A Novel Hybrid MCDM Model for the Evaluation of Sustainable Last Mile Solutions

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Research Article

A Novel Hybrid MCDM Model for the Evaluation of Sustainable Last Mile Solutions

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Modern social trends are intensively transforming supply chains and the last mile as their most complex and most expensive segment. For the realization of the last mile, various solutions can be defined which combine initiatives, technologies, and concepts of city logistics. The successful implementation of these solutions depends on the characteristics of the city, the goals of stakeholders, and the ability to achieve economic, social, and environmental sustainability. In accordance with that, this paper defines innovative sustainable last mile solutions and evaluates their potential application in the real-life logistics system of the city. As evaluation requires consideration of a large number of criteria, this is a problem of multicriteria decision-making, and for solving it, a novel hybrid model that combines Delphi, FARE (Factor Relationship), and VIKOR (Višekriterijumska Optimizacija i Kompromisno Rešenje) methods in the fuzzy environment has been developed. The applicability of the model is demonstrated in the example of evaluating the last mile solution for the central business district of the City of Belgrade. A combination of microconsolidation centers and autonomous vehicles is obtained as the most favorable solution.

1. Introduction

Globalization, growth of consumer society, the shift of production paradigm based on individualization, personalization and shorter product life, development of the industry 4.0 based on technological progress, automation, digitalization, networking and new forms of communication, development of e-commerce, sustainability, and other modern trends intensively transform the ways of realization of goods and transport flows. Requirements for efficient realization of supply chains are becoming increasingly strict, which is especially expressed in the realization of the last mile as their most complex and most expensive segment. The last mile is realized in the urban environments that are characterized by various economic, geographical, sociological, cultural, historical, and demographic features, architectural heritage, habits, and perceptions of the population, etc. [1]. In addition, there are various stakeholders in the cities (users, logistics providers, residents, and city administration) whose goals define the requirements for planning and implementation of the last mile in accordance with the principles of economic, social, and environmental sustainability. Accordingly, the subject of this paper is the creation of sustainable last mile solutions (LMSs) by combining different initiatives, technologies, and concepts of city logistics (CL). The goal is to evaluate and rank them and analyze the possibility of their application in the real-life logistics system of the city.

As it requires consideration of a large number of criteria, the problem of multicriteria decision-making (MCDM) is defined in the paper. The existing literature demonstrated many examples of combining different MCDM methods, but there are no examples of combining the FARE (Factor Relationship) with Delphi and VIKOR (Višekriterijumska Optimizacija i Kompromisno Rešenje) methods. Furthermore, the scientific literature lacks articles that define innovative, sustainable LMSs and evaluate them from a multicriterial perspective. This article fulfills these research

gaps by defining innovative and potentially sustainable LMSs and evaluating them through a wide set of defined criteria with a novel hybrid model that combines Delphi, FARE, and VIKOR methods in the fuzzy environment. The applicability of the model is demonstrated in the example of ranking sustainable LMSs in the City of Belgrade. A combination of microconsolidation centers and autonomous vehicles was obtained as the most favorable solution in relation to the observed criteria.

The paper is organized as follows: Section 2 provides an overview of the literature on the methods that make up the MCDM model and the initiatives, technologies, and concepts that form the sustainable LMSs. After that, in Section 3, the structure of the defined model is given and the steps of its application are described. Section 4 describes the LMSs applicable in the City of Belgrade, as well as the criteria for their evaluation. The application of the model for solving the defined problem and the sensitivity analysis are also presented in the same section. Sections 5 and 6 discuss the achieved results and the conclusions and directions for future research, respectively.

2. Literature Review

This section provides an overview of the literature on recent applications of MCDM methods, the methods that make up the proposed hybrid MCDM model, concepts, technologies, and initiatives that could be combined to form sustainable solutions for the realization of the last mile, as well as the criteria for their evaluation.

2.1. Overview of Recent MCDM Method Applications. Using MCDM methods for solving multicriterial problems is a popular topic in the existing literature [2]. Besides the conventional form, the developed MCDM models in the literature were also applied in various uncertainty environments—fuzzy, grey, rough, neutrosophic, etc. [3]. Novel MCDM methods [4] and hybrid models [5] are regularly proposed in the literature for solving decision-making problems in various fields.

The long-established and widely accepted MCDM methods, such as AHP, TOPSIS, and VIKOR, find extensive application to this day. In recent years, the AHP method was used for selecting routes for oversized cargo transport [6], identifying the most relevant sustainability issues [7], selecting sustainable projects [8], etc. The TOPSIS method found its application for reverse logistics performance evaluation [9], policy selection for developing electric vehicle systems [10], supplier selection [11], etc. The VIKOR method was recently used for risk evaluation [12], selection of supplier portfolio of key outsourcing parts [13], selection of industrial robots [14], etc. The existing literature is also abundant in newly introduced methods such as CODAS [15], KEMIRA [16], PIPRECIA [17], and MARCOS [18]. Aside from applying MCDM methods independently, many literature articles propose and develop hybrid MCDM models by combining two or more MCDM methods. Various MCDM models can be found in the literature, such

as DEMATEL-AEF-VIKOR [19], SERVQUAL-AHP-TOPSIS [20], DANP-FUCOM-VATOPSIS [21], SSC-VIKOR [22], SWARA-MARCOS [23], and KEMIRA-BWM-MOORA [24].

2.2. Overview of the Methods That Make Up the MCDM Model. The paper proposes a novel hybrid MCDM model that combines the fuzzy Delphi, fuzzy FARE, and fuzzy VIKOR methods. The fuzzy FARE method was used in the first part of the model to evaluate and determine the weights of the criteria. As the evaluation of the criteria is performed by several decision-makers (stakeholders' representatives), the Delphi method was used to consolidate their evaluations. The fuzzy VIKOR method was used in the second part of the model to evaluate, rank, and select the most favorable alternative in relation to the defined criteria.

The FARE method was developed by Ginevičius [25], and it is based on defining the relationship between all decision-making elements (criteria, subcriteria). In the first phase of the application, the method requires a minimum amount of initial data (evaluations) by the experts on the existence of influences between individual decision-making elements, as well as their direction and strength [26]. In later phases, the influences between other elements of decision-making are analytically determined on the basis of these evaluations. In this way, there is a drastic reduction in the required evaluations by experts [27]. The main advantages of the method, compared to the other methods based on the pairwise comparison of decision-making elements, e.g., AHP and ANP, are a small number of necessary evaluations, elimination of contradictions that occur in the comparison matrices, high reliability, consistency, and stability of the obtained results, etc. [26–28]. Due to the stated advantages, FARE was chosen in this paper for evaluation and determination of the criteria weights. However, as with other methods based on expert evaluation, the problem may arise due to ambiguous or unclear assessments, which can be solved by applying fuzzy logic. Therefore, the fuzzy extension of the FARE method, performed by Roy et al. [29], was used in the paper. The FARE method has found wide application in the literature and has so far been used, either alone or in a combination with other methods, either in conventional form or in the fuzzy environment, in various areas for evaluation and selection of 3PL providers [29], selection of production materials [30], evaluation of mechanical processes [27], evaluation of the impact of technology transfer on the value creation [31], selection of political candidates [5], evaluation of visibility in freight vehicles [32], etc.

The Delphi method was developed by Dalkey and Helmer [33] and is generally used to iteratively process decision-makers' opinions until a consensus is reached on the subject of the research [34]. The method is defined as a process of group communication in which the convergence of opinions on a specific real-life problem is achieved. It is suitable for forming consensus through a series of questionnaires which in several iterations collect data from a group of selected respondents (experts). The main advantages of the method

are anonymity, iteration, controlled feedback, statistical group responses, and stability in the decisions of decision-makers on a given topic [35]. The main disadvantages of the method are the need for multiple repetitions of the questionnaire in order to achieve convergence of evaluations and high costs of data collection, especially for large and complicated problems and ambiguity and uncertainty in the assessment by experts [35, 36]. One way to overcome these shortcomings is to extend the Delphi method to the fuzzy environment, which was performed by Murry et al. [37]. The Delphi method, alone or in combination with other methods, in conventional form or in the fuzzy environment, has been used in various fields to evaluate renewable energy development projects [38], locate terminals [39, 40], select plant layout [41], define typical structures of intermodal terminals [42], evaluate battery storage systems [43], plan intermodal terminals [44], etc.

The VIKOR method was developed by Opricovic [45] and is based on the ranking and selection of alternatives in relation to numerous, in most cases conflicting, and mutually incomparable decision-making criteria and determines a compromise solution to the problem. The obtained compromise solution can be accepted by the decision-maker because it achieves the majority maximum group utility and minimum individual regret of the opposing parties. The main advantages over other methods most commonly used to rank alternatives, e.g., ELECTRE, PROMETHEE; TOPSIS, etc., are stability, simplicity in the use of cardinal information, obtaining a unique solution, obtaining the final order of alternatives, obtaining the solution that is closest to the ideal solution, etc. [46–49]. As with the previous methods, one of the biggest problems of the conventional VIKOR method is the impossibility of adequate perception of inaccuracies in the evaluations of decision-makers, which is solved by applying fuzzy logic. The fuzzy extension of the VIKOR method was performed by Opricovic [50]. The VIKOR method is very popular and has been widely used in the literature in various areas for machine tool selection [51], evaluation of sustainable city logistics initiatives [52], health services [53], intermodal transport technology [54], risk management projects [55], CL conceptions [56], etc.

There are no examples in the literature of combining the FARE method with Delphi or VIKOR methods, either in conventional form or in the fuzzy environment. Accordingly, the development of a novel MCDM model that combines these three methods in the fuzzy environment is one of the main contributions of this paper.

2.3. Last Mile Solution Sustainability. Based on different initiatives, measures, technologies, concepts, approaches, etc., a large number of practical solutions can be defined in CL, and even within a single solution, it is possible to define several different scenarios [57]. CL solutions are not universal—solutions that are proven good for particular urban areas can perform significantly worse in others [56, 58, 59]. The key to finding high-quality solutions for CL problems is in the compromise between the goals of stakeholders as well as in the balance among the

identified demands and available resources [60]. A portion of the existing literature research focused on the selection of adequate last mile delivery solutions from a set of individual technologies and measures (e.g., [61–63]). Some research focused on the selection of the most appropriate initiatives from the defined CL initiative groups (e.g., [64, 65]). Most of the existing research focused on individual initiatives and technologies, but there are also examples that analyzed more complex CL solutions, defined by combining different initiatives, measures, and technologies.

The paper [66] analyzed the application of different drone-based CL solutions through a wider set of CL performances. The paper highlights that multiechelon CL solutions can achieve sustainability but require the definition of appropriate regulatory frameworks, especially for the application of autonomous vehicle technologies. Different CL solutions that take into account specific characteristics of the city and the environment are analyzed in the paper [56]. The goal was to find the best CL solution for the City of Belgrade for all stakeholders, but with regard to all the factors that describe the urban area. The solutions combined different categories of logistics centers, the concepts of consolidation, and the application of environment-acceptable transportation technologies. The problem of selecting the most appropriate solution for the logistics system in the central business district of Belgrade is solved in [67]. Different multiechelon systems, with different consolidation levels and the application of different transport technologies, are taken into account. The paper in [68] focused on the selection of the most appropriate CL solution for the City of Brussels where different configurations of urban consolidation centers and their combination with several vehicle categories, toll charging, and time access restrictions are taken into account. The selection of the most appropriate horizontal cooperation model between urban consolidation centers for the City of Bucharest is covered in the paper [69], while the paper in [70] analyzes the sustainability of the urban consolidation center in Copenhagen in scenarios that vary according to the measures of access restrictions for commercial vehicles, toll charging, and the number of public sector subsidies. In the paper [71], a last mile delivery solution that combines parcel lockers and electro-powered cargo cycles is analyzed for the case of Hannover.

A review of the most analyzed initiatives, technologies, and concepts of CL, as well as some of the new ones that stand out as the potential future solutions, is presented in Table 1.

The presence of multiple stakeholders, with often conflicting goals, gives a multicriterial dimension to the problems of selecting the most appropriate CL solutions [129]. Various criteria can be defined for solving CL problems, and those most widely used are presented in Table 2.

There are no papers in the literature that deal with defining innovative and complex sustainable solutions for the realization of the last mile, nor their evaluation by applying a wide set of criteria. This is done below on a real-life example and represents one of the main contributions of this paper.

TABLE 1: Review of CL initiatives, concepts, and technologies.

Initiative/technology/concept	Type	Literature
Cooperation	—	[72, 73]
Consolidation	Urban consolidation centers	[69, 70, 74–76]
	Microconsolidation	[77, 78]
Crowdsourcing	—	[79–86]
Inland waterway transport	—	[87–90]
Rail transport	Regular tram lines	[91–93]
	Integrated rail systems	[94]
	Cargo-hitching	[95, 96]
Parcel lockers	—	[71, 97–100]
Eco-vehicles	Electric	[101]
	Hydrogen	[102]
	Hybrid	[103]
	Cargo bicycles	[104–107]
	Cargo bikes	[108, 109]
	Scooters	[110]
	Rickshaws	[111]
Autonomous vehicles	Ground autonomous vehicles	[112–115]
	Aerial autonomous vehicles (drones)	[66, 112, 116–123]
Underground logistics systems	—	[124–129]

TABLE 2: Relevant criteria review.

Criteria group	Criteria	References
Technical	Efficiency (loading factor, trip effectiveness, volume of goods handled)	[61, 62, 65, 66, 129]
	Reliability, flexibility, customer coverage	[61, 64, 65]
	Service quality, service level, delivery time	[56, 57, 61–63, 65–67, 69, 129]
	Possibility of implementation, operative barriers, issues related to the lack of infrastructure	[56, 62]
	Modal split of transport work	[56, 66]
	Goods flow transformation degree	[56, 66, 67]
	Traceability, Information security	[62]
Economic	Costs (operational, implementation, land and equipment acquisition, staff training, insurance, taxes)	[56, 57, 61–68, 70, 129]
Social	Freeing of public space, consistency with urban planning, the attractiveness of the city zone	[56, 61, 64, 65, 67, 68]
	Congestions, vibrations, noise, safety, mobility	[56, 57, 61, 63–65, 67, 68, 129]
	Cooperation of stakeholders	[62]
	Accessibility	[61, 64, 65, 129]
Environmental	Air pollution, energy conservation, waste generation	[56, 57, 61, 64–68, 70, 129]

3. Proposed Hybrid MCDM Model

For solving the problem of evaluating the sustainable LMSs, a novel hybrid MCDM model was developed in this paper that combines the fuzzy Delphi-based fuzzy FARE and the fuzzy VIKOR method. The structure of the proposed model is presented in Figure 1, while the steps of the model, which is universally applicable and which can, after minimal adjustments, be used to solve the problems in different areas, are described in detail as follows:

Step 1: define the problem structure; i.e., form the sets of alternatives and criteria for their evaluation and identify the stakeholders interested in solving the problem.

Step 2: define the fuzzy scale for the evaluations of criteria and alternatives by the decision-makers.

Linguistic evaluations and corresponding triangular fuzzy values are presented in Table 3.

Step 3: obtain the criteria weights by applying the fuzzy Delphi-based fuzzy FARE method. Also we have the following:

Step 3.1: form the criteria evaluation matrices $\widetilde{A}_h$ based on the linguistic evaluations by the decision-makers that represent various stakeholders, and transform them into triangular fuzzy values using the relations given in Table 3:

$$\widetilde{A}_h = \left[\widetilde{a}_{ijh}\right]_{n \times n}, \quad \forall h = 1, \ldots, p, \tag{1}$$

where $\widetilde{a}_{ijh} = (l_h, m_h, u_h)$ is the evaluation of the strength of impact (importance) of the criterion i in relation to the criterion j by the decision-maker h, l_h,
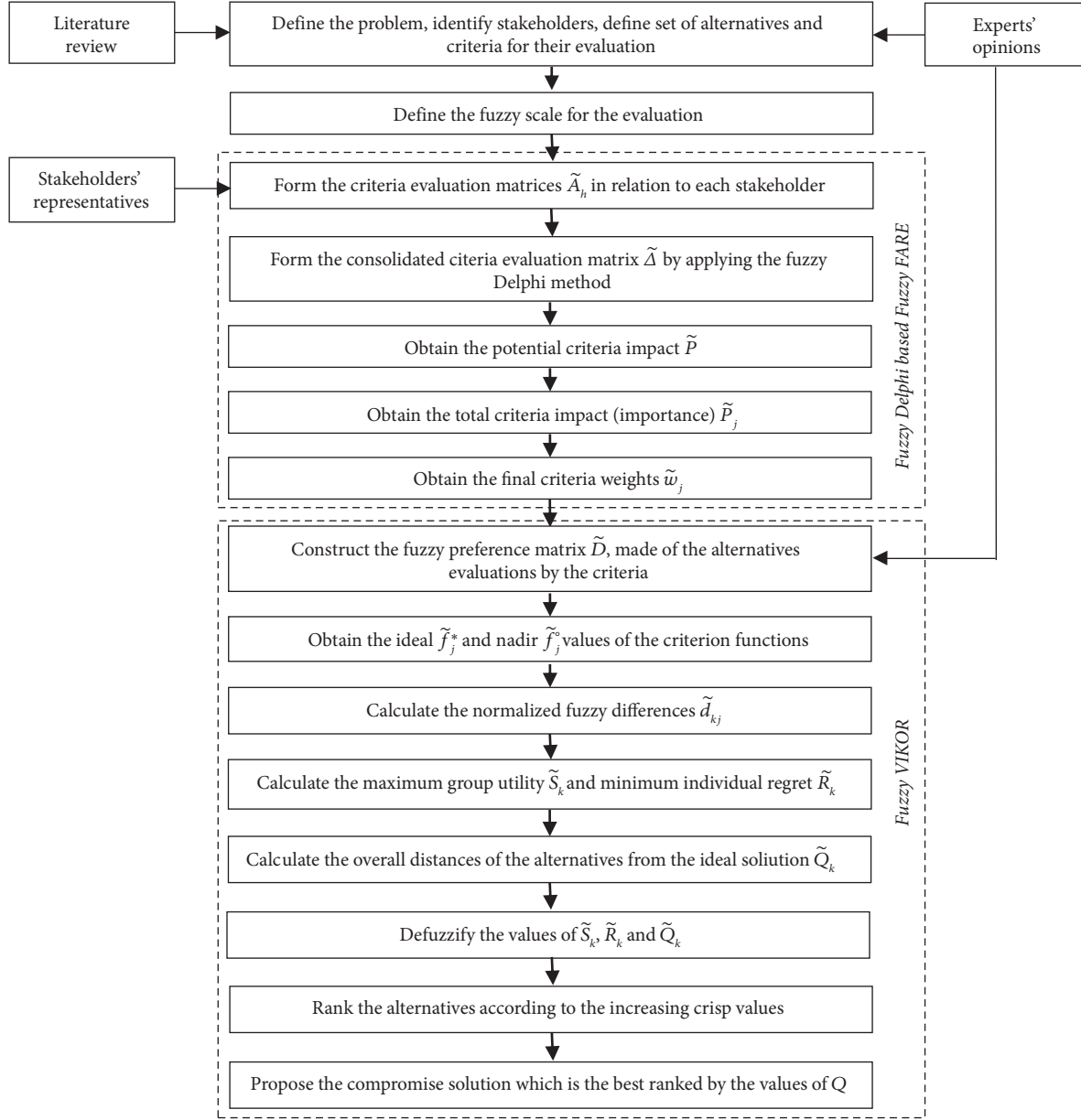
FIGURE 1: Structure of the proposed MCDM model. The model consists of two main parts, Fuzzy Delphi-based fuzzy FARE for obtaining criteria weights and fuzzy VIKOR for ranking the alternatives.

TABLE 3: Fuzzy scale from the evaluations.

Linguistic evaluation	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)

m_h, and u_h are lover, middle, and upper values of the triangular fuzzy evaluation $\tilde{a}_{ijh}$, n is the number of criteria taken into account, and p is the number of decision-makers performing the evaluations. When forming the matrix $\tilde{A}_h$ the following condition must be met:

$$\tilde{a}_{jih} = -\tilde{a}_{ijh}, \qquad (2)$$

and the evaluation is considered consistent if the following is fulfilled:

$$\sum_{j=1}^{n} u_h = -\sum_{j=1}^{n} l_h, \quad \forall h = 1, \dots, p. \qquad (3)$$

Step 3.2: form the consolidated criteria evaluation matrix $\tilde{\Delta}$ by applying the fuzzy Delphi method [130]:

$$\tilde{\Delta} = \left[\tilde{\delta}_{ij}\right]_{n \times n}, \qquad (4)$$

$$\tilde{\delta}_{ij} = (\alpha, \beta, \gamma), \qquad (5)$$

$$\alpha = \min(l_h), \quad h = 1, \dots, p, \qquad (6)$$

$$\beta = \left(\prod_{h=1}^{p} m_h\right)^{1/p}, \quad h = 1, \dots, p, \qquad (7)$$

$$\gamma = \max(u_h), \quad h = 1, \dots, p, \qquad (8)$$

where α, β, and γ are lower, middle, and upper values of consolidated fuzzy evaluation $\tilde{\delta}_{ij}$, respectively, and $\alpha \leq \beta \leq \gamma$.

Step 3.3: obtain the potential criteria impact in the following way:

$$\tilde{P} = \tilde{H}(n-1), \qquad (9)$$

where $\tilde{P}$ is the potential impact (importance) of all criteria for the defined problem, and $\tilde{H}$ is the highest value of the scale used for the evaluations.

Step 3.4: obtain the total impact (importance) of criterion $\tilde{P}_j$ by applying the following equation:

$$\tilde{P}_j = \sum_{i=1}^{n} \tilde{\delta}_{ij}, \quad \forall j = 1, \dots, n, \ j \neq i. \qquad (10)$$

Step 3.5: obtain the final fuzzy criteria weights $\tilde{w}_j$ by applying the following equation:

$$\tilde{w}_j = \frac{\tilde{P}_j^r}{\tilde{P}_H}, \quad \forall j = 1, \dots, n, \qquad (11)$$

where $\tilde{P}_H$ is the total potential impact (importance) of the considered set of criteria obtained in the following way:

$$\tilde{P}_H = n \times \tilde{P} \qquad (12)$$

and $\tilde{P}_j^r$ is the real total impact of the criterion j obtained in the following way:

$$\tilde{P}_r^j = \tilde{P}_j + \tilde{P}, \quad \forall j = 1, \dots, n, \qquad (13)$$

Step 4: evaluate the alternatives by applying the fuzzy VIKOR method. The procedure is adapted from the paper [131], and the steps are described as follows.

Step 4.1: construct the fuzzy preference matrix ($\tilde{D}$). It is necessary to perform the evaluation of the alternatives (LMSs), in relation to the criteria using the triangular fuzzy values given in Table 3:

$$\tilde{D} = \left[\tilde{f}_{kj}\right]_{o \times n}, \qquad (14)$$

where $\tilde{f}_{kj} = (l_{kj}, m_{kj}, u_{kj})$ denotes triangular fuzzy evaluations of the alternative k in relation to the criterion j. o is the total number of alternatives taken into consideration.

Step 4.2: obtain the ideal $\tilde{f}_j^* = (l_j^*, m_j^*, u_j^*)$ and nadir $\tilde{f}_{j^\circ} = (l_j^\circ, m_j^\circ, u_j^\circ)$ values of all criterion functions which represent the evaluations of the alternatives by the criteria depending on whether they are the benefit or cost criteria. The set of benefit criteria is denoted as J^b, while the set of cost criteria is denoted as J^c.

$$\tilde{f}_j^* = \max_k \tilde{f}_{kj}, \quad \tilde{f}_{j^\circ} = \min_k \tilde{f}_{kj}, \quad \text{for } j \in J^b,$$
$$\tilde{f}_j^* = \min_k \tilde{f}_{kj}, \quad \tilde{f}_j^\circ = \max_k \tilde{f}_{kj}, \quad \text{for } j \in J^c. \qquad (15)$$

Step 4.3: calculate the normalized fuzzy differences $\tilde{d}_{kj}$:

$$\tilde{d}_{kj} = \frac{\tilde{f}_j^* \ominus \tilde{f}_{kj}}{u_j^* - l_{j^\circ}}, \text{for } j \in J^b \ \tilde{d}_{kj} = \frac{\tilde{f}_{kj} \ominus \tilde{f}_j^*}{u_{j^\circ} - l_j^*} \text{ for } j \in J^c. \qquad (16)$$

Step 4.4: calculate the values of $\tilde{S}_k = (S_k^l, S_k^m, S_k^u)$, representing the normalized fuzzy difference, i.e., maximum group utility, and the values of $\tilde{R}_k = (R_k^l, R_k^m, R_k^u)$ representing the maximum fuzzy difference, i.e., minimum individual regret, by applying the following equations:

$$\tilde{S}_k = \sum_{j=1}^{n} \tilde{w}_j \otimes \tilde{d}_{jk}, \qquad (17)$$

$$\tilde{R}_k = \max_j \tilde{w}_j \otimes \tilde{d}_{jk}. \qquad (18)$$

Step 4.5: calculate the values of $\tilde{Q}_k = (Q_k^l, Q_k^m, Q_k^u)$, i.e., the overall distances of the alternatives from the ideal solution, by applying the following equation:

$$\tilde{Q}_k = v \frac{\tilde{S}_k \ominus \tilde{S}^*}{S^{\circ u} - S^{*l}} \oplus (1-v) \frac{\tilde{R}_k \ominus \tilde{R}^*}{R^{\circ u} - R^{*l}}, \qquad (19)$$

where $\tilde{S}^* = \min_k \tilde{S}_k$, S^{*l} is the lower value of the triangular fuzzy number $\tilde{S}^*$, $S^{\circ u} = \max_k S_k^u$, $\tilde{R}^* = \min_k \tilde{R}_k$, R^{*l} is the lower value of the triangular fuzzy number $\tilde{R}^*$, and $R^{\circ u} = \max_k R_k^u$. Value v refers to the weight of the strategy of "the majority of criteria" (or "the maximum group utility"), whereas $1 - v$ is the weight of the individual regret.

Step 4.6: defuzzify the values of $\widetilde{S}_k$, $\widetilde{R}_k$, and $\widetilde{Q}_k$ using the following equation [132]:

$$\text{crisp}(\widetilde{T}) = \frac{\left(T^l + 4T^m + T^u\right)}{6}, \qquad (20)$$

where $\widetilde{T} = (T^l, T^m, T^u)$ is any triangular fuzzy number.

Step 4.7: rank the alternatives (LMSs), according to the increasing crisp values. The results are three ranking lists $\{\text{LMS}\}_S$, $\{\text{LMS}\}_R$, and $\{\text{LMS}\}_Q$ according to crisp(S), crisp(R), and crisp(Q), respectively.

Step 4.8: propose as a compromise solution the alternative $\text{LMS}^{(1)}$ which is the best ranked by the values of Q, if the following two conditions are satisfied:

Co.1. "Acceptable Advantage": $\text{Adv} \geq DQ$ where $\text{Adv} = [Q(\text{LMS}^{(2)}) - Q(\text{LMS}^{(1)})]/[Q(\text{LMS}^{(o)}) - Q(\text{LMS}^{(1)})]$ is the advantage rate of the alternative $\text{LMS}^{(1)}$, ranked as the first, in relation to the alternative $\text{LMS}^{(2)}$, ranked as the second one in the list $\{\text{LMS}\}_Q$, and $DQ = 1/(o - 1)$ represents the threshold from which the advantage rate (Adv) has to be higher.

Co.2. "Acceptable Stability in decision-making": Alternative $\text{LMS}^{(1)}$ must also be the best ranked by S and/or R.

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of the following:

CS1. Alternatives $\text{LMS}^{(1)}$ and $\text{LMS}^{(2)}$ if only the condition Co.2 is not satisfied

CS2. Alternatives $\text{LMS}^{(1)}$, $\text{LMS}^{(2)}$, ..., $\text{LMS}^{(M)}$ if the condition Co.1 is not satisfied; $\text{LMS}^{(M)}$ is determined by the relation $[Q(\text{LMS}^{(M)}) - Q(\text{LMS}^{(1)})]/[Q(\text{LMS}^{(o)}) - Q(\text{LMS}^{(1)})] < DQ$ for maximum M (the positions of these alternatives are "in closeness")

4. Evaluation of the Sustainable Last Mile Solutions

For solving the problem of evaluating the sustainable LMS, a novel hybrid MCDM model was developed in this paper that combines the fuzzy Delphi-based fuzzy FARE and the fuzzy VIKOR method. The structure of the proposed model is presented in Figure 1.

4.1. Proposed Sustainable Last Mile Solutions for the Central Business District of Belgrade. By combining the reviewed initiatives and technologies, it is possible to define a wide set of solutions, but only those that are applicable and in line with the principles of sustainability are taken into consideration (Figure 2). It is assumed that the concepts of co-operation and flow consolidation at the outskirts of urban areas are an integral element of logistics in the city; therefore, they are not explicitly highlighted in the description of the analyzed LMSs. All proposed solutions also include two freight villages (FVs) whose development is planned at the outskirts of Belgrade.

The first solution (LMS_1) is a combination of the ideas of parcel lockers and crowdsourcing (Figure 2(a)). Goods delivery from FVs to parcel lockers, located in the immediate proximity of the end users, is performed with the road freight vehicles. Flow generators independently collect their goods at the assigned parcel lockers, where they can obtain discounts/benefits/financial compensation by taking the role of crowd agents and delivering the goods to the other generators in their surroundings. By utilizing parcel lockers, the providers are relieved of the responsibilities in the last phase of the delivery, and at the same time, the uncertainties that exist in the classic crowdsourcing models are reduced. The implementation of this solution requires the deployment of parcel lockers in the central business district and the development of the software platform used for the communication between logistics providers and crowd agents. The required investments for the development of LMS_1 are relatively low, but delivery reliability is problematic due to the crowd agents' autonomy.

The solution LMS_2 considers the development of microconsolidation centers in the delivery zone which enables the modal shift of transport work on autonomous vehicles (Figure 2(b)). Goods delivery from FVs to microconsolidation centers is performed with road freight vehicles, while the last phase is performed with ground autonomous vehicles and drones. This solution requires the development of logistics infrastructure (microconsolidation centers) in the central business district and the definition of regulatory frameworks for the application of autonomous vehicles. By transforming the delivery system into a two-phased system, efficiency and reliability are improved while negative environmental impacts are reduced. On the other hand, the application of autonomous technologies requires the definition of specific regulations and opens a wide variety of questions, especially those regarding safety.

The third solution (LMS_3) also performs the delivery through two phases, but with road freight vehicles in the role of mobile depots, where the last phase of the delivery is performed with drones (Figure 2(c)). Road freight vehicles visit convenient locations (special parking slots) near flow generators from where the drones are launched to execute the last delivery phase. This solution requires the synchronization between ground vehicles and drones in the delivery process and also the adoption of regulations that would define the application of drones in urban areas. Besides, drone-based delivery is sensitive to unfavorable weather conditions (strong wind, rain, and storm) that are present during the winter months in the City of Belgrade.

The solution LMS_4 delivers goods from FVs to the central business district with rail transportation (regular cargo tram lines), where the last phase of the delivery is performed with light commercial vehicles—cargo bicycles and scooters (Figure 2(d)). The solution utilizes the existing infrastructure, but to improve the flexibility of the solution, the transportation of goods outside regular time schedules is made possible through the idea of cargo-hitching (with regular passenger tram lines). This solution greatly eliminates road transportation and improves the logistics system's efficiency by redistributing the transport work on rail

(a)

- freight village
- flow generator (end consumer)
- commercial vehicle route
- flow generator route
- parcel locker

(b)

- freight village
- flow generator (end consumer)
- commercial vehicle route
- drone route
- autonomous ground vehicle route
- micro-consolidation centre

(c)

- freight village
- flow generator (end consumer)
- commercial vehicle route
- drone route
- moving depot stopping point

(d)

- freight village
- flow generator (end consumer)
- commercial vehicle route
- eco-vehicle route
- cargo tram route
- cargo transhipment station
- passenger tram route
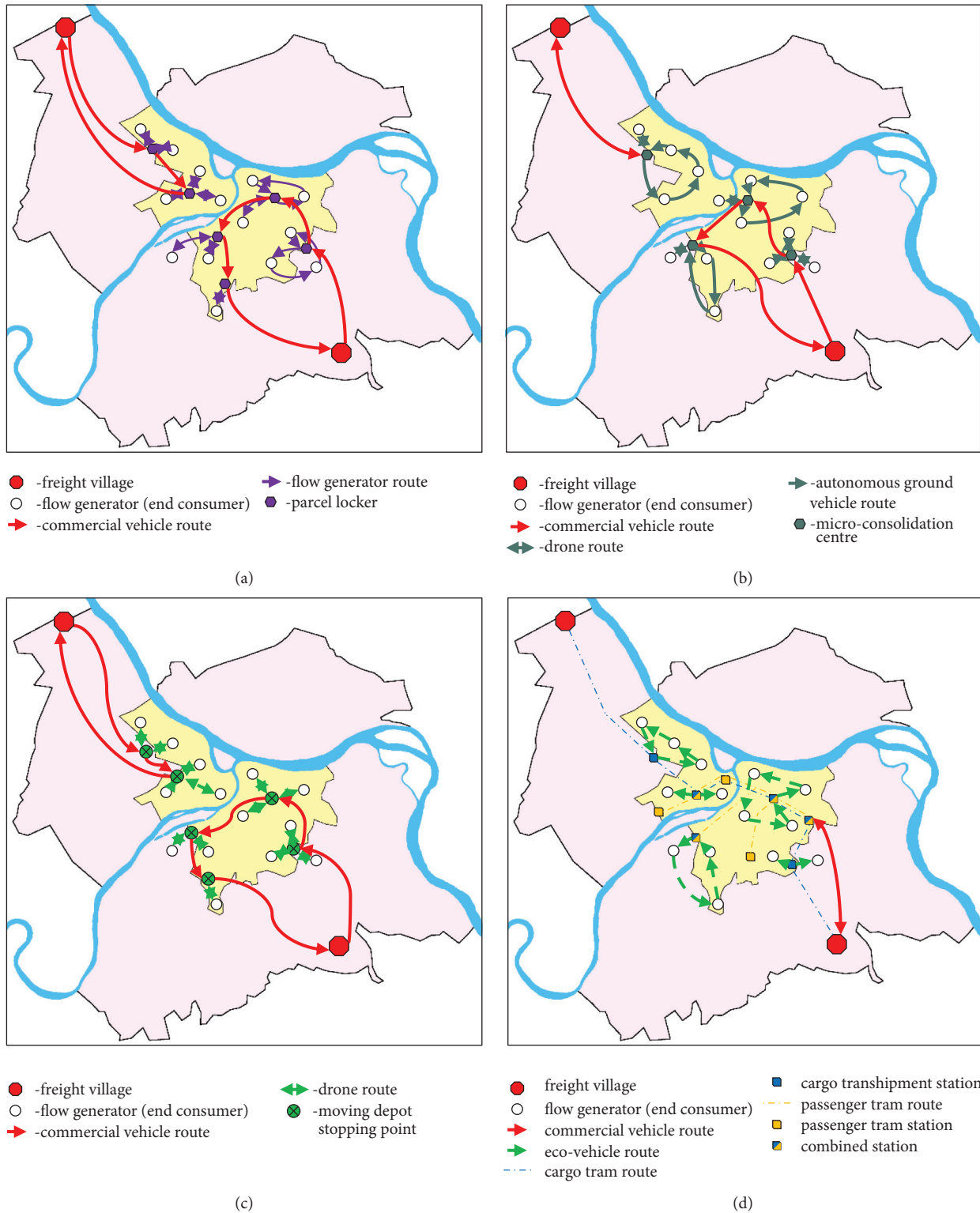- passenger tram station
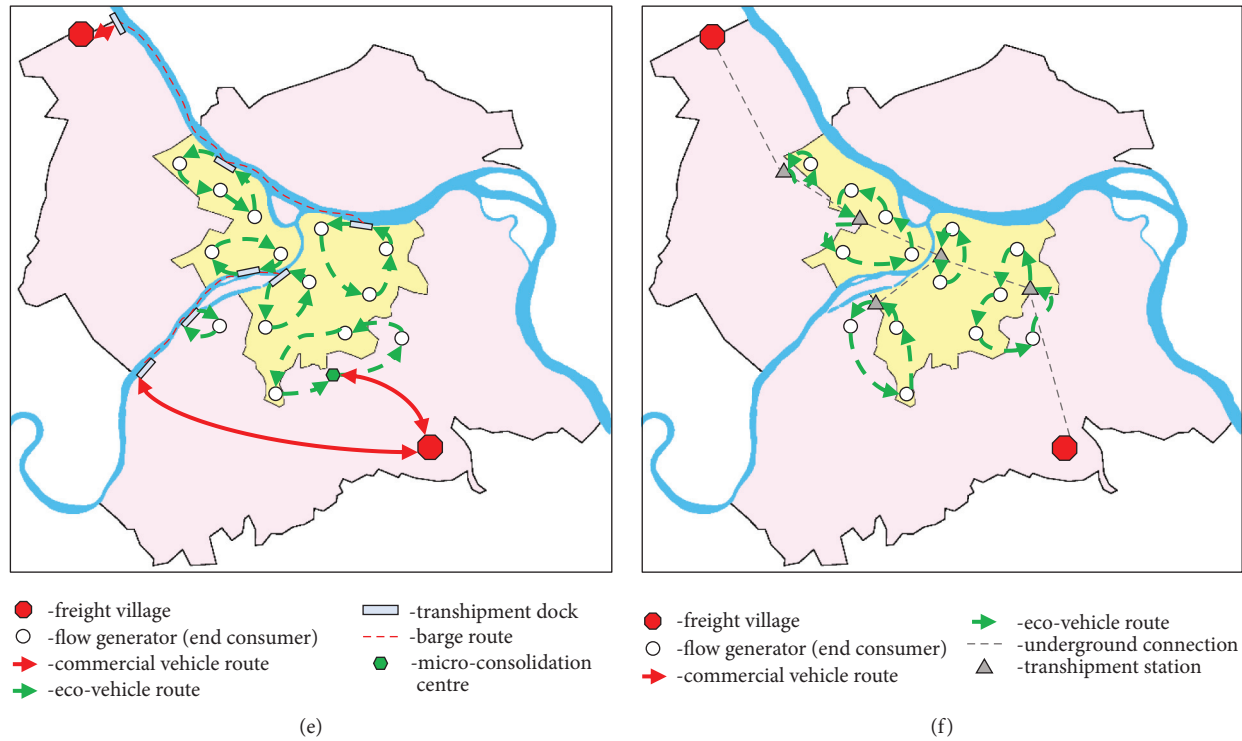- combined station

Figure 2: Continued.

FIGURE 2: Last mile delivery solutions for the central business district of Belgrade. Six different solutions are created, namely, (a) LMS_1, (b) LMS_2, (c) LMS_3, (d) LMS_4, (e) LMS_5, and (f) LMS_6.

transportation. The weakness of this solution is its operational complexity, the demand for installing transshipment stations in the central business district, the general nonflexibility of rail transportation, and mixing passenger and goods flows through the concept of cargo-hitching.

In the solution LMS_5, inland waterways of the rivers Sava and Danube are used for the transportation of goods to the central business district of Belgrade (Figure 2(e)). Along the riverbeds, transshipment stations that enable the transfer of goods on eco-delivery vehicles (bikes, cycles, and smaller electrovehicles) are located. Goods transportation between FVs and the nearest transshipment stations is performed with the road shuttle connections. This solution eliminates road freight transportation in coastal urban areas, but some locations remain outside the delivery zone of transshipment stations. To provide service for these locations, the development of microconsolidation centers in particular urban zones is required. Goods delivery to microconsolidation centers is performed with road freight vehicles, from where the last phase of the delivery is performed with eco-vehicles. The solution utilizes the natural infrastructural resources—inland waterways—but requires the development of additional infrastructure—coastal transshipment stations and microconsolidation centers. Although this solution improves the efficiency of logistics activities, inland waterway transportation is generally nonflexible and sensitive on unfavorable weather conditions.

The solution LMS_6 refers to the utilization of an underground logistics system for goods transportation between FVs and the central business district (Figure 2(f)). Since the

City of Belgrade is characterized by significant spatial dispersion of generators, it is impossible to include all generators in an underground system. Instead, transshipment stations that enable the modal shift on light freight vehicles—bikes, bicycles, scooters, and electrovehicles—used in the last delivery phase, are developed on strategically important locations. Underground logistics systems reduce negative environmental impacts of logistics and improve mobility in urban areas. On the other hand, the solution generates high infrastructural investments, and the development of underground systems is not even possible in historical parts of the city. Aside from the aforementioned, this solution can be the key to achieving logistics sustainability in city areas that are yet to be constructed.

4.2. Criteria for the Evaluation of the Last Mile Solutions. For the evaluation of the LMSs for the central business district of Belgrade, ten criteria are defined and explained in the following text. The criteria are selected according to the literature review, analysis of the CL participants in Belgrade, and the authors' experience in the field.

Efficiency (C_1) represents the rationalization level of logistics activities within a solution. It refers to the utilization of loading space in commercial vehicles, the average traveled distance per delivery, overall delivery completion times, fuel and energy consumption, etc.

Operation complexity of delivery (C_2) depends on the goods flow transformation degree and the applied technologies. In solutions that transform the logistics system into

multiechelon systems, with or without transportation modal shift, the complexity of delivery operations is higher.

Flexibility (C_3) refers to the possibility of the logistics system's adaptation to unexpected changes in demand characteristics. The solutions that imply the use of rail and inland waterway transportation have lower flexibility, while the solutions that rely more on road transportation are more flexible.

Reliability (C_4) refers to the availability of services and goods in acceptable time intervals. Solutions with systems whose activity execution greatly depends on weather conditions (barges and drones) and traffic conditions are less reliable because of frequent delays and bottlenecks.

Implementation possibility (C_5) of a solution refers to its compatibility with existing urban plans for the observed area. This criterion also reflects on the need for defining new laws, regulations, and measures that cover the application of newer delivery technologies (such as drones and autonomous vehicles), as well as on the administrative procedures that precede the implementation of such solutions.

Implementation costs (C_6) refer to the number of infrastructural investments required for the development and implementation of an LMS.

Modal redistribution of transport work (C_7) implies the stimulation (subsidies) for the use of alternative transportation means (rail, inland waterway, or drones) in the LMSs.

Freeing of public space (C_8) describes to what level the solution contributes to the freeing of public spaces (roads, sidewalks, plazas, promenades, parks, green areas, lots, etc.) for the development of more attractive content.

Environmental impact (C_9) refers to the reduction of logistics activities' negative environmental impact—air-pollutant emissions and ecosystem degradation, which follow the implementation of modern LMSs.

Mobility (C_{10}) refers to the conditions that enable the uninterrupted realization of goods and passenger flows in the urban areas. By reducing the participation of road transportation in overall transport, urban mobility rises.

4.3. Evaluation of the Last Mile Solutions. The first step in applying the model, in addition to defining a set of alternatives and criteria for their evaluation, involves identifying stakeholders interested in solving the problem. The evaluation of the criteria was performed from the aspect of four CL stakeholders: residents (Res.), users (Use.), logistics service providers (Pro.), and city administration (Adm.). Residents are people who live, work, and shop in the city. They strive to minimize traffic congestion, noise, air pollution, and traffic accidents near the place of residence, work, and shopping. Shippers and recipients are the users of the services who send or receive goods and generally require the provider to maximize the level of service, which means shorter delivery/collection times, greater reliability and flexibility, and better information at a lower cost of service. Providers strive to minimize the cost of collecting or delivering goods to customers, while maximizing profits. The city

administration aims at economic development of the city and increasing employment opportunities on the one side and reducing traffic congestion, improving living conditions, and increasing traffic safety on the other [133]. In accordance with their preferences, stakeholders' representatives evaluated the importance of the criteria with linguistic assessments (Table 4).

By applying the relations given in Table 3, the evaluations were transformed to the fuzzy values, thus forming the criteria evaluation matrices (1), while satisfying conditions (2) and (3). For the matrices obtained in such way, the consolidated criteria evaluation matrix is formed by applying equations 4–(8). By applying equation (9), the potential criteria impact was calculated, and by applying equation (10), the total impact (importance) of criteria was determined. The final criteria weights were obtained by applying equations (11)–(13). The following criteria weights were obtained: $(\tilde{w}_1; \tilde{w}_2; \tilde{w}_3; \tilde{w}_4; \tilde{w}_5; \tilde{w}_6; \tilde{w}_7; \tilde{w}_8; \tilde{w}_9; \tilde{w}_{10}) = (0.050, 0.102, 0.200; 0.050, 0.096, 0.193; 0.050, 0.100, 0.197; 0.050, 0.104, 0.206; 0.051, 0.103, 0.198; 0.051, 0.105, 0.217; 0.050, 0.092, 0.167; 0.050, 0.096, 0.192; 0.050, 0.097, 0.198; 0.051, 0.107, 0.213)$.

The evaluation of alternatives in relation to the criteria (Table 5) was performed in the next step. Evaluations were converted into fuzzy values using the relations given in Table 3, thus forming a fuzzy preference matrix (14). By applying equation (15), the ideal and nadir values of all criterion functions were obtained and then the normalized fuzzy differences by applying equation (16).

By applying equations (17) and (18), the values of maximum group utility and minimum individual regret were obtained, and then the overall distances of the alternatives from the ideal solution by applying equation (19) (value of 0.5 was taken for parameter v). These values were then defuzzified using equation (20), and the final ranking of the alternatives was performed. The results of the conducted ranking process are presented in Table 6.

LMS_2 is selected as the best ranked alternative since it is ranked as the first one according to the Q, S, and R, thus satisfying the condition Co.2. The condition Co.1 is also satisfied since Adv = $0.346 \geq DQ = 0.200$.

4.4. Sensitivity Analysis. In order to examine the stability of the obtained solution, a sensitivity analysis was performed. Eight scenarios have been defined in which individual model parameters have been changed. In the first four scenarios (Sc.1–Sc.4), the ranking of alternatives was performed based on the criteria weights obtained by the evaluation of representatives of each stakeholder, namely, providers, users, administration, and residents, respectively. In the next three scenarios (Sc.5–Sc.7), one of the three most important criteria, C_{10}, C_6, and C_4, was excluded from the model, respectively. In the last scenario (Sc.8), all three most important criteria were excluded from the model. The obtained results of ranking by scenarios and changes in relation to the baseline scenario (Sc.0) are presented in Table 7, while the graphical representation of the sensitivity analysis is presented in Figure 3.

TABLE 4: Criteria evaluation by the stakeholders' representatives (Res., Use., Pro., and Adm.).

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
C_1	(/,/,/,/)	(FL,VL,/,L)	(/,/,L,VL)	(/,/,L,VL)	(/,L,FL,/)	(VL,L,VL,/)	(FL,H,FH,/)	(/,FH,EH,/)	(/,M,EH,/)	(/,N,H,/)
C_2	(/,/,N,/)	(/,/,/,/)	(/,/,L,/)	(/,/,L,/)	(/,VL,FL,/)	(/,VL,VL,/)	(/,FH,FH,/)	(/,M,EH,/)	(/,FL,EH,/)	(/,/,H,/)
C_3	(N,L,/,/)	(FL,FL,/,VL)	(/,/,/,/)	(/,/,N,/)	(/,M,VL,/)	(VL,M,/,/)	(FL,EH,FL,/)	(/,VH,H,/)	(/,H,H,/)	(/,L,M,/)
C_4	(FL,L,/,/)	(H,FL,/,VL)	(FL,N,/,N)	(/,/,/,/)	(L,M,VL,/)	(M,M,/,/)	(H,EH,FL,/)	(/,VH,H,/)	(/,H,H,/)	(/,L,M,/)
C_5	(VL,/,/,M)	(M,/,/,H)	(VL,/,/,FH)	(/,/,/,FH)	(/,/,/,/)	(L,N,/,/)	(M,M,L,L)	(/,FL,FH,VL)	(/,L,FH,L)	(/,/,FL,N)
C_6	(/,/,/,H)	(L,/,/,EH)	(/,/,VL,VH)	(/,/,VL,VH)	(/,/,L,L)	(/,/,/,/)	(L,M,M,M)	(/,FL,VH,FL)	(/,L,VH,M)	(/,/,FH,L)
C_7	(/,/,/,L)	(N,/,/,M)	(/,/,/,FL)	(/,/,/,FL)	(/,/,/,/)	(/,/,/,/)	(/,/,/,/)	(/,/,FL,/)	(/,/,FL,/)	(/,/,VL,/)
C_8	(M,/,/,FL)	(VH,/,/,FH)	(M,/,/,M)	(VL,/,/,M)	(FL,/,/,/)	(FH,/,/,/)	(VH,VL,/,VL)	(/,/,/,/)	(/,/,/,VL)	(/,/,/,/)
C_9	(FH,/,/,L)	(EH,/,/,M)	(FH,/,/,FL)	(L,/,/,FL)	(M,/,/,/)	(H,/,/,/)	(EH,L,/,N)	(VL,VL,N,/)	(/,/,/,/)	(/,/,/,/)
C_{10}	(FH,/,/,M)	(EH,VL,/,H)	(FH,/,/,FH)	(L,/,/,FH)	(M,L,/,/)	(H,L,/,/)	(EH,H,/,L)	(VL,FH,L,VL)	(N,M,L,L)	(/,/,/,/)

TABLE 5: Evaluation of the alternatives in relation to the criteria.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
LMS_1	L	EH	VH	L	EH	EH	VL	H	L	VH
LMS_2	FH	VH	H	H	H	H	FH	FH	H	M
LMS_3	VL	H	EH	M	L	VH	L	H	VL	VL
LMS_4	H	M	FH	VH	VH	M	H	M	FH	FH
LMS_5	EH	VL	L	VL	FL	FH	EH	VH	EH	H
LMS_6	VH	FH	VL	EH	VL	VL	VH	EH	VH	EH

TABLE 6: Final ranking of the alternatives.

		LMS_1	LMS_2	LMS_3	LMS_4	LMS_5	LMS_6
	S^l	0.049	0.025	0.123	0.045	0.059	0.035
	S^m	0.328	0.284	0.478	0.320	0.353	0.303
S	S^u	1.105	1.022	1.404	1.101	1.166	1.066
	Crisp ($\tilde{S}$)	0.411	0.364	0.573	0.405	0.440	0.386
	Rank	4	1	6	3	5	2
	R^l	0.028	0.011	0.028	0.017	0.028	0.029
	R^m	0.072	0.048	0.083	0.064	0.081	0.082
R	R^u	0.184	0.160	0.213	0.192	0.206	0.217
	Crisp ($\tilde{R}$)	0.083	0.061	0.096	0.077	0.093	0.095
	Rank	3	1	6	2	4	5
	Q^l	−0.286	−0.334	−0.257	−0.314	−0.281	−0.289
	Q^m	0.191	0.117	0.272	0.169	0.221	0.205
Q	Q^u	0.837	0.749	1.018	0.856	0.915	0.905
	Crisp ($\tilde{Q}$)	0.219	0.147	0.308	0.203	0.253	0.240
	Rank	3	1	6	2	5	4

Based on the presented results, it can be seen that there are no significant changes in the ranking of alternatives in any of the scenarios. Alternative LMS_2 is the best and LMS_3 the worst ranked in all scenarios. LMS_4 ranks second in all scenarios except Sc.3 and Sc.7. Other alternatives changed the rank, but without significant deviations. Sensitivity analysis proved that the obtained solution in Sc.0 is sufficiently stable and can be adopted as the final.

5. Discussion

The possibility of applying the defined MCDM model was successfully demonstrated in the previous section. It has been shown that the FARE method is very suitable for obtaining criteria weights because it results in consistent values based on a small number of pair vise comparisons of criteria. This characteristic would be even more pronounced

TABLE 7: Sensitivity analysis results.

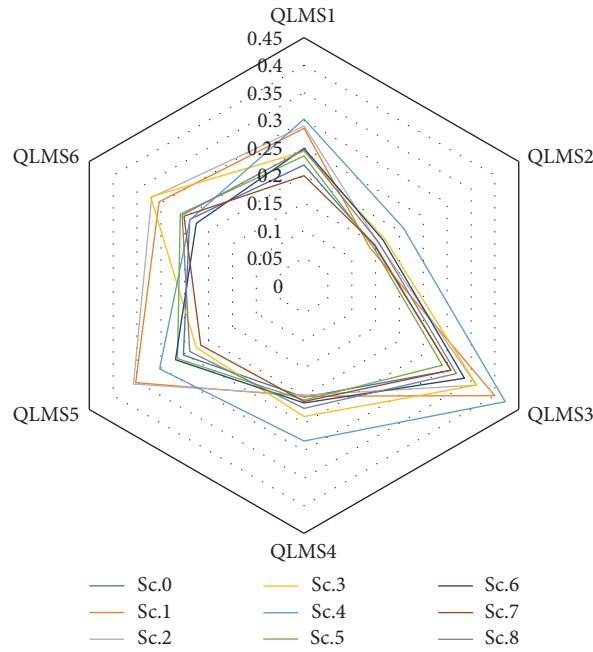|	Sc.0	Sc.1	Sc.2	Sc.3	Sc.4	Sc.5	Sc.6	Sc.7	Sc.8
Q_{LMS_1}	0.219	0.285	0.290	0.244	0.302	0.235	0.249	0.199	0.246
Q_{LMS_2}	0.147	0.138	0.155	0.169	0.209	0.144	0.166	0.148	0.157
Q_{LMS_3}	0.308	0.400	0.361	0.362	0.422	0.290	0.336	0.308	0.319
Q_{LMS_4}	0.203	0.201	0.199	0.238	0.282	0.208	0.213	0.210	0.223
Q_{LMS_5}	0.253	0.353	0.357	0.225	0.303	0.265	0.269	0.216	0.240
Q_{LMS_6}	0.240	0.304	0.320	0.321	0.239	0.259	0.225	0.252	0.255

FIGURE 3: Sensitivity analysis. Eight scenarios, each differing according to the model parameters, were compared to the baseline scenario in order to examine the stability of the obtained solution.

in the case of considering a greater number of criteria. The Delphi method made it possible to easily consolidate the evaluation of criteria by the representatives of different stakeholders, which is the first step in finding a compromise solution. The VIKOR method has enabled the ranking of alternatives based on the values that determine their distance from the ideal solution much more precisely, compared to some other methods. The combination of these methods in the fuzzy environment, which enabled an adequate perception of ambiguity and inaccuracy in the evaluations of decision-makers, further contributed to the quality of the obtained results. The implications of the developed model are the possibility of its application for ranking any initiatives, technologies, concepts, or solutions of city logistics, as well as for solving other MCDM problems in the field of logistics and industrial engineering, as well as in other areas.

The defined MCDM model was applied in this paper for the evaluation of LMS for the central business district of Belgrade. LMS_2—the combination of the concept of microconsolidation of flows and autonomous vehicle technologies—is evaluated as being the best one. By locating microconsolidation centers in the immediate proximity of the flows generators, technical limitations of autonomous vehicles

are overcome, and the efficiency of their application is improved. By transforming the system into a two-echelon system, the interdependence of flow performance is reduced in different levels—the transportation of goods to the microconsolidation centers and the delivery of goods to the generators. This means that after the delivery of goods to a microconsolidation center, the freight vehicle continues its task, while, at the same time, the last phase of the delivery is being adapted for the autonomous vehicles, thus improving the flexibility of the system. By selecting LMS_2, significant positive effects on logistics sustainability in urban areas are expected—better activity efficiency, reduction of negative effects (air-pollutant emissions, noise, vibrations, traffic congestions), the improvement in attractiveness of the central business district, and the promotion of the application of modern goods delivery technologies. The implementation of this solution is practically feasible, while the application of different autonomous vehicle classes (ground vehicles and drones) provides greater flexibility during the system's planning as well. Certainly, the implementation of the solution is preceded with solving all relevant problems on the strategical and tactical decision levels (the required number of microconsolidation centers, their locations and capacities, dimensioning the required number of

autonomous vehicles in microconsolidation centers, etc.) and appropriate preparations for solving operational problems (vehicle routing and synchronization) during its exploitation. Besides, the application of such solutions opens a wide variety of questions regarding the definition of required regulatory frameworks for autonomous technologies, which have not received adequate treatment in the world so far.

The main theoretical implications of the paper are the development of a framework for the establishment of sustainable last mile solutions and efficient mathematical tool, in the form of a hybrid MCDM model, which can be used for solving the problems in the field of logistics, as well as any other. The main practical implications, on the other side, are the definition of the set of solutions that could serve as a good base for policy-making and plan development, in Belgrade or any other city, as well as the application of the developed model for selecting sustainable solutions for city logistics and last mile delivery by the decision-makers and practitioners.

6. Conclusion

The aim of this paper was to rank sustainable solutions for the realization of the last mile. The solutions defined in the paper are combinations of initiatives, technologies, and concepts of city logistics, and their application depends on the goals of different stakeholders. Accordingly, a set of criteria was defined for the evaluation of the solutions, and a novel MCDM model which combines Delphi, FARE, and VIKOR methods in the fuzzy environment was developed for solving the problem. The applicability of the defined model was demonstrated by ranking the sustainable LMSs for the central business district of Belgrade. A combination of microconsolidation centers and autonomous vehicles was obtained as the most favorable solution.

The main contributions of the paper are the definition of the innovative sustainable last mile solutions, the creation of a wide set of criteria for their evaluation, and the development of a novel hybrid MCDM model. In future research, the defined solutions could be upgraded, e.g., with some newly developed technologies of Industry 4.0. The potential effects of the application of defined solutions on the realization of logistics processes could also be examined in more detail, primarily in Belgrade, but also in some other cities. The defined MCDM model is universally applicable, and with certain adjustments, it could be used to solve various problems, so an important direction of future research is its application to solve problems in this or other areas. In addition, the model, or some of its parts, could serve as a basis for the development of some new MCDM models in the future.

Data Availability

All data underlying the findings of the study are included within the paper.

Disclosure

The research was performed as part of the employment of the authors at the University of Belgrade, Faculty of Transport and Traffic Engineering, and Chalmers University of Technology.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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