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Last Word in Last-Mile Logistics: A Novel Hybrid Multi-Criteria Decision-Making Model for Ranking Industry 4.0 Technologies

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Abstract: The complexity, increasing flow number and volumes, and challenges of last-mile logistics (LML) motivate or compel companies, authorities, and the entire community to think about ways to increase efficiency, reliability, and profits, reduce costs, reduce negative environmental impacts, etc. These objectives can be met by applying Industry 4.0 (I4.0) technologies, but the key question is which one. To solve this task, this paper used an innovative method that combines the fuzzy analytic network process (fuzzy ANP) and the fuzzy axial-distance-based aggregated measurement (fuzzy ADAM) method. The first was used for determining criteria weights and the second for selecting the best variant. The best solution is e/m-marketplaces, followed by cloud-computing-supported management and control systems and blockchain. These results indicate that widely adopted and implemented technologies are suitable for last-mile logistics. Newer technologies already producing significant results have serious potential for further development in this area. The main novelties and contributions of this paper are the definition of a new methodology based on multi-criteria decision-making (MCDM) methods, as well as its application for ranking I4.0 technologies for LML.

Keywords: last-mile logistics; industry 4.0; logistics 4.0; technology; selection; MCDM; fuzzy ANP; fuzzy ADAM

MSC: 90B06; 90B50

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1. Introduction

Different societies and countries were, and still are, solving the problems of market underdevelopment and monopolization with different historical dynamics. Customers used to have access to products and services from only one or a few manufacturers or service providers. Through political, economic, scientific, technological, and cultural development, as well as the influence of globalization, economies now offer a wider range of products and services. Today, in some countries, supply and demand differentiation has reached such proportions that the opposite challenge has arisen: the problem of choosing one of many possibilities, i.e., a kind of "tyranny of choice" [1]. Users choose the manufacturer, the seller, the product (different sizes, packaging, etc.), the purchase (traditional or online) and collection (collection at the store, home delivery, delivery to the parcel locker, etc.) methods, and even the method and place of production in the case of additive manufacturing.

With the massiveness, diversity, and volatility of the market, supply, demand, and flows of goods and services, logistics takes on an increasingly important role, and logisticians are faced with various decisions. Scientific and technological progress and the latest industrial revolution have contributed to new knowledge, methods, strategies, technologies, and services in logistics and supply chains. Accordingly, decision-makers often have the freedom and obligation to choose one of several alternatives. In doing so, their task is to purposefully and comprehensively define a set of alternatives and a set of appropriate criteria by which to evaluate them and choose the best one. Therefore, multi-criteria decision-making (MCDM) methods are an important tool and support for decision making in logistics. Finally, the choice of the appropriate MCDM method is another multi-criteria decision, bearing in mind the variety of logistics and supply chain problems to which they are applied, the number of methods that can be used, the categories of criteria that must be considered, the different and subjective approaches in evaluating their importance, different ways of defining and evaluating alternatives according to criteria, etc. Therefore, developing new methods is a significant contribution to MCDM theory.

There is great interest in I4.0 in the context of LML, both in research and practice. However, applying I4.0 technologies to LML is much less often the focus of researchers' attention. Thus, between 2016 and 2022, about 250 papers dealing with I4.0 in LML were published, but only about 20 papers dealt with technologies or new technologies in LML [2]. The number of papers in which MCDM methods were applied for selecting I4.0 technologies in LML is even smaller. Furthermore, these and later published papers mainly deal with different transportation technologies (e.g., drones, green vehicles, cargo bikes, autonomous electric vehicles, etc.) and receipts of goods (e.g., parcel lockers) [3–6], while ignoring other technologies, logistics subsystems, processes, and activities (warehousing, inventory management, data management, etc.). Also, most of these papers do not comprehensively consider criteria regarding technology evaluation, i.e., they neglect certain technological, economic, political, and social aspects. On the other side, in logistics practice, there is interest in applying I4.0 technologies, but mostly in transportation technologies, such as drones. The current and potential importance of such technologies is evidenced by the estimate that, in 2022, over 2000 last-mile deliveries were made by drones worldwide [7], and the prediction that, within the next five years, the share of drone deliveries will reach as much as 20% [8]. The variety, number, development, and application potentials of this and other I4.0 technological solutions undoubtedly motivate and will motivate companies to consider a wide set of technologies for application in LML. Accordingly, there is a need for a model for the multi-criteria evaluation and selection of the most desirable I4.0 technology in LML, which will be more comprehensive from the aspect of technologies as well as their evaluation criteria. The goal of this paper is to compensate for this research gap through the application of a new MCDM model.

MCDM methods are undoubtedly one of the most useful instruments for choosing the optimal Industry 4.0 (I4.0) technology for application in last-mile logistics (LML). The adoption of I4.0 technologies can play a key role in trying to optimize the service, not only in terms of digitization, automation, and interconnection along the supply chain but also in its last mile [9]. Although each technology brings certain benefits, there are also problems and obstacles to its application related to infrastructure, technological integration, ecology, etc. [10]. Therefore, it is crucial to carefully assess the implementation effectiveness of certain technologies in LML, especially using MCDM processes. According to the authors' knowledge, such undertakings have not yet been made in the literature. Since choosing a new technology is a multidimensional problem with many interdependencies between quantitative and qualitative factors, the analytic network process (ANP) method determines the importance of criteria for technology evaluation and effectively addresses these requirements [11]. More precisely, given the impossibility of precise assessment, a fuzzy modification of this method—fuzzy ANP—is suitable for this task. However, the fuzzy axial-distance-based aggregated measurement (fuzzy ADAM) method is appropriate for ranking alternatives according to defined criteria. The primary advantages of the ADAM method compared to other methods lie in its simplicity, ease of understanding, adaptive nature, resistance to an increasing number of criteria, high intuitiveness, and minimal risk of changes in ranking [12]. Its fuzzy version was chosen for the same reasons as in the case of fuzzy ANP.

A model based on two MCDM methods, fuzzy ANP and fuzzy ADAM, was defined and used to select the most favorable I4.0 technology for LML in this paper. The paper contributes to research in the areas of MCDM, LML, and I4.0 through the following:

- The newly developed hybrid mathematical model;
- Model application to solving the defined problem;
- Consideration of a wide range of alternatives and criteria.

This paper is organized as follows. After the introduction, the second section provides a comprehensive review of relevant research on the application of MCDM methods in logistics, LML, and I4.0 technologies that are applied in it. A methodology based on fuzzy ANP and fuzzy ADAM methods is proposed in the third section. In the fourth section, this methodology is used to select the optimal I4.0 technology for LML after the alternatives and criteria for their evaluation are defined. The fifth section presents a discussion on the application of the methodology, results, implications, etc. At the end, concluding considerations and directions for future research are given.

2. Literature Review

To describe the background of the problem, a comprehensive literature review was conducted. Google Scholar was used for the literature search. By systematically entering combinations of two or more terms from two or more groups shown in Table 1, papers were found, from which relevant and useful ones were selected. Examples of entries are "last-mile definition", "home delivery smart technologies", "selection of I4.0 technologies in logistics", "MCDM parcel delivery 4.0", etc. Sources whose titles contain such combinations and those that do not but deal with this topic were analyzed. Additionally, the authors searched the sources using the "divergence of research" system [13].

Table 1. Search keyword groups.

I Group of Keywords	II Group of Keywords	III Group of Keywords	IV Group of Keywords	V Group of Keywords
last mile, last-mile, last miles, final mile, home, parcel, B2C, door, customer	definition, concept, review	delivery, logistic, logistics, transport, storage, warehouse, loading, package, inventory, order	technology, new technologies, 4.0, industry 4.0, smart, *names of technologies and corresponding abbreviations* (Internet of things, IoT, automated guided vehicles, etc.)	selection, choice, evaluation, ranking, multi-criteria decision-making, MCDM, multiple-criteria decision analysis, MCDA, *names of MCDM methods and corresponding abbreviations* (analytic hierarchy process, AHP, Promethee, etc.)

2.1. Application of MCDM Methods in Logistics

As previously stated, "the victims" of "the tyranny of choice" are users and those who provide them with products or services. First, it is necessary to fulfill the heterogeneous and changing user requirements and simultaneously decide how they will be performed. Manufacturers, retailers, logistics providers, and other supply chain participants face daily choices and decisions at the operational, tactical, and strategic levels. Manufacturers choose between different types of raw materials, their suppliers, production strategies, production technologies, etc. Sellers choose between manufacturers, sales channels, distribution channels, etc. Logistics service providers choose between different locations of logistics facilities, logistics strategies, storage and transportation technologies, routes, etc. In each of these decisions, it is most often necessary to consider various aspects of efficiency, functionality, expediency, economic profitability, ecological and social adequacy, etc.

Accordingly, MCDM methods are increasingly important in supply chain management and logistics. They were applied to the selection of the location of logistics centers and terminals [14,15], the selection of handling equipment [16], the analysis of country logistics performance indices [17], the selection of logistics providers [18], the evaluation of concepts, initiatives, and scenarios of city logistics [19,20], the optimization of cold chain logistics [21], the selection of the initial delivery point [22], etc.

In the field of LML, different MCDM methods and their combinations and modifications have been used for locating logistics centers [23], evaluating logistics providers [24], and ensuring sustainability [4,25] and smart solutions and strategies [5], for different concepts based on the same technological solution, e.g., drones [26,27], for the analysis of barriers to their application in the last mile [28], etc. Recently, MCDM methods have been used to evaluate I4.0 technologies in various areas and aspects of logistics: logistics centers [29,30], material handling technologies [31], reverse logistics [32], etc. According to the authors' knowledge, the evaluation and selection of technology I4.0 in LML using the MCDM method have not been carried out in any previous research.

The ANP method and its modification in a fuzzy environment, fuzzy ANP, have been applied independently or in combination with other methods to solve numerous problems in logistics and supply chains. The ANP method was applied independently for the selection of a logistics provider [33], for the evaluation of logistics performance indicators [34], etc., but also in combination with the quality function deployment (QFD) method for selecting a sustainable supplier [35], with benefit–opportunity–cost–risk (BOCR) analysis for determining the location of the logistics center [36], etc. Decision-making trial-and-evaluation laboratory (DEMATEL)-based ANP (D-ANP) or the ANP method combined with the DEMATEL method has been used for supplier selection [37], evaluation of logistics flows [38], etc. Gray D-ANP was used to identify interactions between production and logistics systems [39].

The fuzzy ANP method was used independently for the selection of a container port [40], the risk assessment of a virtual logistics enterprise cooperation [41], etc. It was also used in combination with fuzzy DEMATEL for logistics personnel selection [42], with fuzzy DEMATEL and fuzzy VIKOR (Serb. *VIšekriterijumsko KOmpromisno Rangiranje*) for city logistics concept selection [19], with fuzzy DEMATEL and fuzzy technique for order of preference by similarity to ideal solution (TOPSIS) for supplier evaluation [43], etc. ANP based on type-2 fuzzy sets (type-2 fuzzy ANP) in combination with BOCR was applied for logistics provider selection [44].

The ANP method and its related and very similar analytic hierarchy process (AHP) method are the most applied MCDM methods for decision making in the field of I4.0 [45]. Their fuzzy modifications have found significant application in this area, especially in technology-related decisions. For example, the fuzzy ANP method combined with the fuzzy AHP method was applied to select the best I4.0 technology in production [46]. Also, these methods were used to make decisions regarding certain technologies of I4.0. Thus, the fuzzy ANP method, integrated with the fuzzy ISM method, was used for the comparative analysis of traditional and supply chains based on blockchain technology [47] and in combination with the modified total interpretive structural modeling (mTISM) method to identify the key adoption factors of blockchain technology in freight transport [48]. The fuzzy AHP method was used independently for the selection of the production process in additive manufacturing [49], in combination with TOPSIS for the selection of printers for additive manufacturing [50], etc.

ADAM is a young MCDM method from a new group of so-called geometric methods. It was applied independently in conventional form for evaluating business models based on the circular economy in supply chains [12], selecting the starting point of electronically ordered goods delivery [22], etc. Also, it was applied in combination with other methods and mathematical approaches, e.g., with the fuzzy factor relationship (FARE) method for risk analysis of the use of drones in city logistics [51], with mathematical programming for city logistics concept evaluation [20], with fuzzy Delphi and an extended fuzzy analytic hierarchy process (AHP) for railway infrastructure manager performance evaluation [52], etc. The fuzzy ADAM was also developed and applied in combination with different methods (e.g., fuzzy stepwise weight assessment ratio analysis (SWARA) for the evaluation of transshipment technologies in intermodal terminals [53]). According to the authors' knowledge, the combination of fuzzy ANP and fuzzy ADAM has not yet been applied.

Table 2 provides an overview of the application of MCDM methods in LML. Unlike earlier studies, in which scoring (additive) (S), distance-based (DB), pairwise comparison (PC), and outranking methods (O) were used, the model defined in this paper, in addition to ANP as a PC method, applies the method ADAM, which represents the geometric method (G) [12]. Also, previous studies dealt with a completely different type of problem (locating, provider selection, delivery method selection), evaluation of various types of the same I4.0 technology, evaluation of concepts based on it, and selection of the most favorable one from a narrow set of I4.0 technologies, and/or considered a set of criteria less comprehensive than defined in this paper. On the other side, some of the previous studies, unlike this one, considered the stakeholders' viewpoints.

Table 2. Application of MCDM methods in LML.

Method(s)	Field of Application	Differences	Source
AHP	Selection of last-mile logistics center location	PC method; the paper does not deal with technologies but with the problem of locating the place of delivery	[23]
Fuzzy AHP, fuzzy measurement of alternatives and ranking according to compromise solution (MARCOS)	Logistics service provider evaluation	PC and DB methods; the paper does not deal with technologies but with the evaluation of providers	[24]
Fuzzy Delphi, fuzzy FARE, fuzzy VIKOR	Evaluation of sustainable delivery solution	S, DB, and O methods; the paper deals with concepts based on several I4.0 technologies	[25]
AHP, TOPSIS	Evaluation of sustainable delivery solution	PC and DB methods; less comprehensiveness of alternatives; taking into account the views of different stakeholders	[4]
SWOT (strengths, weaknesses, opportunities, and threats) analysis, 2-tuple VIKOR, AHP	Evaluation of smart solutions and strategies	PC and DB methods; less comprehensiveness of alternatives and criteria	[5]
Interval-valued inferential fuzzy TOPSIS	Evaluation of delivery drone types	DB method; the paper deals with the selection of the type of one I4.0 technology	[26]
Spherical fuzzy MARCOS	Evaluation of drone-based delivery concepts	DB method; the paper deals with concepts based on one I4.0 technology	[27]
Fuzzy Delphi ANP	Analysis of barriers to the use of drones in delivery	PC and S methods; the paper deals with barriers to the application of an I4.0 technology	[28]
Fuzzy AHP, fuzzy TOPSIS	Evaluation of delivery methods	PC and DB methods; the paper is not concerned with technologies but with delivery methods	[54]
Multi-criteria decision analysis (MCDA)	Evaluation of transport technologies	Less comprehensiveness of alternatives and criteria; Taking into account the views of different stakeholders	[6]
Fuzzy ANP, fuzzy ADAM	Evaluation of I4.0 technologies for LML	PC and G methods; greater comprehensiveness of alternatives and criteria	This study

2.2. Last-Mile Logistics

Various authors have discussed in detail the definitions of the last mile and the scope of this and/or related terms (e.g., [55,56]). In most interpretations, this term means the implementation of logistics operations from the last intermediate point, i.e., the distribution center, to the user [57]. Although there is much consensus on the coverage of the last mile as part of the supply chain, there are differences in the understanding of this term from the perspective of the executor of goods delivery to the desired location of the user. Namely, while some authors associate the concept of the last mile only with delivery to the user, which is performed by a seller, manufacturer, or third party (e.g., [58]), others consider this term to be the distance that, apart from these entities, the user himself can travel to pick up and deliver goods (traditional shopping) [59–61]. In addition to deliveries to users, some authors (e.g., [62]) also include deliveries to stores, companies, etc., under last-mile deliveries. Additionally, some authors link the last mile to the urban area [63,64], while others also refer to rural areas (e.g., [65]). Definitions and interpretations of the last mile and related concepts can also differ in terms of starting point, endpoint, involved operations, etc. [55]. In this paper, the term LML considers operations from ordering (including order picking and preparation) to delivery at the end user's home address, or another desired address, performed by the seller, manufacturer, or third party.

2.3. Industry 4.0 Technologies in Last-Mile Logistics

Smart technologies and I4.0 significantly affect reality and change it in many aspects, including logistics [66–68]. LML, as an important area of logistics, is also subject to this influence, so, in recent years, more and more researchers are analyzing the application of I4.0 technologies in that area. Jose et al. [69] assessed the feasibility of implementing I4.0 technologies in LML processes. Kostrzewski et al. [6] performed a comparative analysis of modern and conventional last-mile transport technologies. Ferrari et al. [2] analyzed socio-economic factors influencing the investments and implementing of I4.0 technologies in LML. The role of these technologies in achieving logistics sustainability has also been analyzed in numerous papers [10,70]. Tadić et al. [13] comprehensively reviewed the application of I4.0 technologies in home delivery. Various aspects of the application of certain I4.0 technologies in LML have been analyzed in numerous studies. Thus, the application of the Internet of Things in this area was considered in combination with other technologies, such as drones [71,72], big data [73], blockchain [74,75], the Global Positioning System (GPS), the transport management system (TMS), cloud computing [76], etc. Slabinac [77] discussed innovative last-mile transport technologies, analyzing certain I4.0 technologies. Engesser et al. [78] reviewed research on applying automated guided vehicles, autonomous vehicles, and drones in LML, and Fehling and Saraceni [79] analyzed the technical and legal critical success factors. In recent years, there has been more and more research on the application of artificial intelligence in LML [80,81] and e-commerce [82], both in urban [83] and rural areas [84]. Naclerio and De Giovanni [85] investigated the effects of blockchain applications on multi-channel solutions and logistics strategies to solve last-mile problems and improve performance. In recent years, there has been growing interest in the impact of additive manufacturing on LML [86,87].

3. Methodology

The problem that is the subject of this paper will be solved by applying a novel methodology (Figure 1), which consists of the following steps:

Step 1: An extensive literature review of the subject areas is conducted to identify potential alternatives and criteria for their evaluation.

Step 2: The alternatives and the evaluation criteria are defined based on the literature review.

Step 3: The evaluation scale for criteria and alternatives is defined. Considering the methods that will be applied, it is necessary to make evaluations using descriptive ratings, which are translated into triangular fuzzy numbers, as shown in Table 3.

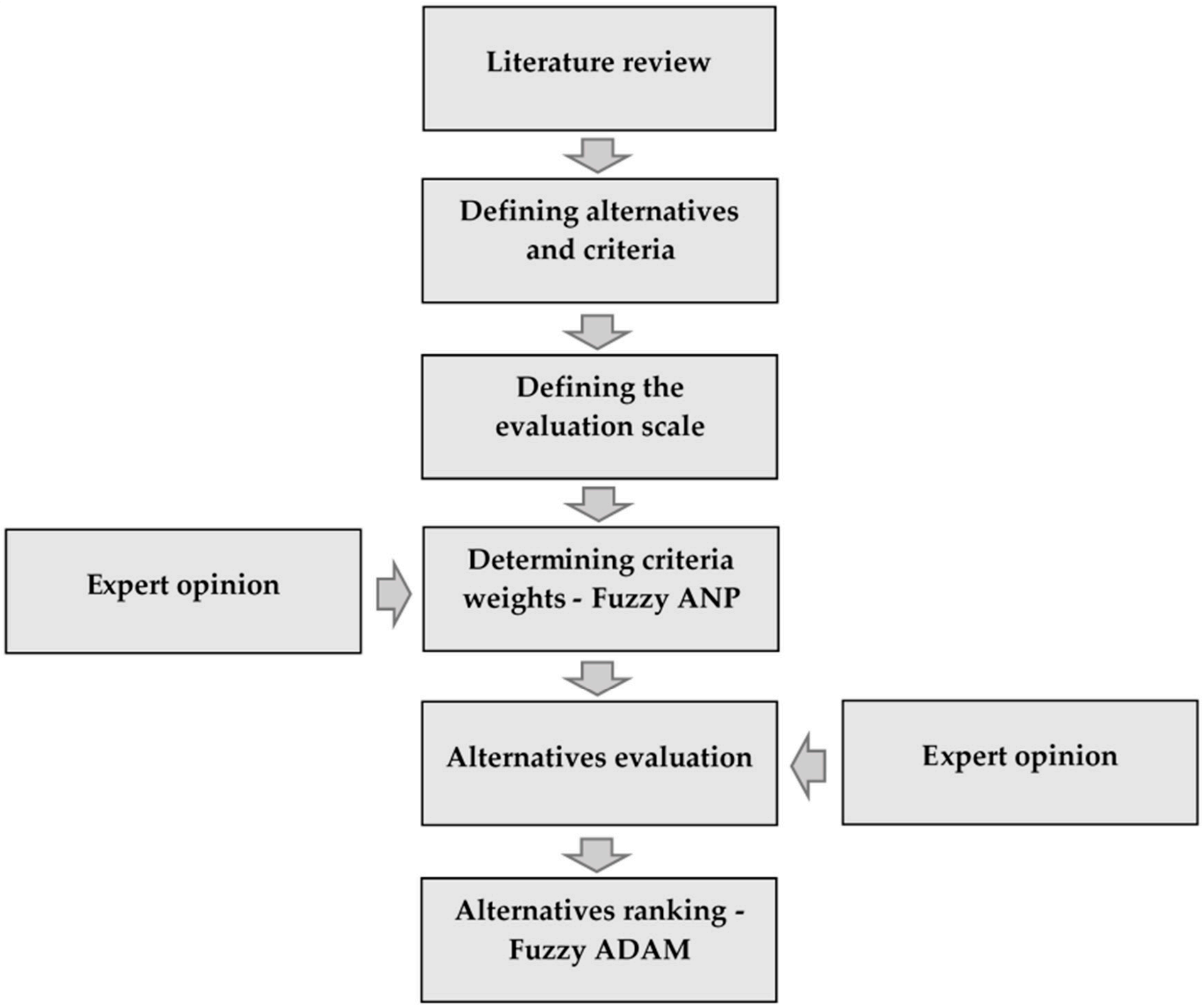

Figure 1. Flowchart of the proposed model.

Table 3. Alternative and criteria evaluation scale [51].

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

Step 4: The ANP method is used to determine the weights of the criteria. First, it is determined whether there is mutual dependence between criteria, both within criteria groups and between them. Then, the group of experts declares the importance of criteria or criteria groups concerning other criteria or criteria groups using one of the descriptive evaluations offered in Table 3. These evaluations are transformed into corresponding fuzzy numbers. For each pair of criteria or criteria group, the arithmetic mean of the fuzzy

numbers obtained by the experts is determined. The arithmetic mean of multiple triangular fuzzy numbers is a triangular fuzzy number whose lower, medium, and upper values are obtained as the arithmetic means of the lower, middle, and upper values of those fuzzy numbers. The fuzzy number from Table 3, closest to the obtained arithmetic mean, is taken as the overall evaluation of the entire focus group. Therefore, the following equation holds:

$$\tilde{a}_{ij} \approx \frac{1}{\partial} \odot \left(\oplus_{k=1}^{\partial} \tilde{E}_k^{i,j} \right), \tag{1}$$

where E_k^{ij} is the assessment of the importance of criterion i according to criterion j by the k-th expert, for i, j = 1, ... n, (n is the number of criteria, ∂ is the number of experts from the focus group), and $\tilde{a}_{ij}$ is the overall valuation of the importance of criterion i according to criterion j by the entire expert group.

The matrix was obtained by mutual comparison of the following criteria:

$$\tilde{A} = \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{a}_{nn} \end{bmatrix} \tag{2}$$

where $\tilde{a}_{ij} = (l_{ij},\ m_{ij},\ u_{ij})$ represents the importance of element i according to element j, i = j = 1, 2, ..., s expressed in fuzzy values, and n is the number of criteria (in the case of comparison of criteria), that is, the criteria group (in the case of comparison of criteria group).

The logarithm of the matrix $\tilde{A}$ is determined according to the following equation:

$$\ln \tilde{a}_{IJ} \approx (\ln l_{ij}, \ln m_{ij}, \ln u_{ij}),\ i, j = 1, 2, \ldots, n, \tag{3}$$

that is, the logarithm of the triangular fuzzy score $\tilde{a}_{IJ}$ can still be viewed as an approximate triangular fuzzy number, whose membership function can be defined as follows:

$$\mu_{ij}\left(\ln\left(\frac{w_i}{w_j}\right)\right) = \begin{cases} \frac{\ln(w_i/w_j) - \ln l_{ij}}{\ln m_{ij} - \ln l_{ij}},\ \ln\left(\frac{w_i}{w_j}\right) \ \le\ \ln m_{ij} \\ \frac{\ln u_{ij} - \ln(w_i/w_j)}{\ln u_{ij} - \ln m_{ij}}, \ln\left(\frac{w_i}{w_j}\right) \ \ge\ \ln m_{ij} \end{cases} \tag{4}$$

where $\mu_{ij}\left(ln\left(\frac{w_i}{w_j}\right)\right)$ is the membership degree of $ln\left(\frac{w_i}{w_j}\right)$ belonging to the approximate triangular fuzzy score $ln\tilde{a}_{IJ} \approx (lnl_{ij}, lnm_{ij}, lnu_{ij})$, and w_i is the crisp values of the priority vector

$$W = (w_1, \ldots, w_n)^T > 0,\ \sum_i^n w_i = 1). \tag{5}$$

It is necessary to find a crisp priority vector to maximize the minimum membership degree

$$\lambda = min\{\mu_{ij}(ln(w_i/w_j)) \mid i = 1,\ \ldots,\ n-1; j = i+1,\ \ldots,\ n\} \tag{6}$$

The resulting model can be constructed as

$$Max\lambda s.\ t. \begin{cases} \mu_{ij}\ (ln(w_i/w_j))\ \ge\ \lambda,\ \ i = 1,\ \ldots,\ n-1; j = i+1,\ \ldots,\ n \\ w_i \ge 0,\ i = 1,\ \ldots,\ \ n, \end{cases} \tag{7}$$

or

$$
\begin{gathered}
Max 1-\lambda \\
s.t.
\end{gathered}
$$

$$
\begin{cases}
lnw_i - lnw_j - \lambda \cdot ln\left(m_{ij}/l_{ij}\right) \geq lnl_{ij}, \quad i = 1, \ldots, n-1; j = i+1, \ldots, n, \\
-lnw_i + lnw_j - \lambda \cdot ln\left(u_{ij}/m_{ij}\right) \geq -lnu_{ij}, \quad i = 1, \ldots, n-1; j = i+1, \ldots, n, \\
w_i \geq 0, \; i = 1, \ldots, n.
\end{cases} \tag{8}
$$

In order to avoid a degree of membership λ taking a negative value, the variables of non-negative deviation δ_{ij} and η_{ij} for $i = 1, \ldots, n-1$, and $j = 1, \ldots, n$ are introduced to satisfy the following inequalities:

$$
\begin{gathered}
lnw_i - lnw_j - \lambda \cdot ln\left(m_{ij}/l_{ij}\right) + \delta_{ij} \geq lnl_{ij}, \quad i = 1, \ldots, n-1; j = i+1, \ldots, n, \\
-lnw_i + lnw_j - \lambda \cdot ln\left(u_{ij}/m_{ij}\right) + \eta_{ij} \geq -lnu_{ij}, \quad i = 1, \ldots, n-1; j = i+1, \ldots, n,
\end{gathered} \tag{9}
$$

The values of deviation variables are most desired to be as small as possible. Accordingly, the following nonlinear priority model based on LFPP is proposed to calculate the weight (w_i):

$$
\begin{gathered}
Min\ J = (1-\lambda)^2 + M \cdot \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left(\delta_{ij}^2 + \eta_{ij}^2\right) \\
s.t. \begin{cases}
x_i - x_j - \lambda \cdot ln\left(m_{ij}/l_{ij}\right) + \delta_{ij} \geq lnl_{ij}, \quad i = 1, \ldots, n-1; j = i+1, \ldots, n, \\
-x_i + x_j - \lambda \cdot ln\left(u_{ij}/m_{ij}\right) + \eta_{ij} \geq -lnu_{ij}, \quad i = 1, \ldots, n-1; j = i+1, \ldots, n, \\
\lambda, \; x_i \geq 0, \; i = 1, \ldots, n, \\
\delta_{ij}, \eta_{ij} \geq 0, \; i = 1, \ldots, n-1; j = i+1, \ldots, n.
\end{cases}
\end{gathered} \tag{10}
$$

where $x_{i,j} = \ln w_{i,j}$ for $i = 1, \ldots, n$, $j = i + 1, \ldots, n$, and M is a sufficiently large constant ($M = 10^3$).

Let $x_i^*(i = 1, \ldots, n)$ be the optimal solution for model (9). The normalized weights for the matrix $\widetilde{A} = \left(\widetilde{a}_{IJ}\right)_{n \times n}$ can be obtained as follows:

$$
w_i{}^* = \frac{e^{x_i^*}}{\sum_{j=1}^{n} e^{x_j^*}}, \; i = 1, \ldots, n, \tag{11}
$$

This method gives crisp normalized weights. To control the result, the consistency ratio CR is calculated for each matrix as follows:

$$
CR = CI/RI. \tag{12}
$$

CI represents the consistency index and is calculated as follows:

$$
CI = \frac{\lambda_{max} - n}{n-1}, \tag{13}
$$

where λ_{max} is a principal eigenvalue of matrix $\widetilde{A}$, and RI is a random index whose values for matrices of different sizes are given by Saaty [88]. Comparisons are only acceptable if CR values are less than 0.10.

Step 5: An evaluation of the defined alternatives according to the defined criteria is carried out by the experts in the same way as in the case of the criteria evaluation.

Step 6: The fuzzy ADAM method is used to rank the alternatives according to the criteria and select the most favorable one.

The following matrix is defined:

$$\widetilde{E} = \left[\widetilde{e}_{qj}\right]_{g\times n}, \tag{14}$$

where $\widetilde{e}_{qj} = (p^e, r^e, t^e)$ is the evaluations of alternatives q in relation to criteria j, and g is the number of alternatives.

The following matrix is defined:

$$\widetilde{F} = \left[\widetilde{f}_{qj}\right]_{g\times n}, \tag{15}$$

where $\widetilde{f}_{qj} = \left(p^f, r^f, t^f\right)$ represents the normalized evaluations e_{qj} obtained as

$$\begin{aligned} p^f &= \frac{p^e}{maxt^e} \\ r^f &= \frac{r^e}{maxt^e} \\ t^f &= \frac{t^e}{maxt^e} \end{aligned} \tag{16}$$

The following matrix is defined:

$$\widetilde{S} = \left[\widetilde{s}_{qj}\right]_{g\times n} \tag{17}$$

where $\widetilde{s}_{qj}(p^s, r^s, t^s)$ denotes the evaluations of $\widetilde{f}_{qj}$ sorted in descending order.

Fuzzy coordinates $\left(\widetilde{v}_{qj}, \widetilde{y}_{qj}, \widetilde{z}_{qj}\right)$, of the fuzzy reference $\widetilde{O}_{qj}$ and fuzzy weighted reference $\widetilde{N}_{qj}$ points are determined:

$$\begin{aligned} \widetilde{v}_{qj} &= (p^{v_{qj}},\ r^{v_{qj}},\ t^{v_{qj}}) = (p^{s_{qj}} \times sin\alpha_j, r^{s_{qj}} \times sin\alpha_j,\ \ t^{s_{qj}} \times sin\alpha_j),\ \ \forall q = 1, \ldots,\ g;\ \forall j = 1, \ldots,\ n; \\ \widetilde{y}_{qj} &= (p^{y_{qj}},\ r^{y_{qj}},\ t^{y_{qj}}) = (p^{s_{qj}} \times cos\alpha_j, r^{s_{qj}} \times cos\alpha_j, t^{s_{qj}} \times cos\alpha_j),\ \ \forall q = 1, \ldots,\ g;\ \forall j = 1, \ldots,\ n; \\ \widetilde{z}_{qj} &= (p^{z_{qj}},\ r^{z_{qj}},\ t^{z_{qj}}) = \begin{cases} (0,\ 0,\ 0),\ for\ \widetilde{O}_{qj} \\ (p^{w_j},\ r^{w_j},\ t^{w_j}),\ for\ \widetilde{N}_{ej} \end{cases},\ \ \forall q = 1, \ldots,\ g;\ \forall j = 1, \ldots,\ n; \end{aligned} \tag{18}$$

where α_j is obtained as follows:

$$\alpha_j = (j-1)\frac{90^\circ}{n-1}\ ,\ \forall j = 1, \ldots,\ n. \tag{19}$$

Fuzzy coordinates are used to form complex polyhedra for each alternative.

Polyhedra are made of pyramids obtained for each pair of criteria as combinations of all possible reference and weighted reference points.

Then, fuzzy values of the volume of complex polyhedra are obtained as

$$\widetilde{V}_q^C = \oplus_{k=1}^{n-1}\widetilde{V}_k,\ \forall q = 1, \ldots,\ g; \tag{20}$$

where $\widetilde{V}_k$ is fuzzy volumes of the pyramids determined by each pair of two consecutive criteria, obtained as

$$\widetilde{V}_k = \frac{1}{3}\check{B}_k \otimes \widetilde{h}_k,\ \forall k = 1, \ldots,\ n-1; \tag{21}$$

where $\widetilde{B}_k$ is fuzzy values of the surface areas of the pyramid bases, calculated as

$$\widetilde{B}_k = \widetilde{c}_k \otimes \widetilde{a}_k \oplus \frac{\widetilde{a}_k \otimes \left(\widetilde{b}_k \ominus \widetilde{c}_k\right)}{2}, \tag{22}$$

where $\widetilde{a}_k = (p^{a_k}, r^{a_k}, t^{a_k})$ is fuzzy values of Euclidean distances in which

$$\begin{array}{c} p^{a_k} = min\left(\sqrt{\left(t^{v_{j+1}} - p^{v_j}\right)^2 + \left(t^{y_{j+1}} - p^{y_j}\right)^2}, \sqrt{\left(p^{v_{j+1}} - t^{v_j}\right)^2 + \left(p^{y_{j+1}} - t^{y_j}\right)^2}, \right. \\ r^{a_k} = \sqrt{\left(r^{v_{j+1}} - r^{v_j}\right)^2 + \left(r^{y_{j+1}} - r^{y_j}\right)^2} \\ t^{a_k} = max\left(\sqrt{\left(t^{v_{j+1}} - p^{v_j}\right)^2 + \left(t^{y_{j+1}} - p^{y_j}\right)^2}, \sqrt{\left(p^{v_{j+1}} - t^{v_j}\right)^2 + \left(p^{y_{j+1}} - t^{y_j}\right)^2}\right) \end{array} \tag{23}$$

$\widetilde{b}_k = \left(p^{b_k}, r^{b_k}, t^{b_k}\right)$ and $\widetilde{c}_k = (p^{c_k}, r^{c_k}, t^{c_k})$ are equal to:

$$\widetilde{b}_k = \widetilde{z}_j \tag{24}$$

$$\widetilde{c}_k = \widetilde{z}_{j+1} \tag{25}$$

Following Equations (23)–(25), Equation (22) can be expressed as $\widetilde{B}_k = \left(p^{B_k},\ r^{B_k},\ t^{B_k}\right)$, where

$$\begin{array}{l} p^{B_k} = p^{c_k} \times p^{a_k} + \frac{p^{a_k} \times \left(p^{b_k} - t^{c_k}\right)}{2} \\ r^{B_k} = r^{c_k} \times r^{a_k} + \frac{r^{a_k} \times \left(r^{b_k} - r^{c_k}\right)}{2} \\ t^{B_k} = t^{c_k} \times t^{a_k} + \frac{t^{a_k} \times \left(t^{b_k} - p^{c_k}\right)}{2} \end{array} \tag{26}$$

$$\widetilde{h}_k = \frac{2\sqrt{\widetilde{s}_k\left(\widetilde{s}_k - \widetilde{a}_k\right)\left(\widetilde{s}_k - \widetilde{d}_k\right)\left(\widetilde{s}_k - \widetilde{e}_k\right)}}{\widetilde{a}_k} \tag{27}$$

where $\widetilde{h}_k$ is the fuzzy values of the height of the pyramid, and $\widetilde{s}_k$ is the fuzzy values of the semicircumference of the triangles defined by the reference points of two consecutive criteria and the coordinate origin.

$$\widetilde{s}_k = \frac{\widetilde{a}_k \oplus \widetilde{d}_k \oplus \widetilde{e}_k}{2}, \tag{28}$$

where $\widetilde{d}_k$ can be expressed as $\widetilde{d}_k = \left(p^{d_k}, r^{d_k}, t^{d_k}\right)$, where

$$\begin{array}{l} p^{d_k} = \sqrt{(p^{v_j})^2 + (p^{y_j})^2} \\ r^{d_k} = \sqrt{(r^{v_j})^2 + (r^{y_j})^2} \\ t^{d_k} = \sqrt{(t^{v_j})^2 + (t^{y_j})^2} \end{array} \tag{29}$$

and $\widetilde{e}_k$ can be expressed as $\widetilde{e}_k = (p^{e_k}, r^{e_k}, t^{e_k})$, where

$$\begin{array}{l} p^{e_k} = \sqrt{(p^{v_{j+1}})^2 + (p^{y_{j+1}})^2} \\ r^{e_k} = \sqrt{(r^{v_{j+1}})^2 + (r^{y_{j+1}})^2} \\ t^{e_k} = \sqrt{(t^{v_{j+1}})^2 + (t^{y_{j+1}})^2} \end{array} \tag{30}$$

Following Equations (29) and (30), Equation (28) can be expressed as $\widetilde{s}_k = (p^{s_k}, r^{s_k}, t^{s_k})$, where

$$\begin{aligned} p^{s_k} &= \frac{p^{a_k}+p^{d_k}+p^{e_k}}{2} \\ r^{s_k} &= \frac{r^{a_k}+r^{d_k}+r^{e_k}}{2} \\ t^{s_k} &= \frac{t^{a_k}+t^{d_k}+t^{e_k}}{2} \end{aligned} \tag{31}$$

And, Equation (27) can be expressed as $\widetilde{h}_k = \left(p^{h_k}, r^{h_k}, t^{h_k}\right)$, where

$$\begin{aligned} p^{h_k} &= \frac{2\sqrt{p^{s_k}|p^{s_k}-t^{a_k}|\left|p^{s_k}-t^{d_k}\right||p^{s_k}-t^{e_k}|}}{t^{a_k}} \\ r^{h_k} &= \frac{2\sqrt{r^{s_k}|r^{s_k}-r^{a_k}|\left|r^{s_k}-r^{d_k}\right||r^{s_k}-r^{e_k}|}}{r^{a_k}} \\ t^{h_k} &= \frac{2\sqrt{t^{s_k}|t^{s_k}-p^{a_k}|\left|t^{s_k}-p^{d_k}\right||t^{s_k}-p^{e_k}|}}{p^{a_k}} \end{aligned} \tag{32}$$

According to the transformed Equations (22) and (28), Equation (21) can be expressed as $\widetilde{V}_k = \left(p^{V_k}, r^{V_k}, t^{V_k}\right)$, where

$$\begin{aligned} p^{V_k} &= \frac{p^{B_k} \times p^{h_k}}{3} \\ r^{V_k} &= \frac{r^{B_k} \times rp^{h_k}}{3} \\ t^{V_k} &= \frac{t^{B_k} \times t^{h_k}}{3} \end{aligned} \tag{33}$$

and Equation (20) can be expressed as $\widetilde{V}_q^C = \left(p^{V_q^C}, r^{V_q^C}, t^{V_q^C}\right)$, where

$$\begin{aligned} p^{V_q^C} &= \sum_{k=1}^{n-1} p^{V_k} \\ r^{V_q^C} &= \sum_{k=1}^{n-1} r^{V_k} \\ t^{V_q^C} &= \sum_{k=1}^{n-1} t^{V_k} \end{aligned} \tag{34}$$

Alternatives are ranked according to crisp values (adapted from [89])

$$Crisp\left(\widetilde{V}_q^C\right) = \left(4 \times r^{V_q^C} + t^{V_q^C} + 2p^{V_q^C}\right)/3\left(t^{V_q^C} - 2p^{V_q^C}\right) \tag{35}$$

4. Methodology Application for the Selection of I4.0 Technology for LML

The technologies most often considered in the context of I4.0 in logistics are [66] additive manufacturing, advanced robotics, artificial intelligence, augmented reality, automatically guided vehicles, drones, and autonomous vehicles, big data and data mining, blockchain, e/m-marketplaces, the Internet of things, and cloud-computing-supported management and control systems.

Additive manufacturing (A$_1$), or 3D printing, involves creating objects layer by layer from digital models. It enables the complex and customized design and fast production of items. Some authors (e.g., [90]) believe that additive manufacturing can lead to changes similar to those caused by the advent of personal computers and the Internet. In LML, this technology is applied through the implementation of "fab shops" in which additive production is carried out and from which delivery is made to users, but also through production in the households of end users [13]. In the field of additive manufacturing, various decisions require the use of MCDM methods [91].

Advanced Robotics (A$_2$) includes designing and developing robots with sophisticated capabilities, precision, efficiency, and autonomous action. They are used in production, healthcare, research, and logistics to perform various tasks. In LML, they are used for activities in logistics centers (warehousing processes, order picking, palletizing, etc.) [92], performing partial or complete deliveries [13].

Artificial Intelligence (AI) and Augmented Reality (AR) (A_3) are technologies whose applications may also have significance for LML. AI refers to developing machines capable of intelligent behavior while AR overlays digital information with the real world. These technologies enhance human capabilities, experiences, and decision making. Artificial intelligence methods, such as neural networks, genetic algorithms, the ant colony optimizer, the fuzzy logic model, etc., are applied in various fields [84,93–96]. Some of the applications in LML are various operations in warehouses and logistics centers, dynamic data analysis and intelligent delivery scheduling, demand and delivery time forecasting, distribution optimization and shipment tracking, projecting movement information onto vehicle windshields during transportation, etc. [13].

Automated guided vehicles (AGVs), drones, and autonomous vehicles (AVs) (A_4) are transportation systems with a certain degree of autonomy. They are used both in logistics centers and for the delivery itself. AGVs transport materials in controlled environments, drones perform aerial operations for various purposes, and AVs are most commonly used for ground-based autonomous delivery. These technologies are often integrated with other traditional or modern technologies. Thus, drones are often combined with trucks and other conventional freight road vehicles [27], but also with solutions such as tricycles [97].

Big Data and Data Mining (A_5) are also increasingly used in logistics, including LML. Big data refers to large amounts of information generated and collected from various sources. Data mining is the process of analyzing those data to uncover trends and useful information. These technologies are widely used in business, healthcare, research, etc. In LML, they have been applied for the real-time routing optimization of delivery vehicles, planning, and implementation of crowd delivery processes [98].

Blockchain (A_6) is a decentralized data storage system that uses a series of linked blocks to ensure the transparency and security of transactions. The key characteristics of blockchain technology, essential for logistics and supply chains, are anonymity, persistence, decentralization, and verifiability [99]. This technology, often associated with cryptocurrencies, can be used for supply chain tracking, logistics, and digital records, and has great potential for LML applications. Currently, it is applied [13] for collecting commodity data, security monitoring, delivery assurance, and the cooperation of courier express and parcel services (CEPs) for establishing micro-hubs.

E/M-marketplaces (A_7) have received growing attention in recent decades. E-marketplace implies a form of electronic trade on the Internet where goods and services can be bought and sold. M-marketplace refers to the mobile market, where trade takes place via mobile devices. These platforms are practical and offer a wide range of products worldwide. Delivery in the last mile can be generated by different systems of ordering goods (in person, by phone, by mail, by fax, interactive TV, etc.), initiated by ordering via the Internet, i.e., e/m-marketplaces [65].

Internet of Things (IoT) (A_8) involves connecting different entities to the Internet to exchange data and communicate with each other. This technology is applied in smart homes, industry, healthcare, etc. It is also widely applied in logistics [100]. In LML, it is used, among others, for real-time tracking, vehicle data collection, goods and security tracking, delivery assurance, virtual customer addressing, etc. [13].

Cloud Computing-supported management and control systems (CC-supported MCSs) (A_9) are technologies that help to manage and control business processes. These include software for inventory tracking, project management, data analytics, and similar tools that facilitate decision making and the efficient management of organizations. Systems such as electronic data interchange (EDI), enterprise resource planning (ERP), intelligent transportation systems (ITSs), etc., are used in LML independently or in integration with other technologies for the digitization and monitoring of activities in the logistics system, optimization of delivery time and distance, organization of crowd delivery, etc. [13].

The considered criteria are divided into three groups [32]: ***technological (C_1)***: organizational readiness, implementation complexity, security, degree of development, adaptability, integration possibility (modularity), standardization possibility; ***economic (C_2)***: investment costs, logistics services quality, impact on the labor market, efficiency of energy consumption; ***political–social (C_3)***: safety, regulatory framework, political framework, cultural framework, and environmental impact (Figure 2, Table 4).

Organizational readiness (C_{11}) determines the number of changes within the organization, such as changes in business procedures and operations, required to achieve the technology's full potential. Although almost all I4.0 technologies, in a certain sense, have disruptive characteristics significantly different from the previous ones, those that require more changes in the organization are less favorable. Additive manufacturing, advanced robotics, artificial intelligence, AGVs, and AVs imply significant organizational changes. Therefore, the score according to this criterion is lower than for other technologies.

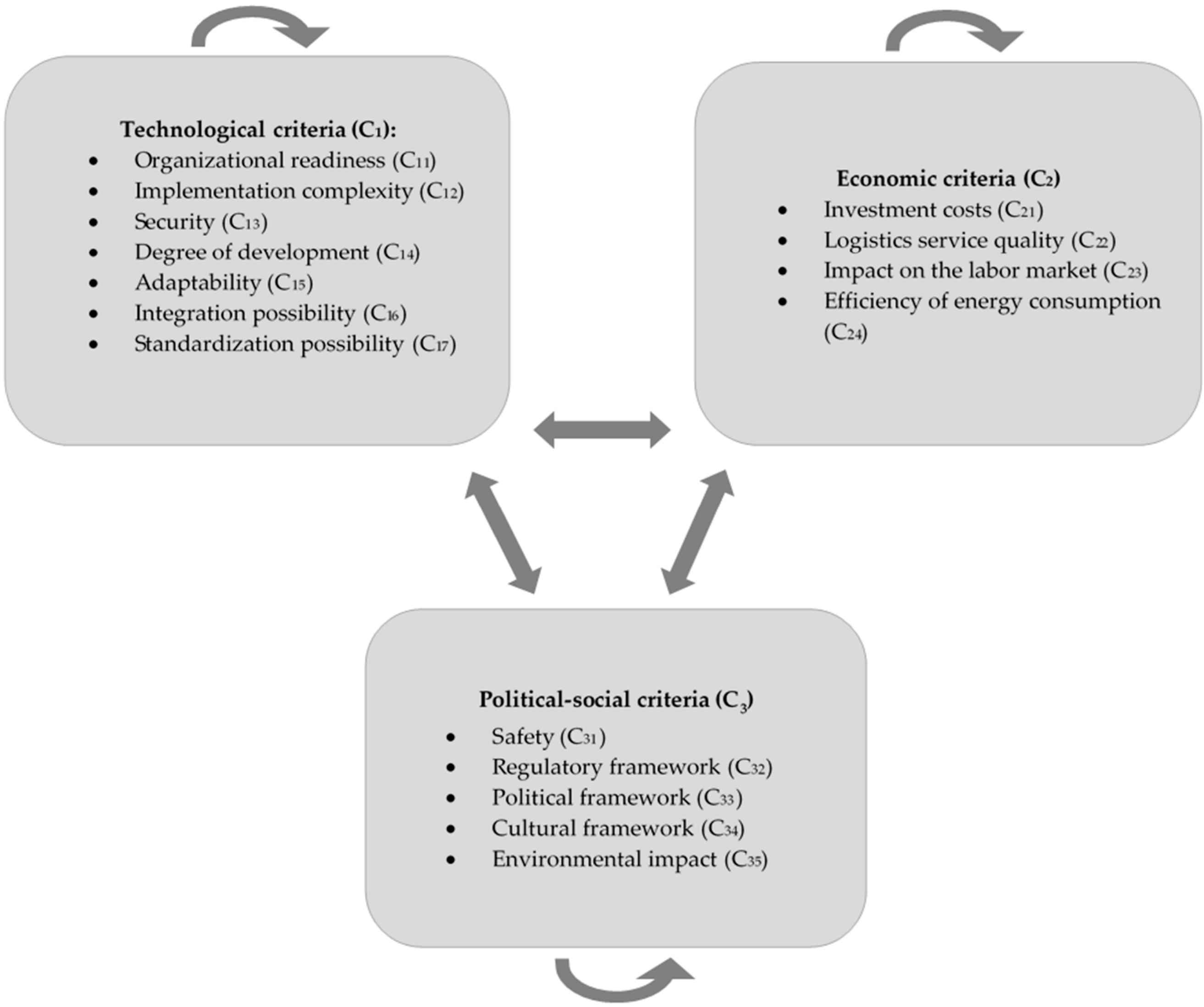

Figure 2. Criteria network.

Table 4. Criteria for evaluating alternatives.

Technological Criteria (C_1)	Description	Source(s)
Organizational readiness (C_{11})	The number of changes within the organization implies procedures, employees, etc., required to realize the full potential of the technology	[32,101–103]
Implementation complexity (C_{12})	The amount of effort required to implement the technology implies workforce training, software, hardware, and supporting systems	[32]
Security (C_{13})	Implies the vulnerability of technology to unauthorized download, misuse, or deletion of data	[32,101]
Degree of development (C_{14})	The degree of technology development, the activities for which it is applied, and the methods of application	[32]
Adaptability (C_{15})	Ability to modify and/or improve technology to adapt to changes in the business environment	[3,104]
Integration possibility (C_{16})	Compatibility and likelihood of joint application with other technologies and concepts	[32,101,104]
Standardization possibility (C_{17})	Possibility of standardization of technological aspects, such as processes, procedures, equipment, etc.	[32,103]
Economic criteria (C_2)	**Description**	**Source (s)**
Investment costs (C_{21})	Costs of equipment, software, worker training, technology development, and implementation	[32,103,105,106]
Logistics service quality (C_{22})	Reliability, speed, user needs understanding, flexibility, availability, accuracy, visibility, traceability, real-time monitoring, sustainability, etc.	[32,102,103]
Impact on the labor market (C_{23})	Effect on increasing or decreasing the number of jobs or their transformation	[32]
Efficiency of energy consumption (C_{24})	Degree of efficiency of use and protection of limited energy resources	[32,105]
Political–social criteria (C_3)	**Description**	**Source (s)**
Safety (C_{31})	Impact on the safety of the environment, population, ecosystem, facilities, workforce, etc.	[6,32]
Regulatory framework (C_{32})	Favorability of legal conditions at different levels	[6,32,101,103]
Political framework (C_{33})	Favorability of political conditions at different levels, influence of political entities, degree of political will	[32]
Cultural framework (C_{34})	Favorability of cultural conditions, degree of acceptance of innovations	[32,102,103]
Environmental impact (C_{35})	Effects on the environment in terms of greenhouse gases, noise, vibrations, particulate emissions, waste generation, space occupation, etc.	[6,32,101]

Implementation complexity (C_{12}) implies effort required to implement the technology, including finding the right workforce, training and education, software and hardware development, and developing and implementing various supporting systems [32]. Some technologies are particularly complex to implement due to the necessary and complex training (e.g., additive manufacturing) or the required infrastructure (e.g., specialized sensors and network infrastructure for IoT, infrastructure for the movement of AGVs and AVs, infrastructure for the takeoff and landing of drones, etc.). Some are somewhat simpler to implement, but even those face certain challenges (e.g., adapting to the specific organization's needs).

Security (C_{13}) refers to the vulnerability of technology in terms of the unauthorized download, misuse, or deletion of data. Most of the I4.0 technologies exchange a large amount of sensitive data and are therefore more or less susceptible to abuse by persons who want to harm their users or to achieve their benefit in some way. There are risks related to electronics, operating systems, and other software, networking, machines, and people [107], and they can refer to the introduction of the I4.0 concept or certain technologies. The level of risk of misuse, their potential consequences, ways, and complexity of solving risks and consequences determine the level of acceptability of technologies according to this criterion. The risks of endangering the security and privacy of data with technologies such as big data, IoT, and CC-supported MCSs are particularly pronounced, as are the risks of the unauthorized and harmful modification of the algorithms on which artificial intelligence, AR, and advanced robotics are based. Another important barrier to using drones concerns security and privacy issues [28,108].

Degree of development (C_{14}) implies the level of the technology development, i.e., whether it is in the stage of an idea, concept, pilot, or real-life application [32], as well as the areas and activities for which it is applied. Technologies in later stages of development and with a wider range of applications are more likely to be considered for LML. Technologies such as additive manufacturing are not sufficiently developed for widespread use in LML and are still in the pilot project phase. However, solutions widely used in LML are e/m-marketplaces, the main generators of deliveries in the last mile, and the CC-supported MCS. Other solutions that have already been implemented still have significant development potential but require improvements (e.g., security risks, challenges of full autonomy in the A4 alternative, etc.). Also, additional affirmation of adopting these technologies in LML is needed.

Adaptability (C_{15}) implies the possibility of modifying and/or improving technology to adapt to changes in the working environment [32]. Schließmann [109] believes that adaptability makes human work superior to technology. As in the case of the possibility of integration, adaptability is a desirable and often represented characteristic of all I4.0 technological solutions in LML, but there are also certain peculiarities and differences between technologies. For example, advanced robotics can be reprogrammed and adapted to different work tasks, types of goods, logistics units, etc. Artificial intelligence implies algorithms that can be easily changed. AR enables easy changes in the way that information is displayed. The inherent properties of additive manufacturing are adaptability and variability according to user needs. However, some experts emphasize the flexibility and adaptability provided by blockchain and IoT [110].

Integration possibility (modularity) (C_{16}) implies compatibility and the probability of joint application of I4.0 technologies, as well as application with other, earlier, current, or future technologies and concepts [32]. Highly compatible and modular technologies are significantly more favorable for application. Although one of the general characteristics and qualities of almost all I4.0 technologies is the possibility of integration, there are certain differences. Thus, additive manufacturing has a lower integration possibility than other technologies, while there are numerous integration examples of technologies, such as AI, CC-supported MCSs, and IoT [73,74,76,77,111].

Standardization possibility (C_{17}) refers to certain technological aspects, such as processes, procedures, or equipment [32]. Standardization is key to adopting I4.0 technologies [112]. The greater the standardization possibility, the more suitable the technology is for application in LML. A certain degree of standardization has been achieved in applying the technologies in question. However, additional standardization is being sought and worked on, which can be challenging due to various tasks. Standardization possibility is generally less, with technologies still at a lower level of development given that the characteristics of these technologies are still different, insufficiently uniform, etc.

Investment costs (C_{21}) include equipment, software, employee training, technology development, and implementation. Technologies that require higher investment, especially in the initial stages of implementation, are less favorable. Investments depend on the characteristics of the technologies. Thus, in the case of additive manufacturing, it is necessary to acquire printers, materials for production, modeling software, etc. In the application of IoT, the purchase and implementation of sensors and IoT devices for monitoring and collecting data on inventory, transportation, storage, etc., are required. The application of CC requires a subscription to cloud platform services, implementation, etc.

Logistics service quality (C_{22}) refers to various aspects, such as reliability, speed, understanding and analysis of user needs, flexibility, availability, accuracy, visibility, traceability, monitoring of logistics flows in real time, sustainability, etc. [32,113,114]. Although one of the main goals of applying I4.0 technologies in LML is precisely to increase the quality of logistics services, in this context, additive manufacturing, advanced robotics, artificial intelligence, and blockchain stand out, making a special contribution [113]. However, certain technologies can improve service quality, especially in certain areas of logistics (e.g., IoT in cold chain logistics) [115].

Impact on the labor market (C_{23}) implies the effect on increasing or decreasing the number of jobs or their transformation, i.e., potential simplification or complexity of work tasks, etc. Automation and digitization reduce the need for manual work, so there may be a reduction in the number of jobs [32]. On the other side, their introduction can lead to the transformation of work positions, i.e., the creation of new, simpler jobs, primarily in the field of technology supervision [110]. Since LML jobs can be physically demanding, highly automated technologies affect an aging workforce [116]. However, there are challenges in retraining and training the workforce, with the scale of these challenges depending on the complexity and user-friendliness of the technology. Opinions are divided about the impact of certain technologies on the labor market. Thus, while some experts believe that advanced robotics will completely replace people in warehouses, which will resemble "robot beehives", others believe that people and robots will perform work tasks together [110]. Based on the above, it can be concluded that the assessment of each technology according to this criterion reflects its effects on the number of jobs, complexity of work tasks, training needs, etc.

Efficiency of energy consumption (C_{24}) refers to the protection of limited energy resources, i.e., the use of alternative energy sources, the use of renewable energy, lower consumption, and better use of energy [32]. Technologies that enable more efficient energy consumption are significantly more favorable. Research shows that some technologies can reduce energy consumption to a greater extent, e.g., additive manufacturing [117], AR [118], and IoT [119,120], or, to a lesser extent, e.g., advanced robotics [121].

Safety (C_{31}) refers to the positive or negative impact of the technology application on the environment (population, ecosystem, facilities, etc.), the workforce involved in the process, etc. Although the goal is to maximize safety, none of the I4.0 technologies are absolutely safe. As already stated, most of these systems imply greater digitization and automation, that is, the performance of numerous functions without constant, direct human control. Given that technologies can often achieve greater precision, continuity, speed, and uniformity of work, they provide greater safety. However, the absence of direct and continuous control, numerous unresolved technical and technological challenges, insufficient worker adaptation to the new technologies, and malicious behavior of individuals aimed at taking control over technologies contribute to the fear of the I4.0 technologies application in LML. The main risks are the drone falling or being misused and consequently endangering the health and lives of people and the environment, displaying unwanted, confusing, and harmful information on AR devices, malicious modification of artificial intelligence algorithms and advanced robots, etc.

Regulatory framework (C_{32}) includes legal mechanisms at different levels (local, national, and international) and represents the legal basis and prerequisite for technology application. The essence of this criterion is legal obstacles and ways to solve them. The most common obstacles in this context are [122] the complexity of determining the subject, i.e., areas of legal regulation; the lack of developed legal categories and concepts; the problem of the inertia of legal regulation, i.e., the imbalance between the speed of adoption of laws and the fulfillment of expectations; the lack of legal means to minimize risks to people; the need to develop new criteria for the quality of legislation and the complexity of their definitions;

the lack of favorable national jurisdiction; and the problem of ensuring digital sovereignty. The evaluation of technologies depends on the extent of these obstacles and the complexity of their solutions. For example, legal challenges related to data security and privacy exist in technology applications such as CC and big data, particularly in the application of IoT [123]. Additionally, the greatest barrier to drone use is the lack of appropriate regulations [28].

Political framework (C_{33}) refers to the actions taken by administrations at different levels (city, state, and international) and other political actors to affirm or degrade certain technologies. The results of these actions are seen in the form of development strategies, plans, incentives, or subsidies [32], but also in positive or negative media campaigns. The support of the administration and political elites for the development of certain technologies in most countries leads to their wider application. However, resistance from certain, usually conservative, political subjects to technological development or certain achievements often affects the acceptability of I4.0 technologies among their followers.

Cultural framework (C_{34}) refers to tradition, historical development, value system, way of life, openness, propensity for innovation, etc. The acceptability of innovations depends not only on the technology type and characteristics but also on the culture or society in which they should be accepted. Technologies that require more radical changes in people's habits and perceptions tend to be less favorable and less acceptable. In this sense, technologies that directly replace and imitate human physical or mental work (advanced robotics, artificial intelligence), and especially delivery vehicles (AGVs, AVs, and drones) receive greater visibility and attention, and thus a greater number of well-founded or unfounded criticisms, which are most visible to end users. Some users do not have a high level of education and information about scientific and technological development. The good or bad cultural perception of certain technologies is also contributed by the user's experience with commercial applications. An example is the application of the well-known AR-based Pokemon game, which experienced great popularity among fans of the animated series of the same name but also received negative reviews and was even banned in some countries due to accidents during its use. Although the "fear of the unknown" and the new also exist when it comes to the application of technologies such as blockchain or big data, these technologies are largely related to computer systems, which have become widely accepted due to decades of mass application. Additionally, just as the positive aspects of technologies like drones are more obvious, representative, and attractive to the wider community, their negative aspects are also more in focus compared to technologies like big data. This is because the lack of knowledge, 'invisibility', and intangibility of such technologies contribute to less interest in the potential risks and dangers that they may bring.

Environmental impact (C_{35}) implies the effects of technology in terms of greenhouse gases, noise, vibrations, particle emissions, waste generation, occupation of public spaces, etc. At the same time, there are effects of exploitation, but also effects of the production and implementation of technologies and the infrastructure that they require. Automation, digitization, and integration, as the basic processes and characteristics of I4.0 technologies, require the introduction of new equipment and infrastructure, which, on the other side, leads to the additional consumption of materials, energy, issues of dealing with old equipment, etc. [124]. The impacts of I4.0 technologies on the environment are twofold [121], which could be explained using the drone example. Although the application of drones reduces the use of road transport and its numerous negative effects on the environment, there are also some bad environmental effects. The range and payload of drones for commercial delivery are still small. Therefore, their application requires the construction of many logistics centers, which implies the occupation of significant space. Also, research indicates that the toxicity caused by the production of drone parts is not negligible [125]. Finally, drones can threaten parts of the ecosystem (e.g., birds) and create noise.

To define the input data (existence and intensity of mutual influence and dependence of the criteria, their importance, and evaluation of alternatives according to them), 30 experts with different years of experience were interviewed, half of them from the field of LML, or city logistics, and half from the field of I4.0 (Table 5).

Table 5. Characteristics of focus group members.

Sector	Number of Experts	Years of Experience
Last-mile logistics/City logistics	4	<5
	6	5–15
	5	>15
Industry 4.0	4	<5
	7	5–15
	4	>15

They determined whether there is mutual dependence between the criteria, both within groups of criteria and between them (Table A1). Most experts from the first sector were primarily guided by the technological functionalities, possibilities, and advantages of applying technologies in city logistics and LML. That is why these experts gave the greatest importance to technological criteria and investment costs, as an unavoidable economic criterion, but also to criteria more directly related to logistics, such as logistics service quality. For all experts in this sector, the technological criteria of implementation complexity and organizational readiness are among the most important, and are largely expected and logical, but also indicative, bearing in mind their personal professional experiences, knowledge of business practice, its organizational aspects, and development projects. However, as expected, the technological criteria had the greatest importance for experts in the field of I4.0. These experts also consider implementation complexity and organizational readiness, characterized by a strong mutual connection, to be very important. That is why these two criteria gained the most importance in the combined evaluations of the two sectors. Most experts from both sectors also highlighted the safety criterion as important, which is justified considering the importance of protecting people, property, and the environment from potential safety risks.

An example of the evaluation of the importance of criterion C_{11} according to criterion C_{17} by experts from both sectors is shown in Table 6. For easier notation, the evaluation labels $\overset{\sim i,j}{E_k}$ are shown as E_k. The arithmetic mean of the evaluations of all experts is equal (5.83, 6.83, 7.83), so the evaluation (6, 7, 8), i.e., "High" (H), was taken as the unit evaluation of the entire focus group. The arithmetic mean of city logistics/LML experts' evaluations (6.27, 7.27, 8.27) is slightly higher, and the arithmetic mean of I4.0 experts' evaluations is slightly lower (5.40, 6.40, 7.40) than the arithmetic mean of all experts' evaluations. According to experts from the first sector, the importance of organizational readiness concerning standardization possibility is "High" while, according to experts from the second sector, it is "Fairly high".

Table 6. Evaluations of the importance of criterion C_{11} in relation to criterion C_{17} by experts.

Last-Mile Logistics/City Logistics															
E_{11}	E_{14}	E_4	E_{13}	E_3	E_6	E_7	E_{12}	E_2	E_4	E_5	E_8	E_{10}	E_1	E_9	mean
(4, 5, 6)	(4, 5, 6)	(5, 6, 7)	(5, 6, 7)	(6, 7, 8)	(6, 7, 8)	(6, 7, 8)	(7, 8, 9)	(7, 8, 9)	(7, 8, 9)	(7, 8, 9)	(7, 8, 9)	(7, 8, 9)	(8, 9, 10)	(8, 9, 10)	(6.27, 7.27, 8.27)
"M"	"M"	"FH"	"FH"	"FH"	"H"	"H"	"VH"	"VH"	"VH"	"VH"	"VH"	"VH"	"EH"	"EH"	"H"
Industry 4.0															
E_{17}	E_{22}	E_{16}	E_{20}	E_{25}	E_{28}	E_{15}	E_{18}	E_{19}	E_{21}	E_{23}	E_{24}	E_{30}	E_{26}	E_{29}	mean
(3, 4, 5)	(3, 4, 5)	(4, 5, 6)	(4, 5, 6)	(4, 5, 6)	(4, 5, 6)	(5, 6, 7)	(5, 6, 7)	(6, 7, 8)	(6, 7, 8)	(7, 8, 9)	(7, 8, 9)	(7, 8, 9)	(8, 9, 10)	(8, 9, 10)	(5.40, 6.40, 7.40)
"FL"	"FL"	"M"	"M"	"M"	"M"	"FH"	"H"	"H"	"H"	"VH"	"VH"	"VH"	"EH"	"EH"	"FH"

Based on focus group interviews, criteria comparison matrices were defined by pairs (Equations (1) and (2)). The pairwise comparison of groups and the criteria within groups are shown in Table 7. In the same way, a comparison of pairs of criteria belonging to different groups was performed. They were then transformed into fuzzy triangular numbers according to Table 3.

Table 7. Mutual comparison of criteria and groups of criteria.

Technological Criteria							
	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}
C_{11}		“N”	“L”	“FL”	“M”	“H”	“H”
C_{12}			“L”	“FL”	“M”	“H”	“H”
C_{13}				“L”	“FL”	“FH”	“FH”
C_{14}					“L”	“FL”	“FL”
C_{15}						“VL”	“VL”
C_{16}							“N”
C_{17}							

Economic Criteria				
	C_{21}	C_{22}	C_{23}	C_{24}
C_{21}		“L”	“M”	“FH”
C_{22}			“FL”	“FH”
C_{23}				“VL”
C_{24}				

Political and Social Criteria					
	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}
C_{31}		“N”	“FL”	“M”	“H”
C_{32}			“L”	“FL”	“FH”
C_{33}				“FL”	“M”
C_{34}					“FL”
C_{35}					

Criteria Groups			
	C_1	C_2	C_3
C_1		“L”	“FL”
C_2			“VL”
C_3			

Based on Equations (3)–(6), the logarithms of these matrices, the membership functions of approximate triangular fuzzy numbers, the priority vector, and the minimum degree of membership are obtained, respectively. After that, the minimum membership degree is maximized with the given constraints (Equations (7) and (8)). To avoid the membership degrees taking a negative value, additional variables are introduced to fulfill Equation (9). Since the values of deviation variables should be as small as possible, a nonlinear priority model based on LFPP is introduced to calculate the weight (Equation (10)). Then, according to Equation (11), the normalized weights for the matrix $\widetilde{A}$ are determined. Based on Equations (12) and (13), the consistency index and coefficient are calculated. For all criteria comparison matrices, the values of this coefficient are less than 0.1, which means that the evaluations are consistent. The result of applying the ANP method is the criteria weight vector [0.130, 0.192, 0.070, 0.061, 0.016, 0.009, 0.010, 0.103, 0.047, 0.031, 0.015, 0.106, 0.067, 0.043, 0.082, 0.016] for C_{11}, C_{12}, . . ., C_{34}, and C_{35}, respectively.

Overall evaluations of the alternatives according to the criteria, obtained after interviewing the focus group in the same way as in the case of criteria, are given in Table 8. It can be seen that there are no drastic differences in the evaluations of the alternatives according to the criteria; that is, most of them range from “Fairly low” (3, 4, 5) to “Very high” (7, 8, 9). The opinions of experts from the first sector are mostly influenced by their experiences and knowledge about the qualities and risks of applying certain technologies in LML, which they confirmed. Although there were similarities in many evaluations between the two sectors, experts from the second sector influenced the structure of alternatives evaluations toward a more critical attitude. This is certainly a consequence of better knowledge of the various features of these technologies and important aspects of their development. It is interesting that experts from the first sector with fewer years of experience better favored solutions with great visual appeal, such as augmented reality and autonomous vehicles, than the rest of the experts from the same sector and experts from the second sector, who make up the majority and whose evaluations are therefore certainly influenced by the better ranking of other alternatives.

Table 8. Alternatives evaluation (ADAM method).

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}
A_1	“FL”	“FL”	“VH”	“L”	“VH”	“H”	“M”	“FL”	“VH”	“FL”	“EH”	“H”	“FH”	“FH”	“M”	“H”
A_2	“M”	“H”	“FH”	“FH”	“EH”	“VH”	“FH”	“FL”	“EH”	“M”	“H”	“FH”	“M”	“H”	“M”	“FH”
A_3	“M”	“H”	“M”	“H”	“EH”	“EH”	“VH”	“FL”	“EH”	“H”	“VH”	“M”	“FL”	“FH”	“M”	“H”
A_4	“M”	“FL”	“M”	“H”	“FH”	“VH”	“FH”	“M”	“H”	“M”	“FH”	“M”	“FL”	“FH”	“M”	“M”
A_5	“H”	“H”	“M”	“H”	“EH”	“VH”	“VH”	“H”	“FH”	“VH”	“FH”	“FH”	“M”	“H”	“VH”	“VH”
A_6	“FH”	“VH”	“H”	“FH”	“VH”	“H”	“FH”	“H”	“EH”	“VH”	“FH”	“VH”	“H”	“H”	“VH”	“VH”
A_7	“H”	“H”	“H”	“VH”	“EH”	“EH”	“H”	“H”	“FH”	“FL”	“FH”	“H”	“EH”	“VH”	“EH”	“EH”
A_8	“H”	“FL”	“FH”	“EH”	“VH”	“EH”	“VH”	“FH”	“VH”	“FH”	“EH”	“H”	“L”	“FH”	“H”	“VH”
A_9	“VH”	“M”	“M”	“VH”	“EH”	“VH”	“H”	“H”	“H”	“H”	“H”	“VH”	“FH”	“EH”	“VH”	“VH”

The values shown in Table 8 are transformed into fuzzy values according to Table 3 (Equation (14)). Then, these values are normalized (Equations (15) and (16)) and sorted in descending order (Equation (17)). Then, fuzzy coordinates of the fuzzy reference $\widetilde{O}_{qj}$ and fuzzy weighted reference $\widetilde{N}_{qj}$ points are determined, which are used to form complex polyhedra for each alternative (Equations (18) and (19)). Then, the fuzzy values of the volumes of complex polyhedra are obtained (Equations (20)–(34)). Finally, based on the crisp values of the alternatives (Equation (35)) and the software application, the final ranking is obtained (Table 9).

Table 9. Ranking of alternatives according to criteria (ADAM method).

Alternatives	Volume	Rank
A_1	0.026570	7
A_2	0.026451	8
A_3	0.027665	6
A_4	0.021221	9
A_5	0.032206	4
A_6	0.033538	3
A_7	0.037400	1
A_8	0.031686	5
A_9	0.035496	2

When solving various mathematical problems, a small change in the input data can lead to significant changes in the results, which may indicate that the solution is not stable enough. Therefore, a sensitivity analysis of the obtained solution was carried out. In addition to the basic scenario (Sc. 0), the results of which were previously presented, 18 other scenarios were defined (Table 10).

Table 10. Criteria weights in scenarios.

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}
Sc. 0	0.13	0.192	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 1	0.13	0.144	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 2	0.13	0.096	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 3	0.13	0.048	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 4	0.13	0	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 5	0.098	0.192	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 6	0.065	0.192	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 7	0.033	0.192	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 8	0	0.192	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 9	0.13	0.192	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0.08	0.067	0.043	0.082	0.016
Sc. 10	0.13	0.192	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0.053	0.067	0.043	0.082	0.016
Sc. 11	0.13	0.192	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0.027	0.067	0.043	0.082	0.016
Sc. 12	0.13	0.192	0.07	0.061	0.016	0.009	0.01	0.103	0.047	0.031	0.015	0	0.067	0.043	0.082	0.016
Sc. 13	0.13	0.192	0.07	0.061	0.016	0.009	0.01	0.077	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 14	0.13	0.192	0.07	0.061	0.016	0.009	0.01	0.052	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 15	0.13	0.192	0.07	0.061	0.016	0.009	0.01	0.026	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 16	0.13	0.192	0.07	0.061	0.016	0.009	0.01	0	0.047	0.031	0.015	0.106	0.067	0.043	0.082	0.016
Sc. 17	0	0	0.07	0.061	0.016	0.009	0.01	0	0.047	0.031	0.015	0	0.067	0.043	0.082	0.016
Sc. 18	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063

In the scenarios of Sc. 1–Sc. 4, the weight of criterion C_{12} was reduced by 25%, 50%, 75%, and 100%, respectively. In the next 12 scenarios, the same procedure was performed for the next three most important criteria (C_{11}, C_{31}, and C_{21}). In the penultimate scenario (Sc. 17), the four most important criteria were excluded from the analysis while, in the last one, the importance of all was equal. The ranking of alternatives by scenario is shown in Table 11 and Figure 3.

Table 11. Ranking alternatives in different scenarios.

Sc.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
A_1	7	7	7	7	8	7	7	7	7	7	7	7	7	7	7	8	8	7	7
A_2	8	8	8	8	7	8	8	8	8	8	8	8	8	8	8	7	7	8	8
A_3	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
A_4	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
A_5	4	4	4	4	4	4	4	4	5	4	4	4	4	4	4	4	4	4	3
A_6	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	5
A_7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
A_8	5	5	5	5	5	5	5	5	4	5	5	5	5	5	5	5	5	5	4
A_9	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

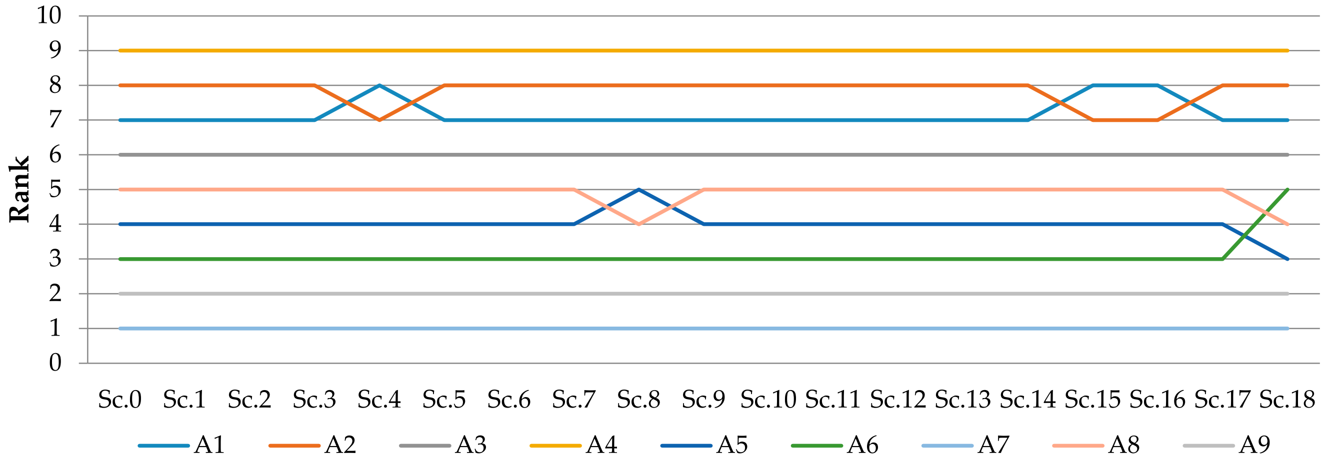

Figure 3. Sensitivity analysis.

5. Discussion

It is certain that the results of the application of the model, i.e., the ranking of the e/m-marketplaces and CC-supported MCS as the two best variants, are the result of already developed applications. The technological, economic, political, and social challenges of their application have already been addressed in logistics practice. The first-ranked technology is one of the basic generators of last-mile deliveries while the second-ranked is widely used in last-mile distribution logistics systems. However, the ranking of blockchain technology indicates that even technologies not yet widely accepted in LML have extraordinary potential. Interestingly, the four worst-ranked alternatives (A_1–A_4) are precisely those technologies that are considered visually attractive and modern, which companies often highlight as examples of innovation in their own logistics practices and which are the favorites of logisticians and, to an even greater extent, of those who do not have logistics education or experience. Although these technologies undoubtedly have importance and great potential for application in LML, this indicates that the selection of I4.0 technology cannot be based only on aesthetic and marketing-promotional criteria but must be the subject of a deeper analysis.

One of the theoretical implications of the research is the possibility of applying the mathematical model defined for similar or different problems in different areas. Another theoretical implication is identifying technologies that require additional research attention, both those recognized as most suitable for application and those ranked as the lowest. The latter represent areas where overcoming obstacles to broader adoption is necessary. The results indicate that there are problems in the application of additive manufacturing, AI, AR, AGVs, AVs, and drones in LML from the aspects of implementation complexity, standardization, and safety, but also from economic, political, and social aspects, and it requires further investigation of the ways for overcoming them.

Similarly, a practical implication of the results is the recommendation and motivation of companies to adopt certain I4.0 technologies for LML, whose implementation can bring the greatest benefits. Additionally, it involves highlighting the nature of these benefits (high scores according to the criteria). However, it can be useful for companies to see the shortcomings (bad ratings according to the criteria) of these and other, lower-ranked technologies, which can be part of their plans, pilot projects, and practices. If companies do not evaluate all technologies according to all significant criteria, their investment in them could be futile, pointless, and economically destructive. Applied technologies, instead of an instrument for improving system efficiency, could be a useless innovation, which could even damage the company's image.

The ranking of the e/m-marketplace and CC-based MCS as the best alternatives indicates that these technologies are becoming, or already are, the business standard of companies that provide LML services. The best ranking of the e/m-marketplace indicates that companies should develop electronic, multi-channel, and/or omni-channel sales in order not to lose a step [126]. Considering the massive use of smartphones, developing quality, user-friendly mobile applications is especially important. However, CC-based MCSs are increasingly important in the context of large volumes of data in logistics and supply chains, which need to be stored and managed, as well as the necessary support for making various decisions. Blockchain as a third-ranked technology should be included in the practice of companies that provide LML services and other companies in supply chains due to the growing demands for visibility, transparency, and sustainability in the supply chain, which this technology can provide [127].

Greater interest in I4.0 technologies in LML, both in research and practice, can lead to overcoming the shortcomings, increasing the positive effects of application, and increasing and differentiating possibilities and application methods. Moreover, solving challenges related to one criterion can lead to, or be a catalyst for, improvement in other aspects. For example, by solving technological challenges related to adaptability and integration possibility, the degree of development of technologies increases, which, on the other side, can lead to a reduction in investment costs. Given that criteria related to the broader social and natural environment (political, regulatory, cultural framework, environmental impact) were also considered, the model results may have implications that surpass those of researchers and companies. Primarily, they can be indicative and suggestive for institutions and governments that can influence I4.0 technologies and their application in different ways (incentives for research into certain aspects of application, development, and implementation projects, work on overcoming regulatory obstacles to mass application, etc.).

The model limitation, and thus the space for the expansion and improvement of the defined model, is taking into account only investment costs but not the costs of operation and maintenance of technologies. Additionally, the model considers the overall ratings of the focus group, composed of various experts, researchers, and practitioners. However, it does not differentiate between the stakeholders, their perspectives, and their objectives as decision-makers.

6. Conclusions

The selection of the right I4.0 technology in LML is one of the critical success factors for companies that want to stay competitive and meet the growing and changing demands of consumers. However, considering the variety of existing I4.0 technological solutions, the trends, and the additional development potential, this decision represents a complex multi-criteria task. Through a detailed analysis of various technological options, this paper offers guidelines for making this kind of decision.

This paper's main goals and contributions in terms of previous research in MCDM, LML, and I4.0 are defining an innovative hybrid MCDM model, which is used to select I4.0 technology for LML, and taking into account a wide range of alternatives and criteria. By describing and evaluating alternatives according to criteria, this paper provides insight into the benefits, shortcomings, and challenges of I4.0 technologies in LML. As such, it can be indicative of further research in the field but also provide good support in shaping the strategies, investments, and development projects of companies and governments.

According to the shortcomings and limitations of the model mentioned in the previous section, the subjects of future research may be extensions or modifications of the model to respect the complete costs. Also, it is necessary to obtain a clearer picture of the stakeholders' viewpoints on the observed issue through their integration into the decision-making process. Thus, the model should be upgraded to consider the opinions of experts in I4.0 and LML and other important actors (representatives of governments, inhabitants, etc.). It would be useful and interesting to consider the benefits of various applications of I4.0 technologies in logistics using the defined or new mathematical model. In conditions of growing natural, climatic, political, and socio-economic challenges, humanitarian logistics has received increasing significance and attention, so the application of the I4.0 technologies in this area should be the focus of researchers and practitioners. When defining the model for this decision, the differences between the commercial and humanitarian sectors (non-profit goals, heavier measurability and performance monitoring, dependence on donations, high degree of unpredictability, greater requirements for speed and flexibility, often increased safety risks, etc.) should be taken into account. Also, household logistics represents a fertile application area for I4.0 technologies and thus for a model similar to the one defined in this paper. People are already implementing I4.0 technologies (e.g., IoT) in their homes, and there is potential for additional applications. Households represent logistics systems that are ubiquitous. Household logistics is an important area, but it is still unknown, underdeveloped, and unstructured. Therefore, it requires greater interest, among others, in the sphere of the application of I4.0 technologies, and the selection of the most favorable of them can be the subject of future research. As in the case of humanitarian logistics, it is also necessary to respect the specifics of the problem (the household is not a classic logistics system with large-scale flows but a place where people live daily, etc.).

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Appendix A

Table A1. Matrix of mutual influence of criteria.

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}
C_{11}		+	+	+	+	+	+	+	+	+	+	+		+	+	+
C_{12}	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+
C_{13}	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+
C_{14}	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+
C_{15}	+	+	+	+		+	+	+	+	+	+	+			+	+
C_{16}	+	+	+	+	+		+	+	+	+	+	+				+
C_{17}	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+
C_{21}	+			+						+					+	
C_{22}		+	+	+											+	
C_{23}	+	+	+	+	+		+	+	+		+	+	+	+	+	
C_{24}	+	+		+			+	+								+
C_{31}	+	+	+	+	+	+	+	+	+	+	+		+	+	+	+
C_{32}		+	+	+								+		+	+	+
C_{33}		+		+				+		+		+	+		+	+
C_{34}		+		+						+	+	+	+	+		+
C_{35}		+		+				+				+	+	+	+	

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