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Ranking of Technologies for Intralogistic Bulk Material Handling Processes Using Fuzzy Step-Wise Weight Assessment Ratio Analysis and Axial-Distance-Based Aggregated Measurement Methods

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Abstract: The logistics network is considered the provider of logistics activities in supply chains. The fluctuating requirements of customers and the logistics network's complex structure are only a few of the factors that cause challenges to its management. Industrial facilities are particularly vulnerable to challenges because material handling operations dominate in addition to manufacturing activities. Disruptions at industrial plants are disseminated through the logistics network, affecting all supply chain participants. As a result, reducing material handling time and costs to decrease material losses, pollution, and productivity is vital to their business. Due to their distinctive properties and significant share in finished goods, bulk materials are particularly vulnerable to issues during manufacturing. Accordingly, this study aims to rank and select technologies for handling bulk materials in an industrial plant where the production of construction materials is performed. This paper proposes four alternative solutions for the observed case study, and nine criteria were selected for the evaluation. A new hybrid multi-criteria decision-making model is proposed. The model combines Fuzzy Step-Wise Weight Assessment Ratio Analysis (SWARA), used to determine the weight of criteria, and the Axial-Distance-Based Aggregated Measurement (ADAM) method, used to rank alternative solutions. The model results indicate that the pneumatic conveyor is the best ranked alternative that significantly increases productivity, reduces losses, and improves working conditions. The key contributions of this study are its analysis of the efficiency of the technologies proposed for bulk material handling and the development and implementation of a model framework for the ranking of these technologies.

Keywords: material handling equipment; bulk material; Fuzzy SWARA; ADAM

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Citation: Tadić, S.; Krstić, M.; Božić, M.; Dabić-Miletić, S.; Zečević, S. Ranking of Technologies for Intralogistic Bulk Material Handling Processes Using Fuzzy Step-Wise Weight Assessment Ratio Analysis and Axial-Distance-Based Aggregated Measurement Methods. *Appl. Sci.* **2024**, *14*, 1549. https://doi.org/10.3390/app14041549

Academic Editors: Mark J. Jackson and Arkadiusz Gola

Received: 1 January 2024
Revised: 8 February 2024
Accepted: 13 February 2024
Published: 15 February 2024

1. Introduction

The supply chain encompasses all processes and activities, from the procurement of raw materials and production to the delivery of goods to customers, including flows of materials, information, finances, and energy. The logistics network consists of hubs and connections. It represents a fundamental component in the supply chain that manages the flow of goods between suppliers, manufacturers, wholesalers, retailers, and end customers [1–3]. Hubs are logistics centers, terminals, industrial (production) facilities, etc. Connections represent the infrastructure that enables the realization of material, informational, financial, and other flows between hubs [1,2]. The logistics network's goal is to ensure the efficient flow of products, information, and finances through the supply chain to provide the best possible service to customers. In contemporary business conditions, material flow management in industrial processes, including various production and logistics activities, is highly demanding [1]. These challenges are particularly pronounced in the logistics network of industrial plants that deal with the production and processing of bulk materials. One of the crucial factors for achieving competitiveness in the market compared to facilities where unit-load materials are produced is related to a significant share of logistics costs [4]. Consequently, this paper analyzes a selection of adequate technologies for intralogistics processes, such as the handling of bulk materials, in terms of their ability to reduce logistics costs and improve the efficiency of a company's operations. Our investigation was based on an actual case study of a cement production company.

Cement is a specific type of bulk material and an essential component in the construction industry. As the construction industry includes high-rise and low-rise construction (from buildings and soils to roads and footpaths), it is clear that cement production plays a significant role in the economic development of countries. The share of cement in high-rise construction has exceeded 40%, while in low-rise construction, the share is almost 30% [5]. This is additionally highlighted by the fact that the rate of country development is often measured by the level of investment in public infrastructure. The construction industry generates jobs in mines, cement factories, traffic engineering, and more [6]. Lately, cement production has been linked to global crises (COVID-19, wars, etc.) and is often related to global disruptions. In these circumstances, a particular challenge for cement production is inventory management. Cement storage is limited due to shelf lives and storage conditions, challenges faced by the world's leading producers, including China and Turkey. Also, there are challenges regarding the aspects of an accumulation and lack of supplies [7,8]. With the growing awareness of the sustainable functioning of supply chains, the analysis and implementation of innovative cement production and handling technologies have become key factors for sustainable business, especially in ecology [6,7,9]. Cement production generates significant harmful emissions that represent potential sources of environmental pollution. The five key pollutant categories produced by cement production include air emissions, solid waste, wastewater, noise pollution, and waste fuels. The main challenges faced by cement producers are the conflicting goals of reducing CO_2 emissions while simultaneously meeting the high demand [10–12]. Cement production enables the reuse of waste as fuel and/or material, and the cement production sector has achieved high importance as an industry that can dispose of considerable amounts of waste generated by other economic activities and the population in an ecologically and economically convenient way. For this reason, cement production globally contributes to environmental protection, and the member states of the European Union have become an important strategic partner for governments in the fight for a cleaner environment [7,12,13].

Cement production is realized in industrial plants, mainly within the construction industry. In addition to the production process, material handling processes are important, and their efficiency directly affects the productivity of the production process and the industrial plant [14–16]. In industrial plants, the problem of selecting material handling technology is most often analyzed from the perspective of technological design and refers to the process of developing and implementing technological solutions that support production processes, improve efficiency, and enable the optimal utilization of resources [17,18]. This paper is focused on the selection of technologies for handling bulk materials, particularly cement. Bulk material handling is challenging, primarily due to its physical and chemical characteristics, including its wide range of forms and granulations, density and volume, viscosity, and impact on the environment and the health of employees. Additionally, the handling of bulk materials has been insufficiently investigated in research and practical analyses, which was another important motive for carrying out this study [14–17].

The processes for handling bulk materials are characterized by certain limitations due to their physical and chemical characteristics. These limitations refer to the potential impact of the material on the environment or technology, and vice versa, including moisture sensitivity, abrasiveness, tackiness, temperature sensitivity, cohesion, hygroscopicity, etc. [16,18]. These limitations could restrict the selection of material handling technology and exclude certain types of technology due to mismatches between the characteristics of the technology and the physical and chemical material characteristics. Accordingly, material handling optimization is required to increase the efficiency of the industrial plant. This paper analyzed the intralogistics activity of the industrial plant of a factory operating in Serbia, the main activity of which is the production of construction materials. Cement is important for our analysis due to its role in material production for the construction industry in general. With cement being present in over 60% of total industrial factory production activities, its role is crucial for the economic development of countries. Cement production requires energy-intensive processes, and the costs of these processes make up almost 15% of the total energy consumption in the industry. The production of one ton of cement requires an average of 3.4 GJ of heat energy and 110 KWh of electricity. In addition, the production of one ton of cement results in the emission of between 0.73 and 0.99 tons of CO_2 [5,6,9]. Because the plant under analysis delivers more than 75% of goods in containers, the process of loading containers and preparation for delivery is particularly challenging. Accordingly, the management of the factory under study includes the deployment of new technologies for the realization of this process. The as-is analysis determined that the optimization of the loading containers process would significantly improve the performance of the factory. Four alternative solutions were proposed for the researched case study: pneumatic conveyors, belt conveyors, elevators, and robotic conveyors. The proposed alternative solutions were analyzed based on nine criteria grouped into three categories: technical–technological, economic, and ecological–social. Given the intricacies of this multi-criteria decision making (MCDM) challenge, a novel hybrid model that integrates the Fuzzy SWARA and ADAM methods is introduced in this paper. This combination stands out as a key contribution of our paper. Through the model's application, it became evident that the optimal solution involves adopting an alternative featuring a pneumatic conveyor.

The physical and chemical characteristics of cement, including unit type, granulation, environmental dusting, abrasiveness, and susceptibility to moisture, are crucial factors influencing handling technology selection. As cement is a bulk material, identifying handling technologies that are suitable for this kind of material and in accordance with the specified characteristics is necessary. The following paragraphs provide an overview of relevant research on bulk material handling technology selection. This is followed by an analysis of potential technologies and selecting the best one based on defined criteria, a challenge commonly addressed in the literature using the MCDM method [19–21]. The combined methods used in this paper to solve the defined problem are outlined below. The problem of selecting material handling technologies is widespread and represented in almost all industrial and production systems. Unit loads and bulk materials are handled in these systems. Special attention is drawn to the handling of bulk materials, and it can be inferred from the existing literature that there is room for improvement in research on this topic. According to the reviewed literature, different conveyor technologies are most often used to handle bulk materials. The use of engaged conveyors for the handling of bulk goods is justified due to their technical and operational characteristics.

Fonseca et al. [19] solved the problem of selecting a conveyor for handling fodder within a production facility. Fodder is categorized as bulk material, and for its handling, they considered the use of belts, chains, rollers, and gravity conveyors. Curry and Deng [20] optimized the handling of bulk materials, analyzing the handling of soil, clay, gravel, etc. They considered the deployment of excavators and backhoes. Hadi-Vencheh and Mohamadghasemi [21] solved the problem of selecting a technology for handling bulk materials. They compared pneumatic, roller, belt, and gravity conveyors. Nguyen et al. [22] dealt with the selection of conveyors for a flexible production system. They considered and analyzed four different types of conveyors. Mathev and Sahu [23] considered four types of conveyors and selected one of them. They observed the deployment of conveyors in the production system for handling bulk goods, smaller boxes, and mini-load units. Shchemeleva [3] and Yazdani-Chamzini [24] selected a conveyor that adhered the needs of handling materials in mining. They considered the deployment of belt, chain, and conveyor scrapers. Masaki et al. [25] performed a comparative analysis of different types of belt conveyors. The analysis aimed to select the best type of belt conveyor for handling bulk materials in production activities.

Based on the reviewed literature, it can be concluded that technologies based on conveyors are most often engaged in the process of handling bulk material. Various types of conveyors are engaged, such as belt, pneumatic, gravity, and more. Consequently, for the cement handling process, research should be directed toward the selection of conveyor technology. Through an analysis, it is necessary to select the type of conveyor that best matches the characteristics of the cement and the data from the specific case study.

Numerous methodologies and tools exist for addressing the challenge of selecting appropriate material handling technologies. Within the existing body of research, authors have employed diverse approaches, such as heuristics, metaheuristics, simulations, mathematical programming, and multi-objective decision making (MADM) and MCDM techniques. In recent years, MCDM methods have gained prominence for tackling such problems. Noteworthy applications encompass the Analytic Hierarchy Process (AHP) [22,26–29], the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [28,30], the Additive Ratio Assessment System (ARAS) [21,30], VIšekriterijumska optimizacija i Kompromisno Rešenje (VIKOR) [22], SWARA [31], Evaluation Based On Distance From Average Solution (EDAS) [23], Combinative Distance-based ASsesment (CODAS) [23,32], Multi-Objective Optimization on the basis of Ratio Analysis (MOORA) [23,29], Cooperation Platform for Research and Standards (COPRAS) [30], COmprehensive Distance-Based RAnking (COBRA) [26], among others, and their various combinations.

The application of MCDM methods enables a comprehensive evaluation of potential solutions, highlighting their advantages, disadvantages, and limitations. In this paper, we integrate Fuzzy SWARA and ADAM methods. Subsequently, we provide an overview of relevant studies wherein these methods have been effectively employed.

Keršulien et al. [33] developed the SWARA method, but Krstić et al. [32] were the first to carry it out in a fuzzy environment. The method is used to determine the weight of a criteria based on the order of importance of each criterion, from the most important to the least important. Decision makers evaluate the criteria based on their knowledge, experience, and information available from the analyzed area. Based on the multiple applications of this method in different areas, it can be concluded that it can be effectively applied in the area of material handling technology selection, in which it has not been used so far, which represents a research gap that this paper addresses. Compared to other MCDM methods, the SWARA method's main advantages are that it is simple to use, the problem-solving algorithm is clear and simple for inexperienced users to understand, it takes a short time to implement, and it is just as effective for group decision making as it is for decision making by a single decision maker. The required number of comparisons (evaluations) is not large, being significantly less than in AHP or Analytic Network Process (ANP) methods. The method is very flexible, and consistency is achieved by ranking the criteria in decreasing order. Additionally, a predefined scale for comparing criteria is not required [34,35]. The SWARA method is a useful tool for problem analysis and decision making. However, because of inadequate data, decision makers' evaluations of decision factors are frequently imprecise, unclear, and vague. This was the reason why the fuzzy extension of the SWARA method was used for this paper.

Deveci et al. [36] applied the Fuzzy SWARA method to determine the weight of observed risks in the mining industry. Karabasevic et al. [37] solved the problem of the selection of personnel in their paper. They used the Delphi method to define their criteria, and the SWARA method was used to determine the weights of the criteria. Zavadskas et al. [38] investigated potential ways to reduce road transport emissions. To select an acceptable solution, they used multi-objective neural optimization MULTIMOORA and the SWARA method. Radović and Stević [34] used the SWARA method for ranking the key performance indicators (KPIs) in transport. In addition to the above, the SWARA method has found applications for solving problems in various areas, such as supplier selection [39], product design [40], the prioritization of sustainability indicators in energy systems [41], machine selection [42], landslide risk assessment [43], etc.

The ADAM method, introduced by Kristić et al. [44], is a geometric MCDM approach that ranks alternatives based on the volumes of complex polyhedra in a three-dimensional coordinate system. The points in this system include the coordinate origin (O), reference points (R) indicating alternative values on the x-y plane, and weighted reference points (P) introducing criteria weights along the z-axis. The polyhedra are formed by these points, where R points represent alternative values based on criteria, and P points indicate weighted criteria values. The method utilizes vectors defined by angles and lengths to establish the geometric relationships among these points, facilitating the decision-making process [44]. Notably, the ADAM method presents distinct advantages over other MCDM approaches: it is easily comprehensible, user-friendly, robust against an increasing number of criteria, highly intuitive, and exhibits minimal susceptibility to alterations in rankings. The method's simplicity is evident in its reliance on straightforward calculations involving the volumes of geometric bodies, specifically polyhedra. Despite being complex, these polyhedra entail straightforward volume computations, requiring only a fundamental knowledge of geometry [44,45]. Consequently, the method proves easily applicable, with the complexity of determining alternative values remaining unaffected by an escalating number of criteria. Leveraging polyhedra volumes, which can be graphically represented with ease, facilitates the straightforward interpretation of results, enabling clear conclusions regarding the final ranking of alternatives. Furthermore, the method's intuitive nature is enhanced by visualizations of the obtained solutions. Method testing proves the remarkable stability of outcomes, with alterations in criterion weights causing only marginal shifts in results—indicating a low risk of altering alternative rankings [44,45].

This is one of the youngest MCDM methods, but its applicability is well proven. Agnusdei et al. [45] analyzed the impact of digitization on achieving circularity in the agro-industry using a combination of a Strengths–Weaknesses–Opportunities–Threats (SWOT) analysis, the ANP method, and the ADAM method. Krstić et al. [44] conducted an assessment of business models to select the best one and achieve a sustainable system of food production and consumption by combining the Best Worst Method (BWM) and the ADAM method. A review of existing research indicates a notable absence of any prior application involving the combination of SWARA and ADAM methods for material handling technology selection or any other problem. This represents an unexplored research gap that the current paper aims to address.

This paper is organized as follows: In the introduction, the background of the cement production and handling problem is described, and based on that, an overview of relevant papers in the field of selection bulk material handling technologies and MCDM methods is provided. The second section outlines the methodology for evaluating these technologies. In the third section, a case study analysis resolves the technology selection issue for the defined alternative solutions and criteria. The fourth section discusses the solution, its practical and theoretical implications, and its limitations. The last section concludes the paper and suggests future research directions.

2. Hybrid MCDM Model

In this paper, a new hybrid MCDM model is proposed, which is a combination of Fuzzy SWARA [32] and ADAM [43] methods. Within the methodology, Fuzzy SWARA is applied to determine the relative weights of the criteria, and the ADAM method is used to rank alternative solutions. The Fuzzy SWARA method is resolved using the mathematical formulation outlined in the paper and implemented through an Excel solver. The ADAM method was tackled using a dedicated software tool that is conveniently accessible online [46]. Below is a step-by-step description of the methodology.

Step 1: Define the problem structure

In the first step, the structure of the problem is defined through the analysis of a set of alternatives and criteria. These criteria are used to evaluate alternatives.

Step 2: Defining evaluation scales

In this step, the scale of linguistic evaluations that decision makers use to evaluate criteria and alternatives is defined. The scale of linguistic evaluations with the associated fuzzy and crisp numbers is given in Table 1.

Table 1. Evaluation scale for the comparison of criteria/alternatives.

Linguistic Evaluation	Abbreviation	Fuzzy Scale	Crisp Scale
"None"	"N"	(1, 1, 2)	1
"Very Low"	"VL"	(1, 2, 3)	2
"Low"	"L"	(2, 3, 4)	3
"Fairly Low"	"FL"	(3, 4, 5)	4
"Medium"	"M"	(4, 5, 6)	5
"Fairly High"	"FH"	(5, 6, 7)	6
"High"	"H"	(6, 7, 8)	7
"Very High"	"VH"	(7, 8, 9)	8
"Extremely High"	"EH"	(8, 9, 10)	9

Step 3: Ranking criteria

In this step and in accordance with the Fuzzy SWARA method, decision makers rank the criteria. The criteria are ranked in descending order of importance.

Step 4: Evaluation of the importance of criteria

After ranking the criteria, decision makers evaluate the relative importance of criterion j compared to the other criteria $(j-1)$, beginning with the second criterion. This relation is called the comparative significance of the average value and is denoted as $\widetilde{\alpha}_j$, where $\widetilde{\alpha}_j = \left(l_j,\ m_j, u_j\right),\ j = 1, \ldots, m$, denotes triangular fuzzy values that correspond to the given linguistic terms in Table 1, and $l,\ m$, and u denote the lower, middle, and upper values of the triangular fuzzy number, respectively.

Step 5: Coefficient calculation $\widetilde{\beta}_j$

After evaluating the criteria, coefficient $\widetilde{\beta}_j$ is calculated. The mathematical formula for the calculation of coefficient $\widetilde{\beta}_j$ is given below.

$$\beta_j = \begin{cases} (1,\ 1,\ 1),\ j = 1 \\ \left(\frac{l_j}{\underset{j}{max}\ u}, \frac{m_j}{\underset{j}{max}\ u}, \frac{u_j}{\underset{j}{max}\ u}\right) + (1,\ 1,\ 1),\ j > 1, \ldots, m' \end{cases} \tag{1}$$

Step 6: Calculation of the preliminary weight of the criteria $\widetilde{\delta}_j$

Based on the results from Step 5, the preliminary value of the criterion weights, $\widetilde{\delta}_j$, is calculated as follows:

$$\widetilde{\delta}_j = \begin{cases} (1,\ 1,\ 1),\ j = 1 \\ \frac{\widetilde{\delta}_{j-1}}{\widetilde{\beta}_j} + (1,\ 1,\ 1),\ j > 1, \ldots, m' \end{cases} \tag{2}$$

Step 7: Calculation of the relative weight of the criteria $\widetilde{w}_j$

After the calculation of the preliminary weight of the criteria, the relative weight of the criteria, $\widetilde{w}_j$, is calculated as follows:

$$\widetilde{w}_j = \frac{\widetilde{\delta}_j}{\sum \widetilde{\delta}_j}, \tag{3}$$

Step 8: Defining the matrix $\widetilde{F}$

In the second part of the methodology, the ADAM method is used to determine the ranking of alternatives. After obtaining the relative weights of the criteria using the Fuzzy

SWARA method, it is necessary to define the input parameters for the ADAM method. At the beginning, the fuzzy matrix $\widetilde{F}$ is defined as follows:

$$\widetilde{F} = \left[f_{ij}\right]_{m \times n}, \tag{4}$$

where f_{ij} denotes value of alternatives i $(i = 1, \ldots, m)$ according to criterion j $(i = 1, \ldots, n)$.

Step 9: Defining the sorted matrix P

The elements of the matrix P are the values of the matrix $\widetilde{F}$, which are ordered by importance (criteria weight) in descending order. The mathematical formula for the sorted matrix is given below.

$$P = \left[p_{ij}\right]_{m \times n}, \tag{5}$$

Step 10: Defining the normalized sorted matrix ϕ

The normalized values of the sorted matrix for the sets of benefit (B) and cost (C) criteria are calculated as follows:

$$\varphi_{kj} = \begin{cases} \frac{p_{ij}}{\max\limits_{i} p_{ij}}, \; for \; j \in B \\ \frac{\min\limits_{i} p_{ij}}{p_{ij}}, \; for \; j \in C \end{cases}, \tag{6}$$

Step 11: Determination of coordinates a, b, and c

In this step, it is necessary to determine the coordinates a, b, c of the reference point $\left(R_{ij}\right)$ and the weighted reference point $\left(N_{ij}\right)$, which define the complex polyhedron. The coordinates are calculated as follows:

$$a_{ij} = n_{ij} \times sin\theta_j, \; \forall j = 1, \ldots, n; \; \forall i = 1, \ldots, m, \tag{7}$$

$$b_{ij} = n_{ij} \times cos\theta_j, \; \forall j = 1, \ldots, n; \; \forall i = 1, \ldots, m, \tag{8}$$

$$c_{ij} = \begin{cases} 0, forR_{ij} \\ w_j, \; forN_{ij} \end{cases}, \; \forall j = 1, \ldots, n; \; \forall i = 1, \ldots, m, \tag{9}$$

The angle, denoted as θ_j, plays a crucial role in determining the direction of the vector that defines the value of the alternative, and this angle is obtained as follows:

$$\theta_j = (j-1)\frac{90^\circ}{n-1}, \; \forall j = 1, \ldots, n, \tag{10}$$

Step 12: Calculation of the volume of a polyhedron V_i^C

In this step, the volume of the polyhedron V_i^C is calculated, which consists of the sum of the individual volumes of the pyramids V_k. The volume of the polyhedron is calculated as follows:

$$V_i^C = \sum_{k=1}^{n-1} V_k, \; \forall i = 1, \ldots, m, \tag{11}$$

where V_k is calculated as follows:

$$V_k = \frac{1}{3} B_k \times h_k, \; \forall k = 1, \ldots, n-1, \tag{12}$$

where B_k is the area of the base of the pyramid defined by the reference and weighted reference points, which is calculated as follows:

$$B_k = y_k \times x_k + \frac{x_k \times (e_k - y_k)}{2}, \tag{13}$$

where x_k is the Euclidean distance between the reference points of two consecutive criteria, calculated as follows:

$$x_k = \sqrt{\left(a_{j+1} - a_j\right)^2 + \left(b_{j+1} - b_j\right)^2}, \tag{14}$$

y_k, e_k are vector magnitudes corresponding to the weights of two consecutive criteria, that is:

$$y_k = b_j, \tag{15}$$

$$e_k = b_{j+1}, \tag{16}$$

h is the height of the pyramid from the defined base to the top of the pyramid located in the coordinate origin (O) and is calculated as follows:

$$h_k = \frac{2\sqrt{r_k(r_k - x_k)(r_k - t_k)(r_k - g_k)}}{x_k}, \tag{17}$$

where r_k is half of the perimeter of the triangle defined by coordinates a and b of two consecutive criteria and the coordinate origin, which is calculated as follows:

$$r_k = \frac{x_k + t_k + g_k}{2}, \tag{18}$$

where t_k and g_k are the Euclidean distances of two consecutive criteria from the coordinate origin and are calculated as follows:

$$t_k = \sqrt{a_j^2 + b_j^2}, \tag{19}$$

$$g_k = \sqrt{a_{j+1}^2 + b_{j+1}^2}, \tag{20}$$

Step 13: Ranking of alternatives

The ranking of alternatives in descending order is carried out according to the value of the total volume $V_i^C (i = 1, \ldots, m)$. The best alternative is the one with the highest V_i^C value.

3. Problem Description

The use of adequate material handling technology is a fundamental component of the efficient functioning of industrial plants. In production plants, in practice, bulk materials are handled to a greater extent than unit-load materials. According to the definitions available in the literature, bulk materials are characterized by physical and chemical characteristics that enable capture and loading during their handling [41]. In addition, the physical and chemical characteristics of bulk materials have a very large influence on the construction and technical and operational characteristics of handling technology. Bulk materials are most often used as components in construction, the food and pharmaceutical industries, etc. [16,17]. Practice knowledge suggests a particular group of challenges is represented by the handling of materials in the construction industry. The most common forms of bulk materials in construction are related to different fractions of stone, sand, and powdered materials. From the group of powdery materials, the most consequential challenges are encountered in the handling of cement, partly due to its presence in all activities of the construction industry and partly due to its properties, including its abrasiveness, stickiness, dustiness, the influence of moisture, etc. [16–18].

This study investigates the industrial plant of one of the largest building materials producers in Serbia, which has a notable and significant presence in the European market. Cement production amounts to about 65%, and more than 75% of the cement is placed on the European market. An analysis of the company's current activities indicates that about 90% of the goods are transported in 20ft bulk containers. According to data from the second half of 2022, the costs of handling all construction materials make up more than 40% of their production costs, while for cement, those expenses exceeded 60%. Given the high costs of handling cement, the company's management aims to improve the material handling processes by investing in technology that will contribute to the environmental, economic, and social sustainability of the analyzed company.

The key challenges in cement handling are identified through an as-is company analysis. Consequently, after the end of production, the cement is stored in a closed storage facility to ensure it has appropriate resilience to atmospheric influences. After receiving the order, a vehicle designed to carry the container arrives at the facility. The process of filling the container is currently realized by the use of a cantilever crane with a grab, which grabs the cement and pours it into the container. After loading, the road vehicles leave the industrial plant. After the as-is analysis of the industrial plant, several gaps were identified:

- Mismatches between the material handling technology characteristics and the task characteristics;
- The need to dust off the workspace;
- The inadequate dosing of the material during backfilling;
- High operating costs;
- The material sticks to the grab;
- The long duration of the container loading process.

These and numerous other issues and gaps in cement handling, in addition to generating significant costs, also hurt the environment and social sustainability. Due to the demand for more humane working conditions and environmental regulations, the company's management at a strategic level aims to invest in material handling technology, with an emphasis on the container loading process. The analyzed alternative solutions aim to reduce and eliminate the observed gaps and increase the efficiency of the container loading process and the processes that follow in the further flow of the supply chain [47]. Therefore, this paper provides basic guidelines for selecting the best bulk material handling technology, respecting the specific conditions considered in this study.

3.1. Defining Alternative Solutions

The physical and chemical characteristics of bulk materials are the critical factors in forming a set of alternative solutions for their handling. In practice, ready-made solutions are mostly used for handling bulk materials, that is, those already used for similar or the same tasks with similar or the same materials. In the analyzed literature, in the handling of bulk materials, different types of conveyor systems are used most often. An analysis of research in the field of selecting material handling equipment reveals that authors commonly examine three or four alternatives [48–52]. Consequently, for loading containers based on the requirements in the analyzed case study, this research will consider a pneumatic conveyor (PC), a robotic conveyor (RC), an elevator (EC), and a belt conveyor (BC).

The PC (A1) includes a safe, reliable, economical, and environmentally friendly way of handling bulk material [48]. The vital function of this technology is the handling of materials, but in addition, it can facilitate mixing, heat exchange, drying, and chemical reactions [49]. A unique feature of pneumatic conveyors is that, with their use, materials can be handled in closed systems from one location to another without any risk of environmental pollution. Additional advantages include the fact that they facilitate the easier and more cost-effective handling of materials, their quick and easy installation, and the fact that they require little space for operation. their disadvantages include the fact that they necessitate high investment costs, their significant energy consumption, the jamming of material(s), and the fact that they cannot be used for coarse material granulation [48,49].

The RC (A2) involves the integration of robots and conveyor systems (in this case, belt conveyors). These advanced systems are fully automated and can control the amount of loaded or unloaded materials without the presence of a human (i.e., they can dose the required amount of material themselves) [50]. Their advantages include their automation of activities, low energy consumption, and the fact that their use can reduce errors [51]. Their disadvantages include the requirement for continuous employee training, advanced computer systems, and relatively high investments [50,51].

An EC (A3) is a technology for material handling that is primarily used for overcoming height differences. In practice, ECs are most often used when handling bulk materials, but they are also used for unit-load goods of smaller dimensions [52]. Depending on their technical and operating characteristics, elevators can achieve high productivity. Their advantages include the fact that they facilitate closed construction that protects the working environment from dust, the fact that the management of this conveyor is usually not complicated, the fact that elevators are not big consumers of energy, etc. [53]. Their disadvantages include the need for relatively high investments and changes in the transport path, their low flexibility, and the frequent failures caused by the inadequate maintenance of elevators. ECs also emit a lot of noise due to the fact that they are constructed from metal [53,54].

The BC (A4) is the most commonly used technology in this field, and it has continual action for material handling. The core element of this conveyor is its belt, which is the most expensive part, used for material handling. Regarding the deployment of BCs, the belt conveyor is universal and suitable for handling bulk and unit-load goods [55]. Its simple assembly, capacity to be combined with other technologies, and low-level noise emission [56] are its main advantages. The disadvantages of BCs include the fact that the belt of the belt conveyor can be subjected to mechanical damage, BCs' sensitivity to chemical influences and temperature fluctuations, their high maintenance costs, and the problems with complex transport paths that arise with their use [53,54].

3.2. Evaluation of Criteria

Using the MCDM method to select the best alternative requires the evaluation of relevant criteria for their comparison. For this study, we grouped our criteria into three categories: technical–technological, economic, and social–ecological. They were defined based on previous research and experts' opinions on handling bulk materials. The selected criteria are described below.

Technical–technological

- Productivity (C1) represents the number of loaded containers in the defined time frame [24–26].
- The ability to handle materials (C2) is the ability of technology to independently handle materials without engaging auxiliary equipment [26,54,55].
- The flexibility of the layout (C3) is the adaptability of the technology to the changing layout of the plant (length and shape of the handling path, lifting height, etc.) [24,26].

Economic

- Investment costs (C4) include the costs of acquiring or renting technology [55–57].
- Maintenance costs (C5) include the costs of regular service, repairs, etc. [58–60].
- Operational costs (C6) include the costs generated during the daily operation of the asset (energy, daily maintenance, auxiliary labor, etc.) [58–61].

Social and ecological

- Employee safety (C7) is the present level of exposure to risk regarding the employees at work [26,58,61–63].
- Training of employees (C8) refers to the need for training and the level of training among the employees responsible for handling assets [28,64].
- The Eco-indicator (C9) is the degree of fulfillment of standards in terms of employee health, noise emissions, environmental protection, etc. [57,64].

3.3. Results of Model Application

Following the establishment of the problem's structure, encompassing alternatives and the criteria for assessment, the Fuzzy SWARA method was employed to determine the relative weights of the criteria. The defined methodology involves initially ranking the criteria in descending order of importance and subsequently assessing the significance of each criterion relative to the next. Multiple experts participated in this decision-making process; they were tasked with evaluating the criteria and alternatives using the linguistic ratings provided in Table 1. These expert ratings underwent statistical combination through a probability distribution. Opting for grades with the highest probability as representative values for the observed criteria (alternatives), these ratings were numerically transformed based on the ratios specified in Table 1. Fifteen experts, with varying levels of experience, from the field of logistics participated in the process of evaluating the criteria and alternatives. Table 2 illustrates the surveyed experts' experience, and the experts were divided into four groups based on their experience. An approximate number of experts was taken from each group to ensure an objective assessment of the criteria and alternatives.

Table 2. Classification of experts in terms of experience.

Experience (Years)	Number of Experts
<7	4
7–14	3
14–21	5
>21	3

Following the expert evaluations of the criteria, coefficient $\widetilde{\beta}_j$ was computed using Equation (1). Subsequently, the preliminary criterion weight $\widetilde{\delta}_j$ was determined using Equation (2), and the relative weight of the criterion, $\widetilde{w}_j$, was derived through Equation (3). Table 3 illustrates the obtained results. In Table 3, the consolidated ratings assigned by the experts are presented. Based on these ratings, the values of coefficients $\widetilde{\beta}_j$, $\widetilde{\delta}_j$, and $\widetilde{w}_j$ and the crisp values of the criterion weights w_j were calculated. The obtained fuzzy SWARA method values were utilized in further calculations for ranking the alternatives.

Table 3. Criteria weights according to the fuzzy SWARA method.

Criteria	Fuzzy Sets	$\tilde{\alpha}_j$	$\tilde{\beta}_j$	$\tilde{\delta}_j$	$\tilde{w}_j$	w_j
C1	/	/	(1.00, 1.00, 1.00)	(1.00, 1.00, 1.00)	(0.380, 0.454, 0.433)	0.438
C2	M	(4, 5, 6)	(1.80, 2.00, 1.60)	(0.63, 0.50, 0.56)	(0.238, 0.227, 0.241)	0.231
C6	FL	(3, 4, 5)	(1.60, 1.80, 2.00)	(0.31, 0.28, 0.35)	(0.119, 0.126, 0.150)	0.129
C7	L	(2, 3, 4)	(1.40, 1.60, 1.80)	(0.17, 0.17, 0.25)	(0.066, 0.079, 0.107)	0.081
C3	L	(2, 3, 4)	(1.40, 1.60, 1.80)	(0.10, 0.11, 0.18)	(0.037, 0.049, 0.077)	0.052
C9	F	(3, 4, 5)	(1.60, 1.80, 2.00)	(0.05, 0.06, 0.11)	(0.018, 0.027, 0.048)	0.029
C4	L	(2, 3, 4)	(1.40, 1.60, 1.80)	(0.03, 0.04, 0.08)	(0.010, 0.017, 0.034)	0.019
C8	VL	(1, 2, 3)	(1.20, 1.40, 1.60)	(0.02, 0.03, 0.07)	(0.006, 0.012, 0.029)	0.014
C5	L	(2, 3, 4)	(1.40, 1.60, 1.80)	(0.01, 0.02, 0.05)	(0.004, 0.008, 0.020)	0.009

After determining the relative weight of the criteria, the experts evaluated the alternatives. The final alternative evaluations were obtained the same way as the criteria evaluations, and the matrix $\widetilde{F}$ (4) was formed. In Table 4, the aggregated ratings of alternatives across criteria assigned by experts are presented. The consolidated expert ratings were transformed into fuzzy sets and served as input data in the ranking of the alternatives using the ADAM method.

Table 4. Assessing the alternatives based on our predefined criteria.

Alternatives Criteria	A1	A2	A3	A4
C1	EH	FH	H	FL
C2	EH	FH	H	L
C3	VH	FL	M	L
C4	FH	L	M	M
C5	FH	L	VL	M
C6	H	M	FL	VL
C7	VH	VH	M	L
C8	FH	L	FL	H
C9	VH	FL	H	VL

The weights of the criteria obtained by applying the Fuzzy SWARA method and the alternative evaluations per criterion represent the input data for the ADAM method. For the application of the ADAM method, the software developed by Krstić et al. was used [18]. The output from the ADAM method represents the polyhedron volume of each alternative, calculated using Equation (11). The obtained polyhedron volumes represent the values for the alternatives ranking, the values of which are shown in Table 5.

Table 5. Calculated values for the ranking of the alternatives.

Alternatives	A1	A2	A3	A4
Volume	0.0493	0.0216	0.0241	0.0093
Rank	1	3	2	4

The ADAM method provides a visualization of the obtained solution, which makes it possible to see the difference in the ranking of the observed alternatives. The output of the ADAM method are the volumes of the three-dimensional complex polyhedra. For each defined alternative, a complex polyhedron is depicted in Figure 1. The visualization of polyhedra supports the numerical data on their volumes shown in Table 5. The visual representation of polyhedron values, as presented in Figure 1, aids in understanding the ranking of alternatives and the decision-making process for selecting the best alternative.

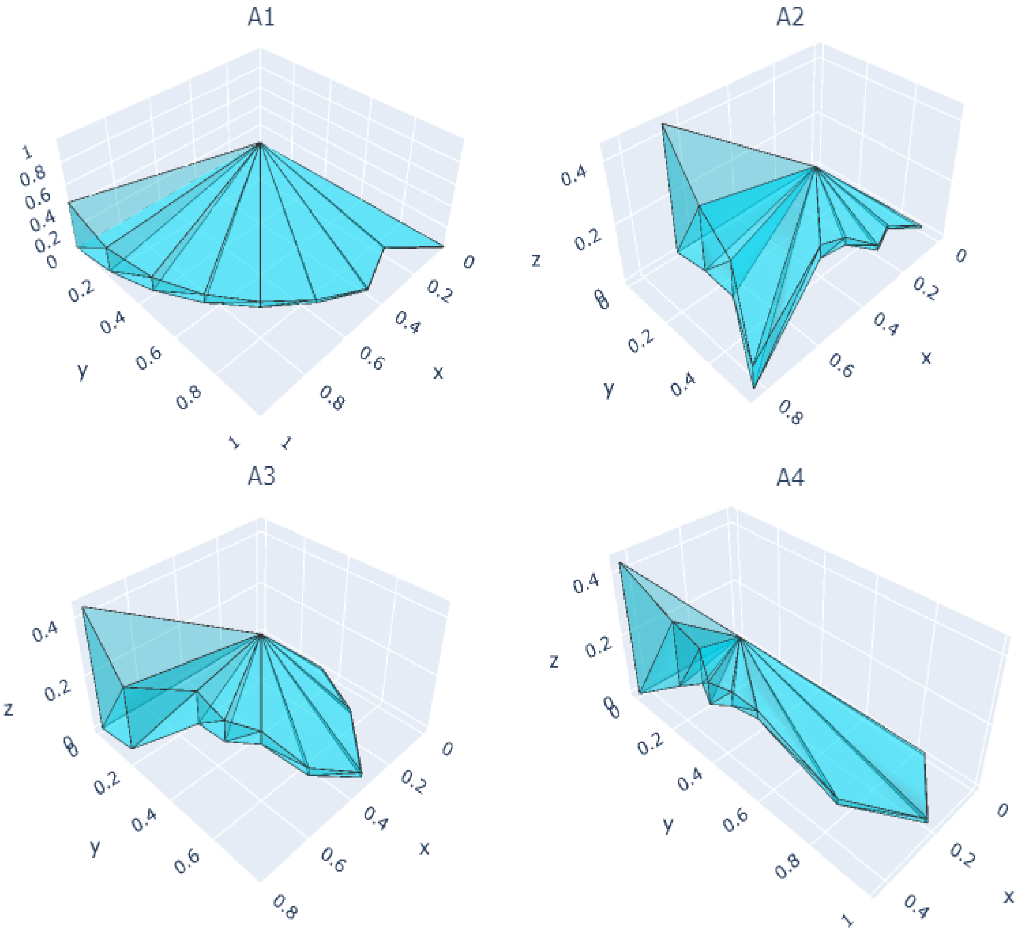

Figure 1. Calculate the complexes of the polyhedra regarding the alternatives.

3.4. Sensitivity Analysis

After testing the developed model, a sensitivity analysis determines the efficiency and accuracy of the obtained solution. The aim is to investigate to what extent the changes in the input data influence the results. As part of the sensitivity analysis, 21 scenarios (Sc.) wherein a change was made in the criteria weights were defined. In this case, those with the highest relative weights were chosen, namely C1, C2, and C6. The criterion value is a reduction in each scenario by 15, 30, 45, 60, 75, 90, and 100%. In Sc. 1–7, the weight of criterion C1 was changed, while the values of the other criteria remained unchanged. In Sc. 8–14, the weight of criterion C2 was changed, and in Sc. 15–21, the same was true for C6 (Table 6). In all cases, the ranking of all alternatives remained unchanged (i.e., the same order was maintained as in the main solution). Based on this, it can be concluded that the method is stable enough.

Table 6. Sensitivity analysis of the obtained solution.

Sc.	A1	A2	A3	A4
Sc. 1	0.0472	0.0207	0.0228	0.0090
Sc. 2	0.0451	0.0197	0.0215	0.0087
Sc. 3	0.0429	0.0188	0.0202	0.0084
Sc. 4	0.0408	0.0178	0.0189	0.0080
Sc. 5	0.0387	0.0169	0.0176	0.0077
Sc. 6	0.0365	0.0159	0.0164	0.0074
Sc. 7	0.0351	0.0153	0.0155	0.0072
Sc. 8	0.0451	0.0207	0.0229	0.0090
Sc. 9	0.0448	0.0199	0.0216	0.0087
Sc. 10	0.0426	0.0190	0.0204	0.0084
Sc. 11	0.0403	0.0181	0.0192	0.0081
Sc. 12	0.0381	0.0172	0.0180	0.0078
Sc. 13	0.0358	0.0164	0.0167	0.0075
Sc. 14	0.0343	0.0158	0.0159	0.0073
Sc. 15	0.0481	0.0209	0.0238	0.0091
Sc. 16	0.0468	0.0203	0.0234	0.0089
Sc. 17	0.0456	0.0196	0.0231	0.0087
Sc. 18	0.0433	0.0189	0.0227	0.0084
Sc. 19	0.0430	0.0182	0.0224	0.0082
Sc. 20	0.0418	0.0176	0.0220	0.0080
Sc. 21	0.0409	0.0171	0.0218	0.0079

Figure 2 shows the obtained ranking of the alternatives. From Figure 2, it can be observed that A2 and A3 are lower ranked compared to A1 but better ranked compared to A4.

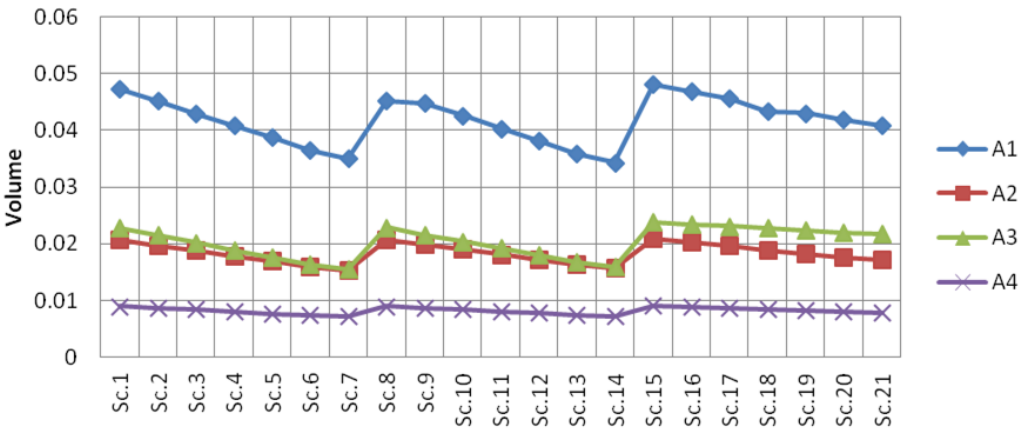

Figure 2. Sensitivity analysis of the obtained solution.

3.5. Solution Analysis

To validate the results, the same problem with identical input parameters was addressed using various other widely represented MCDM methods found in the literature. These methods included TOPSIS, VIKOR, Simple Additive Weighting (SAW), COPRAS, AHP, SWARA, Preference Ranking Organization METHOD for Enrichment of Evaluations (PROMETHEE), and Elimination and Choice Translating Reality (ELECTRE). The ranks assigned to the alternatives are presented in Table 6. To gauge the similarity of the ranks obtained through these methods with those derived from the ADAM method, Spearman's correlation coefficient (SCC) was calculated. A mean SCC value of 1.00 signifies 100% agreement between the results obtained via the ADAM method and those obtained using the other methods. Furthermore, all methods consistently identified the same alternative as the top-ranked choice. Consequently, it can be inferred that the obtained solution is valid, affirming that the chosen alternative is the most favorable concerning the considered criteria.

To investigate the changes in the alternatives ranking using other methods, the results were normalized on a scale ranging from 0 to 1. The obtained values are shown in Table 7. In Table 7, it can be seen that using other methods results in the same ranking of alternatives. Even with the application of different methods, A1 consistently holds the top position compared to others. The difference between the values of A2 and A3 varies with the use of different methods; in some cases, this difference is slightly less compared to the application of other methods. A4 is consistently ranked the lowest. The obtained results indicate that the ADAM method provides a stable solution.

Table 7. Validation of the solution—normalized values and obtained ranking.

Method		**A1**	**A2**	**A3**	**A4**
ADAM	Value	0.4728	0.231	0.2071	0.0892
	Rank	1	3	2	4
TOPSIS	Value	0.4798	0.2831	0.2208	0.0164
	Rank	1	3	2	4
VIKOR	Value	0.3695	0.2669	0.2325	0.1311
	Rank	1	3	2	4
SAW	Value	0.3555	0.2583	0.241	0.1453
	Rank	1	3	2	4
COPRAS	Value	0.3549	0.2604	0.2404	0.1443
	Rank	1	3	2	4
AHP	Value	0.5416	0.2148	0.1714	0.0721
	Rank	1	3	2	4
SWARA	Value	0.2986	0.2646	0.2447	0.192
	Rank	1	3	2	4
PROMETHEE	Value	0.2811	0.2429	0.2468	0.2291
	Rank	1	3	2	4

Figure 3 shows the normalized values of alternatives using other methods (Table 6). The figure shows the deviations in the values for the alternatives obtained using different methods. It was observed that by applying the PROMETHEE and SWARA methods, the alternative values were lower compared to the other methods, but the ranking remained the same.

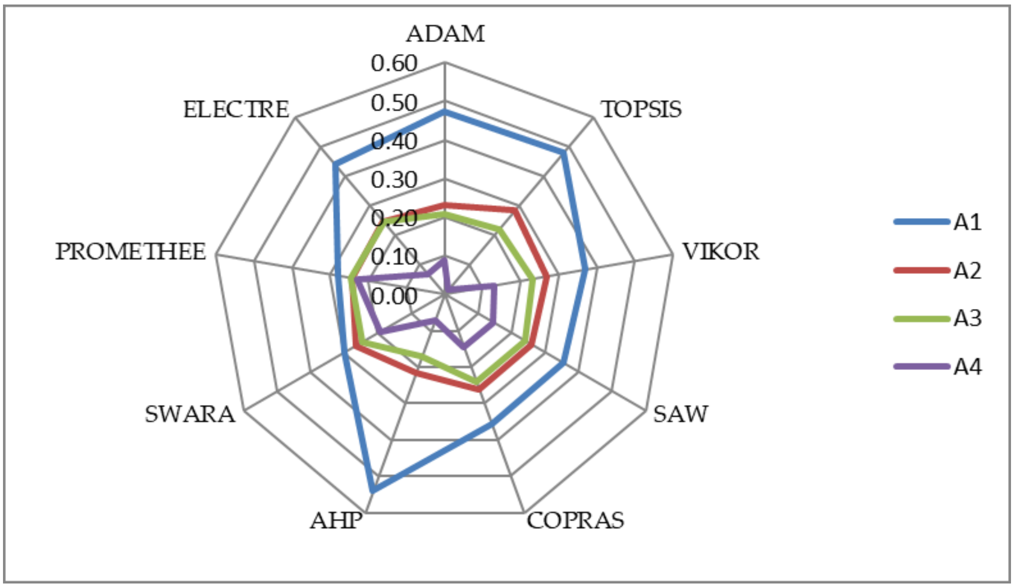

Figure 3. Validation of the obtained solution.

4. Discussion

In industrial plants, among others, there are dominant challenges in material handling processes that significantly affect the realization of the basic and supporting activities of companies. In this paper, the problem of selecting the best technology for handling bulk materials has been solved for a factory in Serbia. This paper aims to eliminate the identified gaps in the industrial plant by selecting the best technology according to a defined criteria. Following these criteria and the data from our case study, alternative solutions have been ranked in this paper to increase the efficiency of the container loading process.

A1 would be the most suitable option for container loading operations and replacing the existing technology. The use of A1 would bring numerous benefits, such as increased productivity, reduced risk of employee injury, and improved resource utilization. Additional advantages that can be gleaned from A1 include its facilitation of easier and more cost-effective material handling and loading into containers; its fast and simple installation; the fact that a small amount of space is required for its installation; and the fact that it quickly adapts to changes in layout. All the advantages brought by the deployment of A1 would lead to a more efficient execution of customer requests than the existing system. After A1, the second alternative is A3. Although it provides relatively high productivity, this alternative requires high investments and provides a lower degree of flexibility when changing the layout compared to A1. Velury and Kennedy [65] analyzed the use of screw, belt, and pneumatic conveyors for handling coal in the mining industry. For this set task, the belt conveyor was the best solution, while the pneumatic conveyor was ranked as the worst one, mostly attributed to the investment associated with its use. Unlike A1, A3 has a partially closed construction that leads to a low level of dust in the working environment. Given the very construction of A3, major failures that generate significant costs and downtime in the system can occur. Shchemeleva [3] considered which type of conveyor was best for overcoming height differences. He compared belt, elevator, and vertical conveyors. For the given conditions, the elevator conveyor placed second. A2 placed third because, first of all, it requires very high investments in automation. Additional limitations of A2 include its open structure and lack of flexibility when changing the layout of the plant. The vital advantage of A2 is its elimination of manpower, which thus provides more safety for employees, but this does not compensate for all its disadvantages. In last place is A4, which was somewhat expected. Disadvantages regarding the dustiness of the working environment and a lack of flexibility are just some of the disadvantages of the A4. The final rank of A4 is dominantly influenced by the fact that it is unable to actively capture the material, thus requiring the deployment of auxiliary equipment and additional manpower. Fonseca et al. [19] identified the belt conveyor as the optimal solution, surpassing chain, roller, and gravity conveyors in handling fodder production processes. The chosen solution was notably influenced by material characteristics.

This paper introduces a novel MCDM model that combines Fuzzy SWARA and ADAM methods, and this is the paper's primary contribution. Fuzzy SWARA establishes relative criterion weights, while the ADAM method ranks alternatives. Motivated by the intricate nature of the observed case study, which involved diverse and conflicting criteria groups, the necessity for a multi-criteria analysis was apparent.

Fuzzy SWARA was chosen for its user-friendly nature, rationality, and efficient application. It accommodates individual and group decision making, necessitates a minimal number of criterion comparisons, and exhibits high flexibility. The ADAM method, chosen for its comprehensibility, ease of use, and robustness against an expanding number of criteria, derives rankings based on geometric body volumes, offering a visually interpretable and intuitive approach.

Our sensitivity analysis revealed stable solutions with minimal sensitivity to criterion weight adjustments, affirming a low risk of altering alternative rankings. The key theoretical contribution of this paper lies in its novel combination of the Fuzzy SWARA and ADAM methods, enriching the existing literature. Practically, the defined methodology serves as a decision support system for similar real-world problems. Regarding the specific problem considered, this paper contributes to the literature on bulk material handling technology selection, particularly in the context of cement use. Additionally, the findings of this study provide valuable insights for optimizing operational efficiency, cost-effectiveness, and sustainability in industries reliant on bulk material handling.

The potential limitations of this study stem from the inherent limitations of the methods used to consider the alternative solutions and selected criteria. ADAM may encounter challenges when criteria exert mutual influence, requiring supplementation with methods that accommodate for such interactions. Fuzzy SWARA's reliance on subjective ranking could potentially introduce irrational decisions. The model's complexity and robustness necessitate significant resource deployment, including time, personnel, and financial resources.

5. Conclusions

Our analysis of research related to the handling of bulk materials indicates that there is potential for improving the activities of the container loading process in the studied factory. In the research available in the literature, the problem of selecting bulk material handling technologies is mainly discussed from a theoretical perspective, while in practical research, there are numerous limitations [16–18]. Therefore, this study aimed to overcome these identified gaps through a case study of a construction material factory operating in Serbia. The analyzed factory produces construction materials, 60% of which are cement. For this case study, alternative solutions that would greatly increase the efficiency of the factory's work and eliminate some of the observed deficiencies were proposed. For the optimization of the intralogistics activities of the factory, a new MCDM model that combines the Fuzzy SWARA and ADAM methods was developed. This is the main scientific contribution of this paper. Also, this paper provides clear guidelines for defining and selecting bulk material handling technology, focusing on those used in the construction industry. The experts who participated in this study, primarily involved in evaluating criteria and alternatives, estimate that deployment of a pneumatic conveyor in the studied factory could enhance productivity by approximately 12–17% and minimize material wastage by at least 15%. Given the crucial significance of this aspect to the deployment of the pneumatic conveyor in the factory, it warrants further investigation in future research.

The investigated alternative solutions and the stated criteria for the researched case study provided a framework for the selection of technology for handling bulk materials. Despite our effective optimization of selecting bulk material handling technology, future research should consider more alternatives and criteria. The practical limitations in implementing the identified solutions could be attributed to a lack of resources for investing in the proposed technology. The complexity and robustness of the applied MCDM model represent the limitations of its application, which would require the involvement of significant time resources. Future research could also be directed towards the expansion of the problem, including factors that would influence the prioritization of criteria and the expansion of the model (e.g., in the gray environment). Also, for the investigated industrial plant, in addition to container loading operations, it is possible to consider other intralogistic activities, such as unloading containers, transshipment, etc., and the handling of other material types. For the observed problem, future research could include interest groups in the decision-making process to achieve a comprehensive analysis and obtain a more effective solution for defined circumstances.

Author Contributions: Conceptualization, S.T., M.K. and M.B.; methodology, S.Z. and M.K.; software, M.K.; validation, S.T., M.K., M.B., S.D.-M. and S.Z.; formal analysis, M.K. and M.B.; investigation, M.K., M.B. and S.D.-M.; data curation, S.T., M.K., M.B. and S.D.-M.; writing—original draft preparation, S.T., M.K., M.B., S.D.-M. and S.Z.; writing—review and editing, S.T., M.K. and S.D.-M.; visualization, M.B.; supervision, S.T., M.K., S.D.-M. and S.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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