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An Intelligent Decision Framework for Optimizing Sustainable Last-Mile Delivery: Parcel Locker Location with IMF SWARA-WASPAS

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Abstract: The rapid development of e-commerce has made last-mile delivery a critical bottleneck in logistics management, with its efficiency directly impacting operational costs, service quality, and environmental sustainability. To address the multi-criteria decision-making (MCDM) problem of parcel locker location selection, this study constructs an intelligent decision-support framework that integrates the Improved Fuzzy Step-wise Weight Assessment Ratio Analysis (IMF SWARA) and the Weighted Aggregated Sum Product Assessment (WASPAS) methods. Based on real-world data from the Brčko Distribution Center of a regional logistics company (X Express), the research first employs the IMF SWARA method to determine fuzzy weights for six key criteria, including availability, frequency of user requests, and accessibility. The WASPAS method is then applied to comprehensively rank twelve candidate locations. Results indicate that location A2 is the optimal choice, followed by A4 and A3. The robustness of the model is verified through sensitivity analysis, including comparisons with other MCDM methods such as ARAS, EDAS, and MARCOS, as well as systematic variation tests of the λ parameter in WASPAS. This framework provides logistics managers with a structured and quantifiable decision-making tool, facilitating data-driven optimization of last-mile delivery networks in complex urban environments and enhancing the sustainability and operational efficiency of logistics systems.

Keywords: IMF SWARA; WASPAS; E-commerce; Last mile; Parcel lockers; Logistics

1 Introduction

Increased urbanization, the growing number of online orders, and the accelerated development of e-commerce significantly contribute to the more complex functioning of logistics systems in modern business. Modern business conditions are increasingly strict, the market is increasingly challenging, user requirements are variable, i.e. stochastic and non-stationary, which affects the increase in the complexity of the functioning of logistics companies. Various factors in urban environments shape the complexity of logistics processes. In response to these challenges, numerous urban logistics initiatives have been developed and implemented, differing in their drivers, actors involved, objectives, implementation requirements, and impact on the sustainability of urban environments [1]. One of the key concepts in urban logistics is "last mile delivery", i.e. the delivery of goods in the last part of the journey from the distribution center to the end user. This segment, although the shortest in terms of physical distance, is considered the most expensive, most complex, and least efficient in the entire logistics system [2]. The challenges of last-mile logistics in densely populated urban areas are the result of a combination of increased traffic, lack of parking capacity and increasingly rigorous environmental requirements. Over the last decade, in response to the increasing challenges in delivery, new solutions have been developed within last-mile logistics, the aim of which is to improve transport efficiency and improve the quality of service to end users. Courier and postal services perform a large part of the delivery tasks, as logistics companies often encounter numerous difficulties and challenges in delivering goods [3].

In this context, the role of intelligent management decision-making becomes paramount. The complexity and dynamism of urban last-mile logistics necessitate a shift from intuition-based to data- and model-driven strategies. Emerging technologies such as big data analytics, artificial intelligence (AI), and Dedicated Decision Support Systems (DSS) are transforming logistics management by enabling real-time visibility, predictive demand forecasting, route optimization, and automated resource allocation. These intelligent systems empower managers to navigate uncertainty, evaluate complex trade-offs, and enhance operational agility. Within this technological toolkit, MCDM methods serve as a foundational framework for structuring complex problems, quantifying subjective judgments, and generating optimal, transparent, and defensible decisions.

To address a concrete logistics challenge with intelligent decision-making, this study proposes an integrated model that combines fuzzy set theory with multi-criteria optimization. The research focuses on the strategic problem of parcel locker location selection—a decision critically affecting last-mile efficiency, cost, and customer satisfaction. The resulting framework provides a systematic, data-driven tool to support logistics planners. Alongside other technological innovations (such as logistics centers, autonomous vehicles, and drones), MCDM methods are often applied in logistics to create various strategies and evaluations [4].

MCDM is a branch of operations research that deals with problems involving multiple, often conflicting criteria [5, 6]. Solving an MCDM problem requires the decision-maker to select the most preferable alternative from a set of options, consistent with their preferences. In this study, based on data from the Brčko distribution center of X Express, the most suitable locations for parcel lockers are determined using a proposed MCDM model.

Following this introduction, the paper is structured as follows: Section 2 presents a literature review focusing on last-mile delivery and the application of MCDM methods. Section 3 details the proposed intelligent decision-support framework and the applied IMF SWARA and WASPAS methods. Section 4 discusses urban logistics concepts in the context of e-commerce. Section 5 applies the framework to select optimal parcel locker locations for the Brčko distribution center. Section 6 validates the model through sensitivity analysis. Section 7 discusses the managerial and practical implications of the results. Finally, Section 8 concludes the paper.

2 Literature Review

Modern logistics systems are increasingly moving from traditional models to flexible, technology-enabled solutions that enable dynamic management of goods delivery in urban environments.

Changes in economic structures, increasing urbanization, urban spatial planning and transport systems, together with the impact of logistics activities in urban areas, lead to increasing challenges in supply chains and logistics. Although this phenomenon has attracted numerous studies, there is still a lack of research that systematically presents the current state of knowledge [7]. In the last ten years, e-commerce has seen a significant increase, and the COVID-19 pandemic has further accelerated the growth of online retail, in all product sectors. This expansion of online shopping has created new logistical challenges, especially in the final stage of delivery, known as ”last mile delivery”. Traditional trucking delivery methods have shown limitations in urban areas, leading to the development and application of innovative logistics solutions as alternatives to parcel delivery [8]. Within urban logistics, the ”last mile” phase remains the most expensive and least efficient distribution segment [9]. Concepts such as shared delivery, electric vehicles and automated systems are increasingly being introduced. Case studies such as DHL confirm these findings. DHL is globally implementing sustainable solutions for "last mile" delivery through an electric fleet, bicycle deliveries and a network of smart parcel lockers [10].

A MCDM approach is used to objectively evaluate and rank alternative locations for parcel lockers. When key issues are at stake, such as capital investment levels, careful assessment of criteria becomes crucial. In such cases, decision-making requires systematic problem structuring and detailed evaluation of all criteria, with the support of specialized software and tools. In practice, MCDM enables decision-making, planning and structuring processes in multi-criteria situations, thus achieving optimal solutions in accordance with the preferences of decision makers [11]. According to performed study [12], the importance of applying MCDM is also reflected in the increasing number of published scientific and professional papers related to this topic, and the launch of an increasing number of commercial software packages on the market that serve as support for existing MCDM and analysis methods. In modern MCDM problems, especially in the field of logistics and urban distribution, methods that allow the inclusion of expert knowledge and subjective assessments under conditions of uncertainty are increasingly being applied. One such method is IMF SWARA, which was developed as an upgrade of the classical SWARA method (Step-wise Weight Assessment Ratio Analysis), which was initially presented in previous study [13].

The IMF SWARA method was initially introduced by Vrtagić et al. [14] for assessing traffic safety in the context of road infrastructure. Its application in transport and traffic has so far remained limited to a few studies. In line with the original research, authors in their research [15] have used IMF SWARA to analyze the impact of vehicles on traffic safety in Montenegro in the period from 1998 to 2020, combining it with DEA (Data Envelopment Analysis) and MARCOS (Measurement of Alternatives and Ranking according to Compromise Solution) methods to identify periods with a high level of safety. Additional applications of the method have been noted in research related to the transport of dangerous goods [16], logistics [17, 18], which highlights its importance in optimizing the distribution of goods through the transport chain, and warehouses efficiency respectively. In the paper, the authors have used the IMF SWARA method to improve the service quality of the public transport system [19]. Apart mentioned fields IMF SWARA has been applied in different studies for solving problems like urban planning [20], green supplier selection [21], organizational resilience measurement [22], etc.

In the framework of MCDM, where there is a need to evaluate and rank multiple alternatives based on previously established criteria and their weights, one of the effective and increasingly used methods is WASPAS [23]. The WASPAS method combines the weighted sum product model (WSM) and the weighted product model (WPM) through an originally defined aggregation coefficient, which achieves high accuracy in multiple estimation of the problem attributes. This method has found numerous applications in solving MCDM problems in construction and other fields. For example, authors in the study [24] used a combination of the WASPAS and ARAS (Additive Ratio Assessment) methods to evaluate potential shopping mall locations, while Dejus and Antucheviciene [25] proposed the application of the WASPAS method to rank alternatives in order to improve occupational safety.

The development of these advanced MCDM methods aligns with a broader shift towards intelligent decision support in logistics. The field has witnessed the growing influence of Intelligent Decision Support Systems (IDSS), which integrate data management, analytical models, and expert knowledge into cohesive computational frameworks to support complex, semi-structured decision-making processes [26]. In supply chain and logistics management, such systems have been applied to enhance areas including dynamic vehicle routing, inventory optimization, and sustainable network design, often leveraging simulation, machine learning, and real-time analytics [27].

However, a discernible gap exists between the theoretical advancement of sophisticated fuzzy MCDM techniques and their practical implementation as integrated, operable decision-support tools. While studies frequently demonstrate the efficacy of individual methods in case comparisons, the final step of synthesizing them into a transparent, replicable, and user-oriented decision-making framework—readily applicable by logistics planners—often remains unaddressed. This gap is particularly evident in strategic problems like last-mile facility location, where handling expert uncertainty and generating a reliable ranking must be seamlessly combined within a structured process.

To bridge this gap, the present study moves beyond a mere application of the IMF SWARA and WASPAS methods. Its primary contribution lies in constructing and validating a complete intelligent decision-support framework. This research demonstrates a systematic workflow—from criteria definition and fuzzy weight determination to comprehensive alternative evaluation and robustness testing—thereby delivering a verifiable and adaptable model for strategic parcel locker location planning in urban logistics.

3 The Proposed Intelligent Decision Support Framework

Figure 1 outlines the architecture of the proposed intelligent decision-support framework, which operates through four consecutive phases:

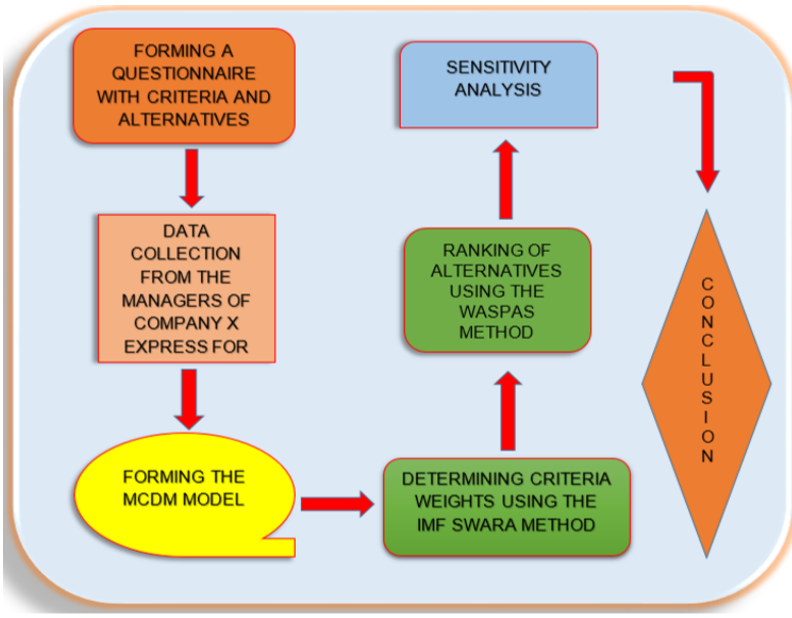

Figure 1. Research flow chart

(1) Problem Structuring & Data Preparation: This initial phase involves defining the decision context, identifying

potential locations (alternatives), and determining the evaluation criteria—the foundational step for any intelligent management system.

(2) Fuzzy Weight Determination via IMF SWARA: In this phase, expert knowledge is intelligently aggregated and processed to handle inherent subjectivity and uncertainty, assigning precise fuzzy weights to each criterion.

(3) Integrated Ranking via WASPAS: Leveraging the weights from the previous phase, this core component generates an intelligent recommendation by ranking all alternatives, balancing between additive and multiplicative aggregation strategies.

(4) Robustness Validation: The final phase involves sensitivity and comparative analyses to test the stability of the framework's output, a critical step to ensure the reliability of the decision support provided.

This structured workflow ensures a transparent, replicable, and data-driven decision-making process.

In this paper, potential locations for the installation of parcel lockers in the Brčko DC area will be evaluated using the MCDM model. The IMF SWARA method was used to determine the weights of the criteria, while the WASPAS method was used to rank the alternatives or locations. Finally, a sensitivity analysis was performed, where the results of the decision-making model were presented, showing the most suitable location. In addition to the sensitivity analysis, a comparative analysis was also performed using other MCDM methods such as ARAS, EDAS (Evaluation based on Distance from Average Solution) and MARCOS methods.

3.1 IMF SWARA

This paper will use the IMF SWARA method, which allows for the generation of weighting coefficients based on expert assessments and the relative importance of criteria. The advantage of this method is its flexibility and ease of application, as well as the ability to incorporate expert knowledge into the decision-making process [13].

The IMF SWARA method was first introduced by authors [14].

Within the proposed framework, the IMF SWARA method serves as the intelligent knowledge-processing engine. It systematically aggregates and refines expert judgments by employing fuzzy logic to model linguistic assessments, thereby simulating nuanced human decision-making in ambiguous environments and converting qualitative insights into quantifiable criterion weights.

Figure 2 shows the steps of the IMF SWARA method.

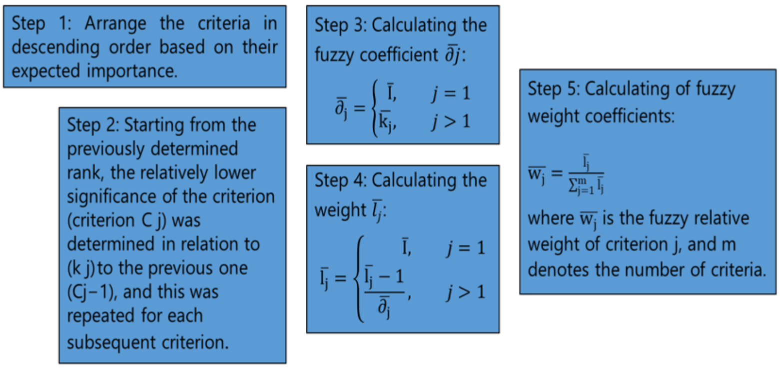

Figure 2. Steps of the IMF SWARA method

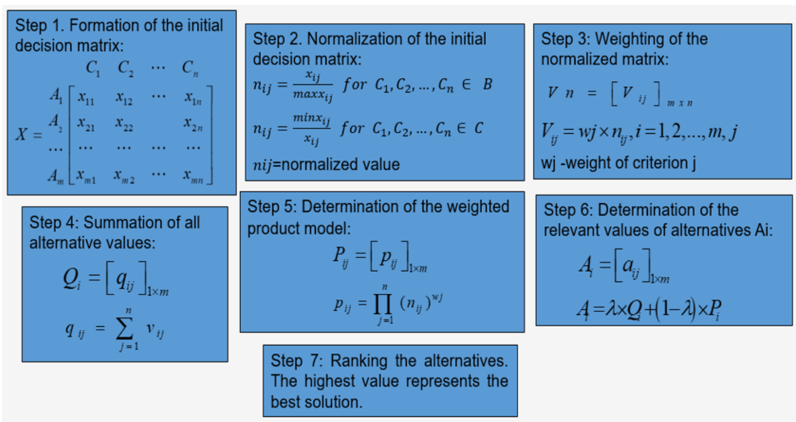

Figure 3. Steps of the WASPAS method

3.2 WASPAS

The WASPAS method was developed in 2012 and is derived from two methods: the WSM and WPM [23]. The steps of the WASPAS method are presented in Figure 3.

A distinctive feature of the WASPAS method, and a key to its adaptability within our decision-support framework, is the aggregation coefficient (λ). This parameter allows decision-makers to calibrate the model's strategy between a risk-averse, additive approach ($\lambda \to 1$) and a risk-tolerant, multiplicative approach ($\lambda \to 0$). This flexibility to incorporate managerial risk preference exemplifies the adaptive nature of an intelligent support system, enabling tailored solutions for different strategic contexts.

4 Urban Logistics Management Concepts

Urban, or city logistics, is the area which covers process of optimizing logistics and transport activities in an urban area, taking into account traffic, environmental and energy factors, i.e. the organization of urban transport with the aim of meeting certain criteria. The tasks and goals of urban logistics are more efficient traffic in cities by reducing the number of freight vehicles, reducing energy consumption, improving the ecological situation and increasing the quality of life in cities [28]. This approach requires cross-sectoral cooperation between the private and public sectors, as well as the introduction of smart technologies, digitalization and spatial management policies. In this context, one of the most challenging and expensive segments of urban logistics is the so-called "last mile delivery", i.e. delivery in the last stage of the logistics chain, which involves the delivery of goods from a local warehouse, micro-distribution center or parcel terminal to the end user [29]. Although it is a relatively short physical distance, the "last mile" phase often generates the highest logistics costs, delays and environmental challenges. Problems associated with this phase include lack of parking space, limited access to central city areas, traffic jams, as well as variability in delivery times [30].

The delivery market is dominated by large logistics companies, such as UPS, FedEx, and DHL, which operate national and global distribution networks. They coordinate the entire flow of a shipment—from pickup at large online retailers and initial sorting at the depot [31], through long-haul transportation and eventual transit through a central hub, to arrival at an urban depot and last-mile delivery. Parts of this process are often outsourced to smaller subcontractors. Amazon or Alibaba do not cover the entire parcel supply chain but focus on the "last mile" delivery. This is precisely why in recent years, there has been increasing investment in alternative delivery models, such as micro-consolidation centers, the use of electric and bicycle delivery vehicles, automated parcel lockers, and delivery by robots and drones. In addition, digital platforms and route management tools, as well as real-time delivery tracking, have enabled logistics companies to respond to changing conditions on the ground, increase delivery accuracy, and minimize customer waiting times [32].

5 Defining the Most Suitable Locations for Installation of Parcel Lockers for the Brčko Distribution Center

The company X Express offers fast, safe, high-quality and reliable delivery services in the territory of Bosnia and Herzegovina. It was founded in 2016 with the aim of setting new standards in the field of express mail services. The network consists of 17 distribution centers, as well as 9 business centers, employing more than 700 people, which have more than 600 vehicles, guaranteeing the highest quality of fast delivery of shipments. This paper focuses on the identification and selection of the most suitable locations for installing parcel lockers in the area covered by the Brčko distribution center. Together with this DC, the cities of Orašje, Šamac and Gradačac are included. Figure 4 shows all potential locations, i.e. alternative options for installing parcel lockers in the specified area.

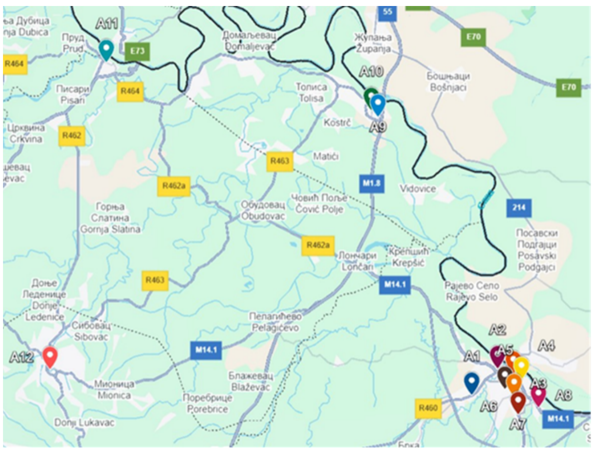

Figure 4. Potential locations of the Brčko DC

The criteria based on which the alternatives were evaluated are: C1—Availability, C2—Accessibility, C3—Costs of maintaining the parcel locker, C4—Safety and security, C5—Density of pedestrian traffic within a small radius of the location, C6 - Frequency of user requests for delivery. Based on the obtained values of the weight coefficients, the ranking according to importance is shown in Figure 5, and according to the importance of the criteria, it can be concluded that the most important criterion is availability, followed by the frequency of user requests for delivery. The third place is the criterion related to accessibility, and the fourth is safety and security. The costs of maintaining parcel lockers are in fifth place, while the density of pedestrian traffic is in last place.

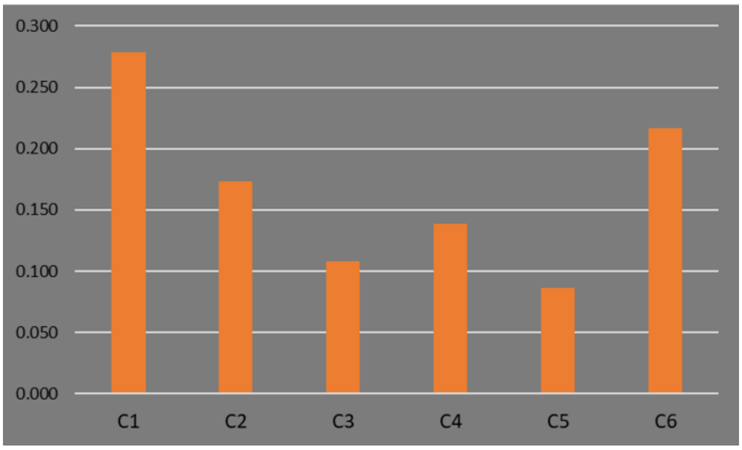

Figure 5. The criteria weights were obtained using the IMF SWARA method

The work then continues with the calculation using the WASPAS method for ranking potential locations and selecting the optimal ones. The results of the WASPAS method are shown in Table 1.

Table 1. Final results obtained using the IMF SWARA -WASPAS model for the Brčko DC

Alternative	P	A	Rank
A1-BČ	0.652	0.673	9
A2-BČ	0.967	0.969	1
A3-BČ	0.830	0.835	3
A4-BČ	0.849	0.859	2
A5-BČ	0.426	0.473	12
A6-BČ	0.762	0.773	5
A7-BČ	0.708	0.728	7
A8-BČ	0.567	0.592	11
A9-Orašie	0.667	0.677	8
A10-Orašje	0.657	0.663	10
A11-Šamac	0.756	0.760	6
A12-Gradačac	0.776	0.782	4

Based on the results obtained, it can be concluded that A2 is the most suitable location for installing a parcel locker. Location A4 holds second place based on the over-all score, followed by location A3 in third position. The locations ranked lowest for the installation of parcel lockers are A8 and A5.

6 Sensitivity Analysis

Sensitivity analysis is a key element of the decision-making process based on multi-criteria analyses, as it allows checking the stability and reliability of decisions made in relation to changes in input parameters, primarily weight coefficients and alternative ratings. According to performed study [33], slight changes in the assigned weights can considerably affect the ranking order of alternatives, which confirms the need for systematic analysis. In this way, the criteria that have the greatest impact on the decision are identified and the robustness of the model itself is assessed. Sensitivity analysis in this paper includes comparative analysis and analysis of the lambda coefficient (λ) in the WASPAS method, which we will present later in the paper.

6.1 Comparative Analysis

In the comparative analysis, the results of ranking the given alternatives obtained by the WASPAS method were compared with the results of other MCDM methods such as: ARAS [34], EDAS [35] and the MARCOS method [36]. The results of the comparative analysis are shown in Figure 6.

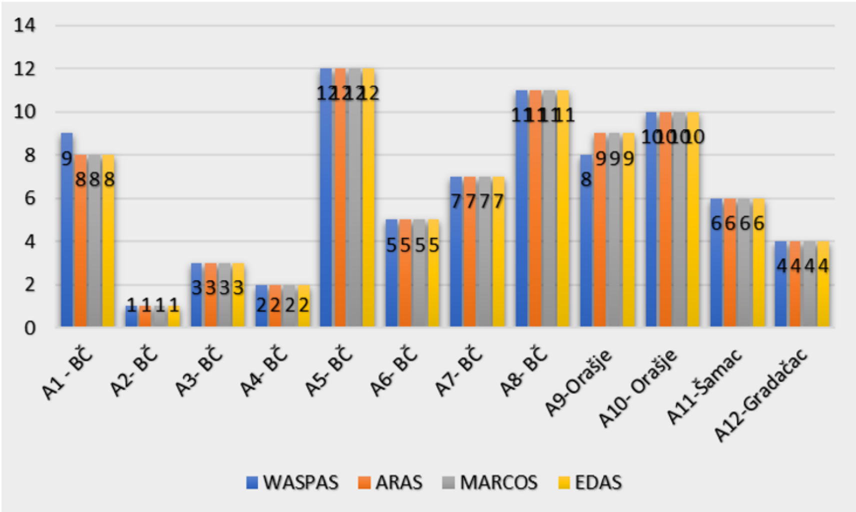

Figure 6. Results of comparative analysis

The results of the comparative analysis show that the results obtained with the WASPAS method are stable, that is, there are no major changes in the ranking of alternatives when other methods are applied, such as ARAS, EDAS and MARCOS methods. Small changes occurred in the A1 and A9 alternatives, but they do not represent great significance because they changed the rank by one place.

6.2 Change of the Lambda Coefficient in the WASPAS Method

Based on the change of the lambda coefficient (λ) that we calculated in the WASPAS method, it is possible to check the stability of the calculated results. In the last step of the WASPAS method, the lambda coefficient (λ) is included with the value $\lambda = 0.5$, which is used standardly in practice. By changing λ, it is possible to monitor how changes in weighting between the linear additive method and the multiplicative evaluation method affect the ranking of each alternative. It also allows the decision maker to discover critical alternatives or criteria that most affect changes in the ranking, which allows focusing attention on key elements of the decision-making. Figure 7 shows the results of the WASPAS method with different values of λ, ranging from 0.1 to 1, on the basis of which the stability of the final ranking of alternatives will be assessed.

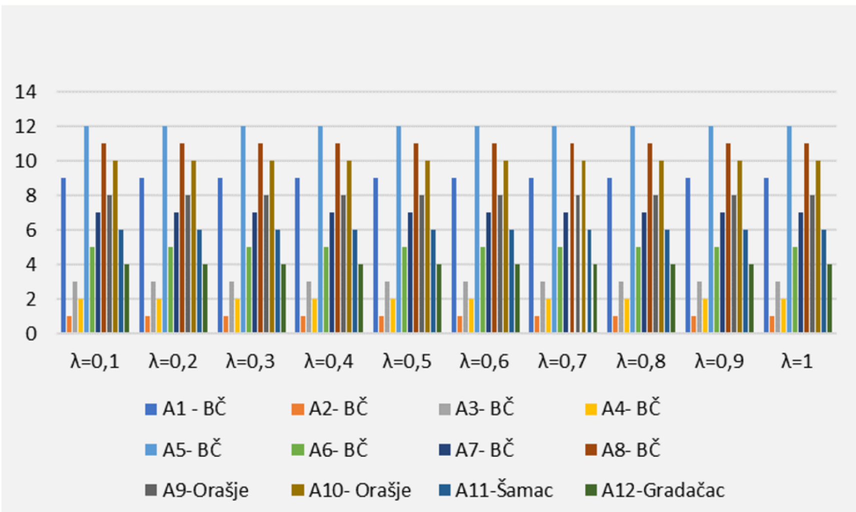

Figure 7. Results of the WASPAS method with different values of λ

Changes in the lambda coefficient λ did not affect the final ranking of the alternatives. All alternatives maintained their ranking position in all changes in the lambda coefficient λ.

7 Discussion

The results presented in Section 5 provide a clear ranking for parcel locker installation. However, the broader value of this study lies in the managerial insights derived from these outcomes and the applicability of the proposed framework.

Managerial Implications of the Ranking

The top-ranked locations (A2, A4, A3) are not merely mathematical outputs but reflect strategic positions that align with key logistical principles. Analysis reveals these sites commonly exhibit high scores in availability, accessibility, and frequency of user requests. For a company like X Express, this implies that prioritizing such locations can simultaneously maximize service coverage, ensure operational reliability, and respond directly to proven customer demand. Investing in these high-potential nodes first allows for efficient capital allocation and a higher likelihood of rapid adoption, directly enhancing last-mile service quality and customer satisfaction.

The Decision-Support Value of the Proposed Framework

Beyond identifying optimal sites for Brčko DC, this research delivers a replicable intelligent decision-support framework. The integrated IMF SWARA-WASPAS model provides X Express, and similar logistics firms, with a structured and transparent methodology. When expanding to new cities or re-evaluating existing networks, managers can directly apply this framework by adapting the criteria and inputs to the local context. This transforms a complex strategic decision into a systematic, data-driven process, reducing reliance on intuition and mitigating investment risk.

Contributions to Sustainable and Smart Urban Logistics

Strategically placed parcel lockers, as identified by the model, contribute significantly to sustainable urban logistics and smart city initiatives. By consolidating deliveries to centralized pickup points, the model inherently promotes a reduction in the number of individual delivery vehicles travelling to dispersed addresses. This leads to decreased vehicle kilometers traveled, lower traffic congestion, and a consequent reduction in carbon emissions and urban noise pollution. Thus, the framework supports not only corporate efficiency but also broader environmental and urban livability goals, aligning logistics operations with the principles of sustainable development.

8 Conclusion

This study addresses the critical management challenge of last-mile delivery optimization by developing and validating an intelligent decision-support framework based on the integrated IMF SWARA and WASPAS methods. The framework was successfully applied to select optimal parcel locker locations for the Brčko distribution center of X Express, demonstrating its practical utility.

The research makes two primary contributions:

(1) Theoretical/Methodological Contribution: It validates the effectiveness and robustness of combining fuzzy set theory (through IMF SWARA) with a hybrid ranking technique (WASPAS) for logistics facility location problems. The sensitivity and comparative analyses confirm that the proposed framework yields stable and reliable results, advancing the methodological toolkit for addressing uncertainty in MCDM within urban logistics.

(2) Practical Managerial Contribution: It provides logistics practitioners with a structured, quantifiable, and intelligent tool for strategic decision-making. The framework guides managers from problem structuring and criteria weighting to alternative ranking and validation, enabling scientific, data-driven planning. This enhances operational efficiency, service levels, and contributes to more sustainable logistics operations.

For future research, the proposed framework can be further enhanced by integrating it into a dedicated DSS with a graphical user interface (GUI), making it more accessible to non-expert users. Furthermore, coupling the model with real-time Geographic Information System (GIS) data and dynamic parameters (e.g., fluctuating demand patterns, real-time traffic) would elevate it into a dynamic and adaptive intelligent system, offering even greater value for real-time logistics management in the evolving smart city landscape.

Author Contributions

Conceptualization, M.F.; methodology, M.F. and S.J.; validation, A.K.; investigation, M.F.; data curation, M.F.; writing—original draft preparation, M.K., A.K.; writing—review and editing, S.J.; supervision, A.K. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare no conflict of interest.

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