when selecting the best autonomous options for the execution of intralogistics activities in warehouse systems as a critical part of every supply chain. Based on the findings, this investigation can also serve as a useful initial base for the evaluation of other solutions for the deployment of similar processes in supply chains.

This paper is structured as follows: Section 2 overviews the problem background, while the next section presents the research methodology and results. Section 4 gives discussions, while the last section provides the concluding remarks.

## 2. Problem Background

The problem background for this paper is analyzed by investigating current and advanced autonomous alternatives and appropriate criteria for the realization of intralogistics activities in the warehouse.

### *2.1 Potential Alternatives for the Realization of Intralogistics Activities in Warehouses*

The widespread use of forklifts substantially decreases manual operations in warehouses, which are considered vital components of supply chains. However, since forklifts are vehicles that do not have autonomy of movement, there are human-caused risks. Injuries to workers and damage to goods and equipment are just some of the reasons for implementing equipment with higher levels of autonomy. These vehicles also affect the improvement of storage performance, which directly affects the more efficient implementation of user requests. Although most companies still use forklifts to carry out intralogistics activities, more and more warehouse managers are thinking about replacing them with AGVs, AMRs, and drones. Although these autonomous solutions have found support for their use in a variety of activities, both in logistics and in other areas of the supply chain, it is important to highlight the ways of operation, advantages, and limitations of their engagement.

Forklifts are defined as internal transport vehicles intended for the transshipment of units inside the warehouse as well as outside it if there is open-air storage of goods. They provide for handling larger units, smaller units on pallets, and bulk in crates or baskets [3]. Forklifts can be equipped with different gripping devices depending on the formation of the goods, and they are operated by a trained worker (i.e., a forklift operator). There are different types of forklifts depending on the drive method: electric forklifts, gas forklifts, and diesel forklifts [4]. The main advantage of forklifts is their carrying capacity, and the main disadvantage is their complete dependence on labor.

AGVs are one category of mobile robots with an integrated sensor device that ensures that this modern vehicle automatically moves along a planned path. This system consists of guidance devices along the movement route, a central control system, a charging system, and a communication system [5]. AGVs are widely used in production, logistics, transport, and other activities in logistics companies, pointing to their importance for the sustainability of intralogistics activities. The advantages of using AGV for the implementation of intralogistics activities are [6–8]:

i. Increased productivity, efficiency, and flexibility of the system;
ii. Increased safety and accuracy in the implementation of intralogistics activities;
iii. Reduced number of manipulative activities and time savings;
iv. Load capacity since AGV forklifts can handle units weighing up to 50 t;
v. Automation of intralogistics activities;
vi. Environmental sustainability is provided by electric drives.

The basic limitation of the AGV's implementation is a fixed path of movement and the inability to overcome barriers. Due to the formation of an obstacle on the path, human intervention is necessary. Routing a significant number of AGVs in warehouse systems represents a special challenge for experts in practice, considering that in this way significant cost and time savings can be achieved and thereby improve user service [9].

AMRs are completely automated systems that handle materials automatically without the requirement for physical controls by using sensors and processors that are already incorporated into the system. Intralogistics duties are increasingly being implemented using AMRs, creating a safer working environment, requiring less manual work, and reducing downtime, which improves the total productivity of WMS and the supply chain. AMRs are comparable to AGVs in that they nearly never need specific equipment for navigation and are simple to integrate into existing warehouse layouts. Some of the key progresses achieved by engaging AMR are [9–11]:

i. Improved efficiency, accuracy, and throughput;

ii. Improved service quality and increased user satisfaction;
iii. Increased speed of realization of activities;
iv. The number of employee steps was reduced by over 95 % (e.g., from 70,000 steps to 4,000 steps because AMRs can deliver goods directly to employees);
v. Increased employee productivity since the focus is on intralogistics activities in production systems;
vi. Advanced safety in the work environment;
vii. Electric drives that impact environmental sustainability.

Some of the key limitations of the AMR application are related to inflexible load capacity, significant initial investments, and the impossibility of active capture and deposition of intralogistics units without engaging additional cranes, robotic arms, and other suitable types of equipment [11].

Drones are defined as unmanned aerial vehicles, a device that can fly without a pilot. The drone can be operated remotely, wirelessly, or autonomously by following a predetermined path [12]. One of the primary drawbacks of the drone is that it is battery-powered, which increases the risk of it crashing from a high height because the battery discharges while it is in flight. Drones can be used in a variety of industries, including agriculture, public safety, transportation, construction, and logistics [12]. Drones are mostly employed in intralogistics activities in warehouse systems for control and supervision of inventory management [13]. The key benefits of using drones for intralogistics activities are as follows [12–14]:

i. Automation of intralogistics activities;
ii. Release the floor of the facility, allowing other activities to take place without hindrance;
iii. Maximizing security;
iv. Increased productivity;
v. Electric drive that provides environmental sustainability.

Due to the necessity of establishing a balance between flight time and payload, one of the most significant disadvantages of employing drones for intralogistics tasks is their low battery capacity. In addition, drones' small payloads (typically 2 to 5 kg) and their limited ranges (roughly 6 km on a single charge) present additional challenges to their engagement in intralogistics activities in warehouses [13–15].

### *2.2 Definition of Criteria for Ranking Autonomous Alternatives*

The ranking of the proposed alternatives for the automation of intralogistics activities in warehouse systems can be viewed from several perspectives. Respect for the warehouse system's requirements, the alternatives' techno-exploitation features, their economic potential, the possibility of fitting into the current layout, as well as social and environmental sustainability, are all important in selecting the best alternative for automation intralogistics activities [3, 7, 14]. The following eight criteria are specified in this study:

i. ($K_1$) *Sensitivity of the warehouse system* [min]: The probability of disruption events (injury of employees, damage to goods and equipment, vehicle failures, etc.) [16];
ii. ($K_2$) *Possibility of mistakes* [min]: The probability of the occurrence of an error in the realization of intralogistics activities [17];

iii. ($K_3$) *Dependence on labor force* [min]: The share of activities without engaging employees in warehouse activities [18];
iv. ($K_4$) *Operating costs* [min]: The volume of direct vehicle costs (i.e., vehicle procurement and maintenance) and system adaptation costs [19];
v. ($K_5$) *Flexibility* [max]: The system's ability to adapt to modifications after disruptions [20];
vi. ($K_6$) *Productivity* [max]: The percentage of finished products/services from resources used for the production of products/services [21];
vii. ($K_7$) *Carrying capacity* [max]: The degree of utilization of the vehicle's cargo space [21];
viii. ($K_8$) *Navigation system level* [max]: The status of autonomy in positioning and routing vehicles in the system [20].

## 3. Research Methodology and Results

This section is divided into two affiliated parts. The TOPSIS approach is briefly presented in the first sub-section. The assessment and selection of the most suitable solution for the automation of intralogistics activities in warehouse systems were accomplished in the next sub-section by using this method. Based on the chosen criteria and purposes of this research, the ranked and investigated alternatives for automation of material handling were evaluated to improve WMS.

### *3.1 The TOPISIS Method*

TOPSIS is often used to evaluate and select alternative solutions for improving current activities under actual business conditions. In supply chains, this MDCM method is widely used for supplier selection, 3PL providers, end-of-life product treatment, type of equipment, etc. However, since it respects predefined criteria for the needs of intralogistics activities, it is very suitable for choosing an alternative for handling materials in warehouse processes [21]. The input data for this method are the values of the alternatives according to the defined criteria, the weights of the criteria, and the type of criteria ("max" and "min"). The TOPSIS method involves the following five steps [21]:

**Step 1** – Using Eq. (1) for vector normalization, it is necessary to first homogenize the matrix's parameters. Each parameter needs to be normalized (the value of each alternative concerning each criterion):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_j x_{ij}^2}}, \tag{1}$$

where the normalized value of the alternative *i* for the criterion *j* is $r_{ij}$ and the value of the alternative *i* for the criteria *j* is $x_{ij}$.

**Step 2** – The generation of a weighted normalized matrix, which multiplies each normalized criterion by its respective weight. It is necessary to normalize the weight of the criteria before creating the weighted matrix if the total weights of the criteria are over one or not equal to one, indicating that the criteria are absolute rather than relative. According to Eq. (2.), the normalization of criteria weights is achieved:

$$w_j' = \frac{w_j}{\sum_j w_j}, \tag{2}$$

where the weight and normalized weight of the criterion j are $w_j'$ and $w_j$ and $w_j'$, respectively.

**Step 3** – The distance vectors from the ideal solution and the anti-ideal solution are established in this step. They take into account the type of selection criterion and the matrix's weighted parameters. The best values for each criterion are all included in the ideal solution vector, while the worst values are all included in the anti-ideal solution vector.

**Step 4** – The fourth step involves calculating the distances between the alternatives and the ideal solution and the anti-ideal solution:

$$S_i^+ = \sqrt{\sum_j \left(A^+ - x_{ij}\right)^2}, \tag{3}$$

$$S_i^- = \sqrt{\sum_j \left(A^- - x_{ij}\right)^2}, \tag{4}$$

where $S_i^+$ is the distance of the alternative $A_i$ from the ideal solution $A^+$, $S_i^-$ is the distance of the alternative $A_i$ from the anti-ideal solution $A^-$.

**Step 5** – The alternatives are ranked based on their respective proximities as:

$$C_J = \frac{A_j^-}{A_j^+ + A_j^-}, \tag{5}$$

where $C_j$ is the relative proximity of the alternative $A_i$. The alternative with the highest closeness value is the most suitable.

### *3.2 Selection of the Best Alternative using the TOPSIS Method*

Table 1 provides the input information required for the TOPSIS method. Each criterion is used to evaluate each alternative solution proposed for the automation of intralogistics activities in current WMS conditions. The first row presents the criteria, while the first column lists the alternatives. Table 2 gives the normalized values according to Eq. (1).

**Table 1**
Input data

| Criteria/Technologies | $K_1$ | $K_2$ | $K_3$ | $K_4$ | $K_5$ | $K_6$ | $K_7$ | $K_8$ |
|---|---|---|---|---|---|---|---|---|
| **Forklifts** | **10** | **9** | **10** | **6** | **6** | **7** | **10** | **6** |
| **AGVs** | **6** | **8** | **8** | **8** | **7** | **9** | **9** | **7** |
| **AMRs** | **6.5** | **6** | **6** | **9.75** | **10** | **10** | **7.5** | **10** |
| **Drones** | **9** | **6** | **7** | **8** | **9** | **9** | **6** | **9** |
| **Criteria weight** | **4** | **6** | **7** | **8** | **9** | **9** | **6** | **9** |
| **Type of criteria** | **min** | **min** | **min** | **min** | **max** | **max** | **max** | **max** |

**Table 2**
Normalized input data

| Criteria/Technologies | $K_1$ | $K_2$ | $K_3$ | $K_4$ | $K_5$ | $K_6$ | $K_7$ | $K_8$ |
|---|---|---|---|---|---|---|---|---|
| **Forklifts** | **0.62** | **0.61** | **0.63** | **0.62** | **0.37** | **0.40** | **0.60** | **0.37** |
| **AGVs** | **0.37** | **0.54** | **0.51** | **0.50** | **0.43** | **0.51** | **0.54** | **0.43** |
| **AMRs** | **0.40** | **0.40** | **0.38** | **0.60** | **0.61** | **0.57** | **0.45** | **0.61** |
| **Drones** | **0.56** | **0.40** | **0.44** | **0.50** | **0.55** | **0.51** | **0.36** | **0.55** |

The specified criteria are absolute since their sum exceeds 1. As a consequence, they need to be normalized using Eq. (2). Table 3 provides the normalized criteria.

**Table 3**
Importance of the criteria

| Criteria | $K_1$ | $K_2$ | $K_3$ | $K_4$ | $K_5$ | $K_6$ | $K_7$ | $K_8$ |
|---|---|---|---|---|---|---|---|---|
| Weighs | 0.11 | 0.17 | 0.06 | 0.22 | 0.14 | 0.19 | 0.08 | 0.03 |

Step 2 produced a weighted matrix by multiplying each matrix's normalized parameter by its corresponding normalized weight. Table 4 contains the weighted matrix's parameters.

**Table 4**
Parameters of the weighted normalized matrix

| Criteria/Technologies | $K_1$ | $K_2$ | $K_3$ | $K_4$ | $K_5$ | $K_6$ | $K_7$ | $K_8$ |
|---|---|---|---|---|---|---|---|---|
| Forklifts | 0.07 | 0.10 | 0.04 | 0.14 | 0.05 | 0.08 | 0.05 | 0.01 |
| AGVs | 0.04 | 0.09 | 0.03 | 0.11 | 0.06 | 0.10 | 0.04 | 0.01 |
| AMRs | 0.04 | 0.07 | 0.02 | 0.13 | 0.09 | 0.11 | 0.04 | 0.02 |
| Drones | 0.06 | 0.07 | 0.03 | 0.11 | 0.03 | 0.10 | 0.03 | 0.02 |
| Type of criteria | min | min | min | min | max | max | max | max |

In Step 3, ideal and anti-ideal solution vectors were obtained using information from the weighted normalized matrix (Table 4). The most favored values for each criterion reflect the parameters of the ideal solution vector, whilst the most unfavorable values represent the parameters of the anti-ideal solution. The following two vectors were determined as $A^{+} = (0.04;\ 0.07;\ 0.02;\ 0.11;\ 0.09;\ 0.11;\ 0.05;\ 0.02)$ and $A^{-} = (0.07;\ 0.10;\ 0.04;\ 0.14;\ 0.05;\ 0.08; 0.03;\ 0.01)$.

In Step 4, the distances from the ideal solution were determined using Eq. (3) and the anti-ideal solution using Eq. (4) based on the acquired vectors and normalized parameters from Table 4. The calculated distances are provided in Table 5.

In Step 5, the ranking of the options was decided upon in the final stage based on relative proximities derived following Eq. (5). The technology with the highest relative closeness value is the most suitable. The relative proximities are displayed in Table 5.

**Table 5**
Relative closeness and distances from the ideal and anti-ideal solutions

| Technologies | Forklifts | AGVs | AMRs | Drones |
|---|---|---|---|---|
| $S_i^+$ | 0.24 | 0.13 | 0.07 | 0.10 |
| $S_i^-$ | 0.02 | 0.16 | 0.21 | 0.18 |
| Relative closeness | 0.08 | 0.55 | 0.75 | 0.64 |

The results indicated that AMRs were the most suitable option for fulfilling intralogistics activities. Drones were placed second, and AGVs were ranked third. Forklifts appeared to be the least viable solution given the goal of automating the warehouse system as a crucial component of supply chain sustainability, despite its many advantages in material handling activities.

## 4. Discussion

Intralogistics activities have an essential role in a sustainable supply chain and require the implementation of contemporary technologies based on Industry 4.0 achievements. The technological improvement and automation of intralogistics systems affect the improvement of warehouse performance. The implementation of modern technologies is of essential importance for the efficient realization of warehouse intralogistics activities in a sustainable supply chain [7, 14]. One of the primary requirements is the automation of material handling, which enables the improvement of intralogistics activities, increases the turnover ratio of goods in the warehouse, and reduces errors and losses caused by the human factor as well as driver salary costs [7, 12, 14].

According to the results, AMRs are the best solution for the realization of intralogistics activities. Namely, complete autonomy is made possible by the modern AMR navigation system, which decreases the need for employee participation in manual intralogistics activities. In addition to minimizing manual work, the routes taken by employees and their involvement in handling hazardous materials are significantly reduced, making working conditions more humane [9]. Increasing flexibility is related to AMR's ability to rapidly adapt to changes without the need for modification of warehouse layouts. The high level of intralogistics activity efficiency is due to the system's ability to operate with little possibility of error thanks to a permanent connection between AMRs and WMS [11]. Although the use of AMR improves customer service, its high implementation costs pose limitations that warrant an investigation of the advantages of other technologies for the automation of intralogistics activities.

Drones are ranked second. Since they free up floor space in the warehouse, these unmanned aerial vehicles can be utilized for a variety of intralogistics activities [14]. They are an environmentally friendly alternative, comparable to all other autonomous options. However, they cannot be employed independently for handling materials in a warehouse because of their limited range and carrying capacity. Due to that, they are frequently combined by WMS with the third-ranked AGVs.

Due to the absence of autonomy in the completion of intralogistics activities, AGVs are placed third. Since they often cannot actively capture and dispose of goods, autonomy is dominant in their movement. Additionally, the safety of warehouse systems is improved by utilizing them. However, the transportation of goods along a fixed route and the inability to overcome obstacles are the main limitations in their application for a sustainable WMS [14].

Forklifts are the alternative that comes last. This solution has the least amount of autonomy, even if their involvement in intralogistics activities has significantly improved WMS efficiency. Of course, forklifts are a necessary component of any warehouse system, given their advantages in material handling [7]. They are typically combined with other autonomous options in contemporary WMS to ensure the sustainability of the whole supply chain.

The requirement for automating intralogistics processes was examined by comparing four alternatives. The comparison highlights the limitations of widespread and partly outdated technology, such as forklifts, as well as the benefits gained using contemporary solutions, with AMRs appearing as the most suitable.

## 5. Concluding Remarks

The rise of e-commerce, the emphasis placed on online ordering, and the high levels of urbanization are only a few of the factors driving requirements for improving customer service. As a result, it is necessary to implement contemporary Industry 4.0 technologies at all levels of the supply chain. The significant portion of manual activities in warehouse obligations that could negatively affect customer service is one of the main challenges to the efficiency of intralogistics operations. Manual work compromises each component of a sustainable WMS, which is vital for supply chain efficiency. In general, process automation reduces manual activities while simultaneously improving other aspects of system performance, including productivity, flexibility, efficiency, accuracy, quickness of user request response, customer satisfaction, etc.

Forklifts are today used for the majority of intralogistics assignments in warehouse systems. These fleets have many benefits, but they still require human interaction for handling, disposal, sorting, commissioning, and management. Automation of intralogistics activities is essential for ensuring the economic, environmental, and social sustainability of WMS. This process is costly and time-consuming, but it is important to recognize that automated alternatives could be customized to the design and continuous operation of the warehouse. WMS, therefore, needs to take into account both the features of intralogistics activities in the warehouse as well as all other components of the sustainable implementation of autonomous solutions. Consequently, this study aims to evaluate the benefits and drawbacks of AGVs, AMRs, and drones for the realization of intralogistics operations, highlighting the ranking of their usage under established criteria concerning automation material handling.

The TOPSIS method was used to select the best solution. Although AMRs were ranked as the most suitable alternative, AGVs and drones ought to be considered as well because they can be utilized effectively when combined with other alternatives or with limited investments. This is one of the main areas for future research given the demands for the autonomy of intralogistics activities for a sustainable WMS. As a crucial component of any supply chain, the layout of the warehouse facility, the type, and quantity of goods, as well as other significant factors, must all be taken into account when choosing material handling technology for the warehouse, which is also a substantial additional recommendation for future research.

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