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Evaluating sustainable last mile delivery solutions: A multi-criteria decision analysis

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Abstract: The rapid growth of e-commerce and urbanization has caused significant last-mile delivery (LMD) challenges, requiring the implementation of sustainable solutions. To address this issue, this study proposes a new multi-criteria decision-making (MCDM) framework using the Best-Worst Method (BWM) to evaluate and rank different LMD alternatives according to thirteen sustainability criteria of economic, technical, environmental, and social aspects within the context of the Netherlands. This method uses structured pairwise comparisons with experts' perspectives to derive the relative importance of all criteria and the performance scores of all alternatives, ensuring a consistent decision-making process. Results indicate that economic and technical factors are valued higher than environmental and social considerations. Parcel lockers emerged as the most sustainable solution, followed by convenience store pickup, green vehicles, and crowdsourced delivery. The study also proposes several policy and managerial recommendations to help policymakers, logistics providers, and urban planners develop strategies that balance sustainability goals.

Keywords: Last mile delivery; MCDM; BWM; Sustainability

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1 Introduction

Logistics and supply chain management are pivotal in driving global economic activities and facilitating the efficient movement of goods and services across regions and industries (Christopher, 2011). With the rapid pace of urbanization worldwide, city logistics, which is the final phase of supply chain management, has attracted increasing attention as a key contributor to sustainability challenges and a potential driver of negative impacts on urban development (Silva et al., 2023, Melkonyan et al., 2020; Nogueira et al., 2022). In particular, the increased number of freight and commercial vehicles often results in greater traffic congestion and higher emission levels (Bosona, 2020). This is also a significant issue in Europe, where the transport sector is responsible for approximately one-quarter of total greenhouse gas emissions, amounting to 7.98 Gt of CO_2 in 2022, and a vast majority of those originate from road transport (International Energy Agency, 2022). Within this context, last-mile delivery (LMD) has been identified as both the most important phase of the value chain and the most problematic, accounting for more than half of the total shipping costs per order (Blagojević et al., 2023; Gevaers et al., 2014). These challenges are largely attributed to the traditional parcel delivery methods, which require deploying numerous vehicles of varying sizes to meet the increasing dispersed demand, small order quantities, and rising consumer expectations for faster delivery times (Schwerdfeger & Boysen, 2020).

Along with the tremendous expansion of e-commerce, the demand for last-mile delivery (LMD) is also forecasted to increase by 78% by 2030, leading to the number of delivery vehicles growing by 36% in 100 cities across the globe (World Economic Forum et a, 2020). Each relevant stakeholder in this field, including the logistics industry, authorities, citizens, and related business entities, has its own expectations and preferences. In such a complex environment, numerous LMD solutions combined with different initiatives, technologies, and city logistics concepts have been considered. However, it is crucial to develop sustainable last-mile delivery solutions. This approach not only meets customer demands for efficient shipments but also helps optimize costs and reduce environmental impacts.

Evaluating the sustainability of LMD alternatives has been an increasing interest among researchers, with studies conducted across different countries, geographical settings, and urban structures. For instance, in Europe, cargo bikes and crowdsourcing logistics have been explored to reduce emissions and congestion in densely populated cities of the UK and Italy (Bortolini et al., 2022; Schliwa et al., 2015). While several studies focus on electric vehicles and smart parcel lockers in Asian megacities, such as those in China and India, by addressing challenges related to rapid urbanization, high population density, and environmental sustainability (Ding et al., 2023; Kumar et al., 2020), others emphasizes the integration of electric delivery vans and micro-hubs in suburban and urban environments of North American (Schorung et al., 2023).

The evaluation of LMD solutions required considering a wide range of criteria, such as cost efficiency, environmental impact, customer satisfaction, and operational feasibility, as identified in previous academic literature. These criteria are expected to have varying levels of importance depending on the preferences of different stakeholders. However, single-objective methods often lack a structured approach needed to incorporate both qualitative and quantitative factors while balancing trade-offs between conflicting objectives. Therefore, multi-criteria decision analysis (MCDA) methods should be used to solve this task, which assists decision-makers in considering a wide set of objectives and evaluating different alternatives in the context of complex strategic decisions. There are applications of different MCDA tools to explore last-mile operations, such as the Analytic Hierarchy Process (AHP) (Aljohani & Thompson, 2019; de Araújo, Dos Reis, et al., 2022; Gogas et al., 2017; Kijewska et al., 2018; Rudolph et al., 2022; Rześny-Cieplińska & Szmelter-Jarosz, 2019; Serrano-Hernandez et al., 2021; X.-Y. Wang et al., 2021), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) (Aljohani & Thompson, 2019; Melkonyan et al., 2022; Rudolph et al., 2022), or Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Madleňák & Madleňáková, 2020; Nur et al., 2020; Resat, 2020).

Although studies on sustainable LMD alternatives have been conducted in various countries, such as Germany, China, and the United States, there is limited research specific to the Netherlands, a country with unique urban characteristics, advanced transport infrastructure, and commitment to sustainable development. Dutch cities feature highly dense and well-connected urban structures, extensive cycling networks, and efficient public transportation systems that promote low-emission mobility (Geurs & van Wee, 2000). Furthermore, the Dutch government has set ambitious sustainability goals, such as achieving zero-emission zones in major cities by 2030, encouraging logistics providers to adopt environmentally friendly delivery solutions (Geurs & van Wee, 2000). These conditions provide significant opportunities to implement innovative last-mile delivery (LMD) alternatives to address urban congestion, reduce emissions, and meet growing e-commerce demands. However, existing literature does not fully address how LMD alternatives perform together within the Dutch context, particularly through a structured, multi-criteria framework. They largely focused on isolated LMD solutions in the Netherlands, such as cargo bikes, electric delivery vehicles, and parcel lockers (Balm et al., 2017; Molin et al., 2022; Moolenburgh et al., 2020).

By addressing these issues, this research aims to evaluate the importance of different sustainability criteria and rank the innovative LMD solutions based on these attributes of their application in the real-life logistics system of the Netherlands. We integrate the Best-Worst Method (BWM) that has not been applied to LMD operations to our best knowledge to evaluate the sustainability of different LMD solutions for the e-commerce industry in the Dutch context. This study also offers a more integrated decision-making approach by applying BWM comprehensively for both criteria weighting and alternative evaluation, addressing the limitation that most existing studies focus solely on deriving criteria weights. Besides considering various criteria on economic, social, and environmental aspects based on the Triple bottom-line framework of sustainability, technical factors are also included. While the BWM method can be easily applied and understood with simple application procedures, it is proven to provide results of pairwise comparisons with higher consistency levels than other MCDA methods (Rezaei et al., 2023). Moreover, the recent empirical findings have indicated that BWM outperforms many other MCDA methods in minimizing cognitive biases, such as anchoring and equalizing bias (Rezaei, 2022). It suggests that decision-makers' judgments are less influenced by biases, leading to more reliable evaluations. This study has both theoretical and practical implications, providing decision-makers with greater insight into which LMD alternatives are the most promising initiatives for sustainable development, while the method and derived weights can be used for further research.

The remainder of this paper is structured as follows: Section 2 provides the set of criteria for sustainable LMD evaluation and different LMD solutions as alternatives identified from the literature review. Section 3 explains the methodology in detail. Section 4 presents the results of the criteria-weighting process. Sections 5 and 6 discuss the achieved results against previous studies and insightful recommendations, respectively. In the final part, the conclusion and future research directions are given.

2 Literature Review

This section provides an overview of relevant studies on two main aspects, (1) LMD alternatives in specific contexts of different countries, and (2) sustainability factors considered for LMD evaluation, then points out the research gap to define the main objectives.

2.1 LMD alternatives in specific contexts

The development and evaluation of LMD solutions have gained significant attention in recent years due to their potential to provide valuable insights for relevant stakeholders, including logistics providers and urban governments. Numerous initiatives have been introduced to mitigate the negative impacts of LMD phase while improving its operational efficiency. Accordingly, several studies have been conducted to explore this topic using various approaches, as well as in different geographical contexts. For example, Kijewska et al. (2018) conducted a multi-criteria assessment of sustainable urban freight transport measures in Poland from the perspective of logistics operators and found that alternative delivery systems, such as parcel lockers, are considered favorably in terms of feasibility and environmental impacts. The use of parcel lockers is also evaluated as the most favorable LMD solution for historic centers in Portugal, according to an AHP-TOPSIS approach with three sustainability dimensions serving as criteria in the study of Silva et al. (2023). Meanwhile, Nocerino et al. (2016) chose to focus on examining the efficiency of electric vehicles for urban deliveries as well as their contribution to mitigate impacts in these areas compared to the traditional ones in the Italian context. Besides, the study conducted by Kumar & Bharj (2020) offered an initial integration strategy for crowdsourcing delivery by evaluating the feasibility of a new LMD solution called "solar hybrid e-cargo rickshaws" for urban logistics in India regarding the cost-effectiveness and energy-saving objectives for perishable products. Also addressing challenges in developing economies, C.-N. Wang et al. (2023) proposed a novel hybrid multi-criteria decision-making (MCDM) model to assess five LMD solutions in Vietnam regarding their sustainable implementation with twelve sustainability factors. Furthermore, Figliozzi (2020) discussed the efficiency of LMD solutions using drones and other ground vehicles in the US, especially regarding environmental impacts. Leyerer et al. (2020) investigated a hybrid LMD solution integrating parcel lockers and electric cargo bikes regarding the operational efficiency with the case study in the city of Hannover in Germany. Nakayama & Yan (2019) proposed the methodology for evaluating the accessibility of convenience stores and their roles in addressing the redelivery issues in Aoba Ward, Yokohama City, which is part of the Tokyo Metropolitan Area in Japan.

Despite the Netherlands' advanced infrastructure and ambitious sustainability goals, there is limited research on LMD solutions in the Dutch context. For instance, studies on cargo bikes highlight their effectiveness in reducing emissions and congestion, particularly in cities like Amsterdam and Utrecht, where dedicated cycling infrastructure facilitates their integration into urban logistics (Balm et al., 2017). Similarly, research on electric vehicles (EVs) demonstrates their feasibility as low-emission alternatives to traditional delivery vans, aligning with the Netherlands' goal of establishing zero-emission zones by 2030 (Quak, Nesterova, van Rooijen, et al., 2016). Other studies have explored urban consolidation centers (UCCs), with pilot programs in Rotterdam and Amsterdam, showing promising reductions in vehicle trips and emissions. However, challenges related to cost efficiency and scalability have limited their widespread adoption (van Rooijen & Quak, 2010). Emerging solutions like parcel lockers and convenience store pickups have also been examined, reflecting the growing demand for flexible and sustainable delivery options. Parcel lockers are increasingly deployed in urban areas to consolidate deliveries and reduce failed delivery attempts, while convenience store pickups leverage the dense network of Dutch retail outlets to offer practical alternatives to home deliveries (Molin et al., 2022; Weltevreden, 2008). More recently, crowdsourcing delivery has gained attention in the Netherlands, with emerging platforms like UberEats and Trunkrs. This solution utilizes innovative shared-economy models to improve delivery efficiency while reducing environmental impact (Lin et al., 2020). However, these studies often focus on specific alternatives, leaving a gap in holistic evaluations that compare multiple LMD solutions in terms of sustainability dimensions. To fulfill this gap, our study aims to provide a comprehensive, stakeholder-driven evaluation of key LMD alternatives in the urban logistics context of the Netherlands.

Based on the literature review of various LMD initiatives, a comprehensive set of most investigated LMD solutions is determined to be further evaluated in this study, including green vehicles, parcel lockers, convenience store pickup and crowdsourcing delivery. Table 1 presents the explanation and the frequency of these LMD solutions in previous studies.

Table 1: Review of initiatives, solutions, and technologies of last-mile delivery

LMD Solutions	Explanation	References
Green Vehicles	The fleet in LMD that do not run on fossil fuels instead use electric/ hydrogen/ hybrid/ manual source of energy, such as cargo bikes, electric vehicles (EVs), autonomous vehicles (AVs), and drones.	Krstić et al., 2021; Lebeau et al., 2018; Nocerino et al., 2016; Tadić et al., 2014; Baum et al., 2019; Das et al., 2017; Figliozzi, 2020; Jennings & Figliozzi, 2019; Jones et al., 2020; Kim et al., 2020; S. Kumar & Bharj, 2020; Melo & Baptista, 2017; Popović et al., 2019; Quak, Nesterova, & van Rooijen, 2016; Rudolph & Gruber, 2017; Schliwa et al., 2015
Parcel Locker	An unattended parcel locker system is located at designated locations, which customers could choose for their orders during the online checkout process. Parcels can be delivered 24/7 and are safely stored until customers are ready to collect at their convenience. Customers are also given a code to access their packages.	Ducret, 2014; González-Varona et al., 2020; Leyerer et al., 2020; Vakulenko et al., 2018; J. H. R. van Duin et al., 2020; Iwan et al., 2016; Krstić et al., 2021
Convenience Store Pickup	This model utilizes the advantage of a widespread network of convenience store chains to use those as pick-up point hubs for e-commerce consumers. E.g. I can place an order on an e-commerce website and choose to receive my order from a nearby convenience store at Albert Heijn.	Collins, 2015; Haider et al., 2022; McLeod et al., 2006; Morganti et al., 2014; Nakayama & Yan, 2019; Seiders et al., 2000; C.-N. Wang et al., 2023; Xu & Hong, 2013; Gielens et al., 2021; Yuen et al., 2018
Crowdsourcing Delivery	This solution involves the participation of a community, individual citizens, or organizations, who will take on the responsibilities of shipping goods to consumers or providing short-term storage in case the home delivery fails.	Castillo et al., 2018; Devari et al., 2017; Estellés-Arolas & González-Ladrón-de-Guevara, 2012; Giret et al., 2018; Huang & Ardiansyah, 2019; Jeremić & Andrejić, 2019; Qi et al., 2018; Y. Wang et al., 2016; Huang & Ardiansyah, 2019; Krstić et al., 2021; Y. Wang et al., 2016

2.2 Sustainability factors considered for LMD evaluation

The evaluation of sustainable LMD solutions involves analyzing multiple factors related to different aspects of sustainable development goals. In MCDA, these factors are referred to as criteria, and their assessment by stakeholders ultimately shapes the decision-making outcomes. Therefore, this section reviews the most used criteria in previous literature that specifically address LMD evaluation.

Bruzzone et al. (2021) stated that sustainability should encompass more than only environmental aspects. It must also include operational and social performance factors. European Commission (2007) highlighted the sustainable development of urban mobility within the EU, emphasizing the environmental, economic, and social aspects. Several studies have investigated these sustainability aspects within the logistics sector, particularly the last mile. Jiang et al. (2023) developed a comprehensive framework for sustainable urban road alignment, considering cost, social, and environmental factors. In a study of Bosona (2020), cost efficiency, customer satisfaction, and environmental considerations are highlighted based on their importance for LMD evaluation. Similarly, Silva et al. (2023) indicated that economic sustainability is the most critical dimension when evaluating new LMD solutions in urban logistics.

The triple bottom line (TBL) model was developed by (Jeurissen, 2000). It is a widely applied framework for assessing sustainability, including three specific dimensions: economic, environmental, and social. Beyond focusing solely on profitability, the TBL theory incorporates environmental sustainability and the respectful treatment of society (Savitz, 2013). This approach emphasizes the comprehensive responsibilities of organizations (Jamali, 2006) and aligns with the sustainability principles in urban logistics (F. Jiang et al., 2023). According to the TBL model, all three dimensions must be equally considered when assessing the sustainability of a product, company, or strategy (Jeurissen, 2000). This framework has been widely applied to explore factors influencing the acceptance of sustainable concepts in various fields. For instance, Goh et al. (2020) examined sustainable construction by evaluating its characteristics based on financial, social, and environmental factors. Besides, the TBL model has also been used in the context of corporate social responsibility in eco-innovation (Pan et al., 2021), Industry 4.0 (Khan et al., 2021), and logistics (Nikolaou et al., 2013).

However, to reflect the importance of assessing the quality of different LMD solutions, the technical aspect is also included to complement the three traditional sustainability pillars of economic, environmental, and social (Garus et al., 2022). For each of these aspects, different objectives were defined, aligning with the direction of global and regional mobility policies. A set of corresponding criteria was then summarized based on the findings of previous research, including only articles that met the following requirements: (1) focused on sustainability practices in LMD, (2) written in English, and (3) published in peer-reviewed journals. Other studies related to public or passenger transport, hospital or humanitarian logistics, telecommunication networks, tourism, and electricity distribution were excluded from consideration. Table 2 presents the explanation and the frequency of these evaluation criteria in previous studies.

Table 2: Review of evaluation criteria on LMD solution

Criteria	Sub-criteria	Explanations	References
Technical	Efficiency	It indicates to what extent the logistics solutions have been optimized, considering indicators such as loading ratio, volume capacity, traveled distance, energy utilization, average lead time, etc.	Awasthi & Chauhan, 2012; Büyüközkan & Uztürk, 2020; Krstić et al., 2021; Švadlenka et al., 2020; C.-N. Wang et al., 2021
	Reliability	It refers to the level of reliance on the type of LDM solution based on on-time-delivery, quality, i.e. damage rate of goods, delays or bottlenecks, resistance to bad weather conditions	Awasthi & Chauhan, 2012; Krstić et al., 2021; Švadlenka et al., 2020; Tadić et al., 2018
	Flexibility	It assesses the ability of the logistics solutions to adapt and respond to unexpected fluctuations in demand and unforeseen crises (such as Covid-19)	Awasthi & Chauhan, 2012; Krstić et al., 2021; Švadlenka et al., 2020; C.-N. Wang et al., 2021
	Traceability & information security	It refers to the safety of personal information, including products and customer data	Büyüközkan & Uztürk, 2020; C.-N. Wang et al., 2021
Economic	Cost of implementation	It involves all the major costs for the development or implementation of LMD solutions (implementation, land and equipment acquisition, partnerships)	Szmelter-Jarosz & Rześny-Cieplińska, 2019; Janjevic et al., 2016; Krstić et al., 2021; C. N. Wang et al., 2023
	Cost of operation	It involves all the major costs for running and sustaining the LMD solutions (energy, wages, other logistical expenses)	Krstić et al., 2021; Švadlenka et al., 2020; C.-N. Wang et al., 2023
	Cost of insurance and taxes	It involves all insurance and taxes as per the Government regulations	Krstić et al., 2021; Švadlenka et al., 2020
Social	Consistency with urban planning	It considers the extent to which the logistics solution supports urban development and enhances the attractiveness of areas by optimizing operations and freeing up public spaces	Krstić et al., 2021; Lebeau et al., 2018; Tadić et al., 2018; van Heeswijk et al., 2019; C.-N. Wang et al., 2021
	Accessibility	It refers to the convenience for the consumers and freight vehicle movement, achieved with the implementation of the solution	Awasthi & Chauhan, 2012; Krstić et al., 2021; Tadić et al., 2018
	Co-operation of Stakeholders	These new LMD solutions could be disruptive, hence, this sub-criterion defines the acceptability of the stakeholders and their competence to implement the new solution	Büyüközkan & Uztürk, 2020; Krstić et al., 2021; C.-N. Wang et al., 2023
Environmental	Air pollution	It refers to the impact of logistics solutions on the amount of harmful gases and emissions by delivery vehicles	Krstić et al., 2021; Švadlenka et al., 2020; C.-N. Wang et al., 2021, 2023
	Energy savings	It refers to the reduction in energy consumption by implementing the sustainable LMD solution, thus indicating the energy efficiency of the solution	Krstić et al., 2021; Švadlenka et al., 2020; C.-N. Wang et al., 2021, 2023
	Waste generation	It refers to the average volume of hazardous materials and solid wastes generated during the operation and after the life cycle, such as tires, batteries	Krstić et al., 2021; Lebeau et al., 2018; van Heeswijk et al., 2019; C.-N. Wang et al., 2023

2.3 Position of this Research

From the literature review, it is observed that there is currently no research providing a holistic evaluation to compare different innovative LMD solutions in terms of sustainability within the context of the Netherlands. This study aims to address this gap by developing a new decision-making approach that integrates the Best-Worst Method (BWM), due to its significant advantages in mitigating anchoring bias and producing more consistent and reliable results, compared to other structural pairwise comparison methods, such as AHP (Analytic Hierarchy Process) (Rezaei, 2015). To the best of our knowledge, this method has not yet been applied to LMD operations (see Table 3). Moreover, unlike most studies that use BWM only for weighting criteria, this research applies it fully to both criteria weighting and alternative evaluation. The evaluation incorporates stakeholder perspectives in the Dutch urban logistics context. In addition to assessing economic, social, and environmental aspects based on the triple bottom line sustainability framework, technical factors are also included, as LMD solutions inherently involve diverse technologies and innovations. This study is crucial for identifying the most effective and sustainable alternatives and promoting their practical implementation in the Netherlands. By considering multiple criteria and stakeholder insights, the study aims to guide policymakers and logistics providers in making decisions that align with the national sustainability goals and urban planning strategies.

Table 3: Summary of relevant literature applying decision-making approaches in LMD

Authors	Research focus	Method	Alternatives	Criteria	Location
Aljohani & Thompson, (2019)	Delivery configurations in the inner-city area	Fuzzy AHP, PROMETHEE	A set of consolidated delivery fleet configurations	Environmental, social, operational, economic	Australia
Bonilla et al., (2024)	Sustainable last-mile logistics practices	DEMATEL	A set of nine last-mile logistics practices	Economic, social, environmental	Brazil
Büyüközkan & Uztürk, (2020)	LMD strategies	AHP, VIKOR	A set of eight LMD strategies	A set of evaluation criteria based on the SWOT analysis	Turkey
de Araújo, dos Reis, et al., (2022)	Decision-making of logistics service providers	Fuzzy AHP	Small truck, motorcycle, drone delivery, smart lockers, multi-modal delivery	Delivery point, time and speed, tracking and tracing, value-added services, security, cost	Brazil
Krstić et al., (2021)	Evaluation of sustainable last-mile solutions	Delphi, FARE, and VIKOR	A set of solutions combining different LMD initiatives	Environmental, social, technical, economic	Serbia
Rześny-Cieplińska & Szmelter-Jarosz, (2019)	Crowd logistics solutions	AHP	A set of crowd logistics (CL) solutions provided by different CL providers	Economic, social, environmental	-
C.-N. Wang et al., (2023)	Sustainable last-mile solutions (LMSs)	OPA and fuzzy MARCOS	Convenience store pickup, parcel lockers, green vehicles, autonomous vehicles, crowdsourcing delivery	Environmental, social, technical, economic	Vietnam
Awasthi & Chauhan, (2012)	City logistics initiatives for improving city sustainability	AD, AHP, fuzzy TOPSIS	Vehicle sizing restrictions, congestion charging schemes, urban distribution center, access timing restrictions	Environmental, social, technical, economic	France

He et al., (2016)	The performance of joint distribution alliance	SE, AHP, TOPSIS	Different partner combinations	Economic, social, environmental, flexible	China
Wątróbski et al., (2017)	Electric freight vehicles (EFVs)	PROMETHEE II, fuzzy TOPSIS	A set of EFVs options	Performance, battery, engine, price	Poland
Amchang & Song, (2018)	Consolidation facility location of LMD	AHP	A set of districts for LMDC location	Delivery service, environment and social preference, policy and regulation, costs	Thailand
X. Jiang et al., (2019)	Rural LMD indicator	Fuzzy AHP, ISM, MICMAC	-	Service convenience, responsiveness, reliability, empathy, economy	China
Zhao et al., (2019)	LMD options	TOPSIS	Four basic distribution options	A set of factors influencing the customers' acceptance	Slovakia
Melkonyan et al., (2020)	LMD distribution channel options	SDS, PROMETHEE	A set of different distribution network designs	Environmental, social, technical, economic	Austria
Zheng et al., (2020)	Optimal facility for a parcel-pickup point	GIS, AHP	A set of candidate facilities	Operation hours, distance to bus stops, facility type, facility area	China
Silva et al., (2023)	Last-mile solution for historic centers	AHP-TOPSIS	Electric vehicle, parcel locker, cargo bike, crowdsourcing	Economic, social, environmental	Portugal
This study	*Sustainable LMD solutions evaluation*	*BWM*	*Green Vehicles, Parcel Locker, Convenience Store Pickup, Crowdsourcing Delivery*	*Environmental, social, technical, economic*	*Netherlands*

AD: Affinity Diagram, Analytic Hierarchy Process: AHP, Best Worst Method: BWM, Decision-making trial and evaluation laboratory: DEMATEL, Factor Relationship: FARE, Geographical Information System: GIS, Interpretive structural modeling: ISM, Measurement of alternatives and ranking in accordance with compromise solution: MARCOS, Cross-impact matrix-multiplication: MICMAC, Ordinal Priority Approach: OPA, Preference Ranking Organization Method for Enrichment Evaluation: PROMETHEE, System dynamics simulation: SDS, Shannon entropy: SE, Technique for Order of Preference by Similarity to Ideal Solution: TOPSIS, Multi-Criteria Optimization and Compromise Solution: VIKOR.

3 Research Methodology

The goal of this study is to determine the most sustainable last-mile delivery (LMD) option. It evaluates four LMD options—Green Vehicles, Parcel Lockers, Convenience Store Pickup, and Crowdsourcing Delivery—from a technical, financial, social, and environmental perspective using a multi-criteria hierarchy. Efficiency, cost, accessibility, and pollution reduction are key factors. To ensure high consistency in comparisons, the Best-Worst Method (BWM) was employed, ranking each criterion based on expert input. This framework facilitates a clear and balanced assessment, aligning the performance of each solution with the strategic objectives of cost-effectiveness, sustainability, and urban compatibility.

In the first step of the research, an extensive literature review was conducted to identify the four LMD options along with the relevant criteria and sub-criteria for these LMD solutions (alternatives). All sub-criteria were clearly defined and categorized under their respective criteria. In the second step, a survey was designed using SoScisurvey.de to perform the linear BWM pairwise comparison. Responses from 22 experts in Supply Chain Management were gathered. These experts include researchers and industry professionals, particularly those who specialize in LMD solutions. Furthermore, in the third step of the research, the collected survey responses were analyzed to calculate the global weights for each sub-criterion and alternative, allowing for the ranking of each alternative based on these weights. Figure 1 illustrates the complete flowchart of the research methodology utilized for this study.

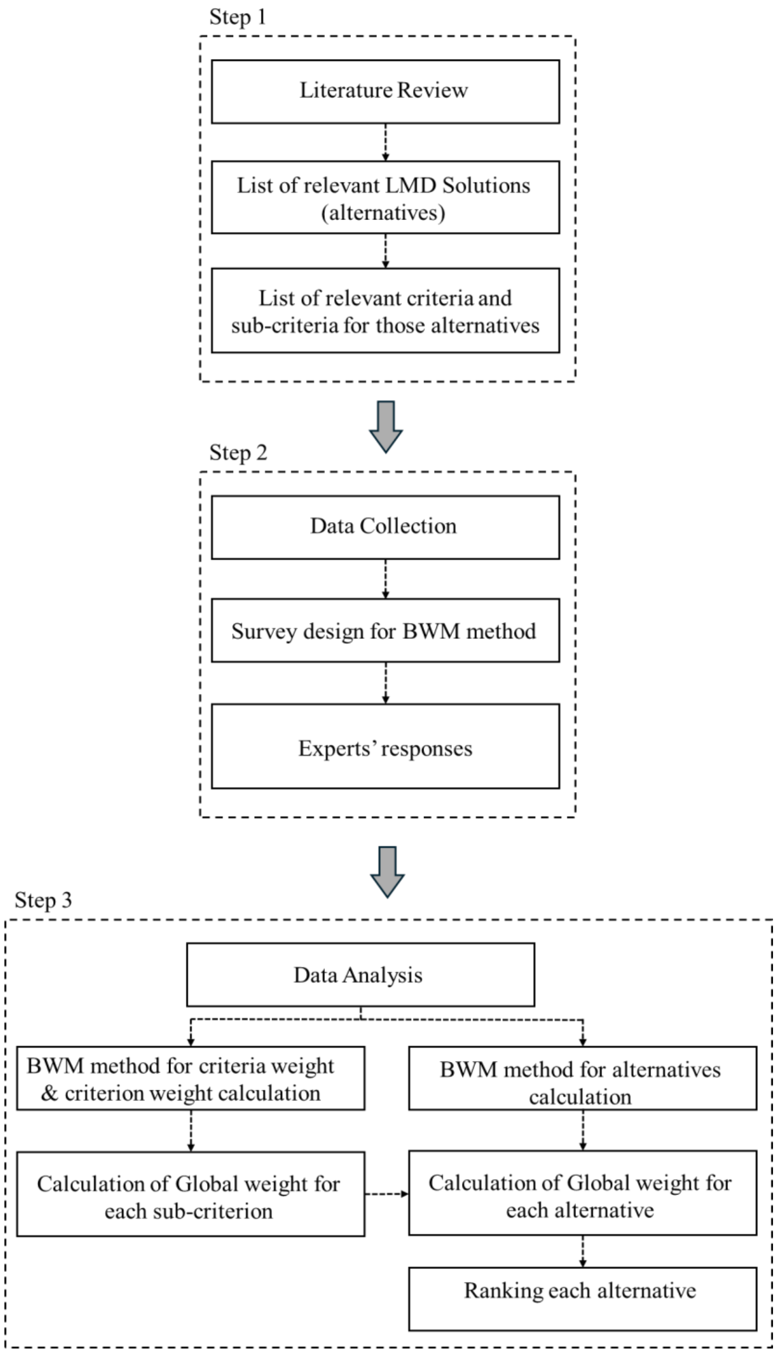

Figure 1: Flowchart for research methodology

3.1 Best-Worst Method

The Best Worst Method (BWM), introduced by Rezaei (2015), is a structured MCDA approach that enables decision-makers to carry out evaluations systematically using pairwise comparisons. It employs two pairwise comparison vectors, constructed by identifying the most and least preferred criteria as reference points. In comparison with the other MCDM Methods, BWM has two major advantages. First, it needs less pairwise comparison data compared to a full pairwise comparison matrix (Rezaei, 2015). Second, the results generated are more consistent than other methods with full pairwise comparisons. The method has been proven effective and was used in several real-life problems, such as supply chain sustainability innovation (Gupta et al., 2020), ecosystem data governance (De Prieëlle et al., 2022), circular economy (Moktadir et al., 2020), supplier selection in online retail (Kaushik et al., 2022) and location selection problems (Kheybari et al., 2019).

The linear Best-Worst Method (BWM) offers significant advantages in addressing cognitive biases and enhancing data efficiency in multi-criteria decision-making (MCDM). By requiring decision-makers to identify only the most and least important criteria, BWM reduces the cognitive load associated with extensive pairwise comparisons. This structured approach mitigates common biases such as anchoring, where initial information unduly influences judgments, and equalizing bias, which leads to assigning similar importance to all criteria. Consequently, BWM enhances the reliability and consistency of the elicited preferences (Rezaei, 2022).

Moreover, BWM is more data-efficient than traditional methods like the Analytic Hierarchy Process (AHP). While AHP requires a complete set of pairwise comparisons, BWM significantly reduces the number of comparisons needed, streamlining the decision-making process without compromising accuracy. This efficiency is particularly beneficial in complex decision scenarios where the number of criteria is large (Wu et al., 2024).

These attributes make the linear BWM a robust and practical tool for deriving reliable criteria weights in various MCDM applications.

The BWM (Rezaei, 2015, 2016) for weighing the criteria and alternatives is structured as follows:

Step 1: Identify a set of decision-making criteria $(c_1, c_2, \ldots, c_n)$. Similarly, for alternatives, a set of alternatives $(a_1, a_2, \ldots, a_n)$ was also identified to be assessed against each decision-making criterion.

Step 2: For each main criterion, the best (most important) and worst (least important) sub-criteria are identified by the experts. Subsequently, the best and worst among the main criteria are also determined. Similarly, the best and worst alternatives are selected against each sub-criterion.

Step 3: In this step, the preference of the best sub-criterion over all the other sub-criteria within the same cluster is determined by the experts. Pairwise comparison among the main criteria is also conducted. Similarly, the preference of the best alternative over all the other alternatives according to each sub-criterion is determined. These comparisons use a scale from 1 to 9, where 1 implies equal importance and 9 means extreme importance.

The Best-to-Other vector is: $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$ where, a_{Bj} refers to the preference of the best criterion B over the criterion j.

Step 4: Pairwise comparison is made by the experts for each sub-criterion against the worst sub-criterion using a 1–9 scale. The same method is applied to alternatives and main criteria, yielding the Others-to-Worst vector: $A_W = (a_{1W}, a_{2W}, \dots, a_{nW})^T$, where a_{jW} is the preference of the factor j over the worst criterion W.

Step 5: According to (Rezaei, 2016) the optimal weights $(w_1^*, w_2^*, \dots, w_n^*)$ are calculated, where we have to find a solution by which the maximum differences of $\left|w_B - a_{Bj}w_j\right|$ and $\left|w_j - a_{jW}w_W\right|$ should be minimized. This is translated to the following mathematical model:

$$\min max_j\{\left|w_B - a_{Bj}w_j\right|, \left|w_j - a_{jW}w_W\right|\}$$

such that

$$\sum_j w_j = 1, \quad w_j \geq 0, \text{ for all } j \tag{1}$$

Model (1) is equivalent to the following model:

$$\min \xi,$$

such that

$$\begin{gathered} \left|w_B - a_{Bj}w_j\right| \leq \xi, \text{ for all } j \\ \left|w_j - a_{jW}w_W\right| \leq \xi, \text{ for all } j, \\ \sum_j w_j = 1 \\ w_j \geq 0, \text{ for all } j \end{gathered} \tag{2}$$

Solving model (2) results in the optimal weights $(w_1^*, w_2^*, \dots, w_n^*)$ and ξ^*.

The consistency ratio is calculated using the following formulas for input-based BWM (Liang et al., 2020):

$$CR = \max_j CR_j$$

Where,

$$CR_j = \begin{cases} \frac{\left|a_{Bj} \times a_{jW} - a_{BW}\right|}{a_{BW} \times a_{BW} - a_{BW}}, & a_{BW} > 1, \\ 0, & a_{BW} = 1. \end{cases} \tag{3}$$

The calculated consistency ratio is then compared to the threshold values presented in Table 4 below.

Table 4: Thresholds for different combinations using input-based consistency measurement (Liang et al., 2020)

Scales	Criteria						
	3	**4**	**5**	**6**	**7**	**8**	**9**
3	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
4	0.1121	0.1529	0.1898	0.2206	0.2527	0.2577	0.2683
5	0.1354	0.1994	0.2306	0.2546	0.2716	0.2844	0.2960
6	0.1330	0.1990	0.2643	0.3044	0.3144	0.3221	0.3262
7	0.1294	0.2457	0.2819	0.3029	0.3144	0.3251	0.3403
8	0.1309	0.2521	0.2958	0.3154	0.3408	0.3620	0.3657
9	0.1359	0.2681	0.3062	0.3337	0.3517	0.3620	0.3662

After collecting all the responses from experts, the local average weights of all main criteria and sub-criteria are calculated based on the geometric mean method. The local average weight of each sub-criterion is multiplied by its respective main criterion to get the global weight of that sub-criterion.

Similarly, step 5 is also followed for the alternatives. The local average weights of the alternatives are multiplied by the respective global weight of the sub-criterion. These steps are performed for all 13 sub-criteria. These values for each alternative are summed up to get the global weights for all alternatives. Based on the value of these global weights, the alternatives are ranked.

3.2 Data collection

In this study, experts' opinions are collected to determine the criteria weights and performance scores of all alternatives, leveraging their in-depth knowledge of initiatives, instruments, and the effectiveness of each solution in addressing the sustainability aspects. Experts were identified through their online profiles, which showcased extensive research experience or practical industry expertise related to last-mile delivery. Their insights were collected via an online survey conducted through the SoSci survey platform.

A total of 103 experts were contacted via email and other social media platforms. After removing incomplete responses, 22 valid responses were retained for analysis. Among the respondents, 12 (55%) were researchers from Delft University of Technology and other universities, while the remaining 10 (45%) were industry experts working in municipalities and several organizations across the Netherlands. The participants had an average of 15 years of work experience. Table 5 below presents an overview of the experts.

Table 5: Overview of experts' profile

Expert	Position	Type of Industry	Years of experience
1	Researcher	Education	2
2	Researcher	Education	30
3	Consultant	Consultancy (Procurement)	4
4	Researcher	Education	30
5	Researcher	Education	23
6	Planning Specialist	Logistics (Delivery Service)	5
7	Researcher	Education	5
8	Researcher	Education	3
9	Systems Engineer	Government	8
10	Researcher	Education	7
11	Logistics consultant	Government	35
12	Researcher	Education	34
13	Program Developer	Logistics	17
14	Researcher	Education	4
15	Researcher	Education	1
16	Citizen Committee Member	Government	10
17	CEO	Logistics	35
18	Banker Sector Mobility	Mobility	15
19	Operations Leader	Logistics	11
20	Researcher	Education	3
21	Researcher	Education	7
22	Managing Director	Logistics	35

4 Results

This section presents the results obtained using the BWM method. As outlined in the methodology section, 22 experts from various logistics-related organizations in the Netherlands were approached to compare the factors associated with sustainability evaluation using BWM. This process derived the weights for the main criteria and corresponding sub-criteria. Subsequently, the experts evaluated four LMD solutions—green vehicles, parcel lockers, convenience store pickup, and crowdsourced delivery—against those sustainability criteria using the same method, resulting in the final ranking. The consistency of the pairwise comparisons provided by the experts was assessed based on the thresholds specified in Table 4, and all responses were found to be acceptable.

4.1 Weight of the sustainability criteria and sub-criteria

Table 6 below shows the aggregated weights of the technical, economic, environmental and social aspects (the four main criteria) as well as their corresponding sub-criteria.

Table 6: Final BWM results for criteria and sub-criteria weights and ranking

Main criteria	Weight	Sub-criteria	Local weight	Global weight*	Ranking
Technical	0.2215	Efficiency	0.2386	0.0833	4
		Reliability	0.3543	0.1237	2
		Flexibility	0.1250	0.0437	11
		Traceability and information security	0.1166	0.0407	12
Economic	0.2682	Cost of implementation	0.2063	0.0872	3
		Cost of operation	0.5383	0.2276	1
		Cost of insurance and taxes	0.1185	0.0501	9
Social	0.1372	Consistency with urban planning	0.2129	0.0460	10
		Accessibility	0.2961	0.0640	7
		Co-operation of Stakeholders	0.2326	0.0503	8
Environmental	0.1518	Air pollution	0.3290	0.0787	5
		Energy savings	0.3177	0.0760	6
		Waste generation	0.1204	0.0288	13

**Note: Only the global weights were normalized, whereas the local weights were calculated using geometric means and remained unnormalized.*

The results indicate that experts assigned the highest importance to the economic aspect (0.2682), followed closely by the technical aspect (0.2215). These two dimensions are found significantly more critical than the environmental (0.1518) and social (0.1372) aspects. This finding aligns with trends observed in previous studies, where the Economic dimension was consistently regarded as the most influential pillar of sustainability alongside the other dimensions (Bonilla et al., 2024; de Araújo, Dos Reis, et al., 2022; Silva et al., 2023). The Netherlands' economic background, which is characterized by the strategic role as a logistics hub, high labor costs, competitive e-commerce market, and supportive regulations, could significantly influence the prioritization of economic aspect in sustainability evaluations.

Within the technical dimension, reliability emerged as the most critical sub-criterion, similar to the result of Švadlenka et al. (2020) with the global weight of 0.1237. It is slightly more important than efficiency with the global weight of 0.0833. Both these sub-criteria are essential for maintaining smooth operation and ensuring customer satisfaction. Additionally, traceability, information security, and flexibility were recognized as other essential sub-criteria in this category.

In the economic dimension, experts identified operational cost as not only the most significant sub-criterion within the economic aspect but also the highest priority across all criteria. This finding is consistent with previous studies by Švadlenka et al., (2020) and Y. Wang et al., (2016) as this is the most evident and direct economic factor.

For the social aspect, accessibility was considered the most important sub-criterion, emphasizing the necessity of effectively implementing last-mile delivery solutions to prevent urban disruptions and enhance consumer convenience. This aligns with findings from Švadlenka et al., (2020). Meanwhile, consistency with urban planning and stakeholder cooperation were assigned relatively equal importance.

The prioritization of the environmental criteria led to interesting results. air pollution sub-criterion was valued higher importance level than energy savings and waste generation. This can be explained by experts recognizing that climate-related concerns are indirectly addressed through emission reduction efforts, as lowering vehicle and system emissions also mitigates greenhouse gases such as CO_2, which significantly contribute to climate (Y. Wang et al., 2016).

4.2 Comparing LMD alternatives

This section continues to discuss the comparison of four LMD solutions as alternatives. Experts were asked to evaluate each alternative based on all criteria, and then performance scores were obtained by using the BWM. The weighted scores for each alternative were calculated by multiplying the performance scores by the average global weights of each criterion, as presented in Table 6. These weighted scores were ultimately used to determine the ranking of the alternatives. Table 7 provides an overview of the average performance scores and weighted scores for each alternative.

Table 7: Weights for the alternatives (LMD solutions) with respect to each criterion

Criteria	Performance scores			
	Green Vehicles	Parcel Lockers	Convenience Store Pickup	Crowdsourcing Delivery
Technical				
Efficiency	0.1620	0.2645	0.1880	0.1277
Reliability	0.1661	0.3627	0.2144	0.0894
Flexibility	0.1390	0.2822	0.1984	0.1557
Traceability and inf. security	0.2187	0.3444	0.1843	0.0901
Economic				
Cost of implementation	0.1133	0.1718	0.2780	0.2134
Cost of operation	0.1087	0.2127	0.2181	0.2214
Cost of insurance and taxes	0.1248	0.2392	0.2610	0.1517
Social				
Consistency with urban planning	0.1774	0.2284	0.1970	0.1447
Accessibility	0.1817	0.1603	0.1745	0.2230
Co-operation of stakeholders	0.1623	0.2360	0.2302	0.1138
Environmental				
Air pollution	0.2991	0.2039	0.1515	0.1138
Energy savings	0.1922	0.2444	0.2008	0.1225
Waste generation	0.1854	0.2128	0.2004	0.1439

The results obtained from all experts' responses indicate that green vehicles score the best regarding the sub-criterion "Air pollution". Due to their low emissions and energy efficiency initiatives, green vehicles provide significant environmental benefits, particularly in reducing air pollution. However, the high initial investment required for implementing such sustainable technologies results in this solution being the least preferred from an economic perspective. Despite their relatively high technical efficiency, green vehicles remain dependent on individual operations and availability, which may limit their overall effectiveness.

The findings also show that parcel lockers received the highest scores across all sub-criteria within the technical aspect, consistency with urban planning, stakeholder cooperation, energy savings, and waste generation. Due to its centralized design, the parcel locker system is regarded as a reliable, efficient, and cost-effective alternative. Additionally, it also achieved competitive economic scores based on the secure infrastructure and lower logistics requirements compared to other solutions. By reducing the need for repeated delivery attempts, parcel lockers also offer environmental advantages. However, they may have limitations in terms of accessibility, as not all locations within cities can be satisfied.

Besides, convenience store pickup scores the best in two of the three economic sub-criteria, namely cost of implementation as well as cost of insurance and taxes. Its perceived cost-effectiveness is primarily attributed to the utilization of existing retail spaces, reducing the need for additional infrastructure. However, when compared to parcel lockers, convenience store pickup has certain technical limitations, as sending packages to stores can introduce additional steps to the delivery process.

Finally, crowdsourcing delivery performed the best in terms of cost of operation, and accessibility. Due to the decentralized model, this solution received relatively lower scores across most sub-criteria, particularly in reliability and traceability. It can be challenging to maintain reliable service quality and secure tracking when relying on self-employed drivers with private vehicles. Additionally, its lowest ranking for air pollution reduction suggests that frequent use of personal vehicles could still contribute to increased emissions. However, it also offers significant advantages in terms of accessibility and implementation cost, since there is no requirement of a large initial investment.

4.3 Ranking of LMD alternatives

Based on the performance scores of all alternatives and the criteria weights, Table 8 below shows that parcel lockers (0.3138) emerged as the most sustainable solution according to 13 sub-criteria, while convenience store pickup (0.2724) achieved the second ranking. Green vehicles (0.2092) and crowdsourcing delivery (0.2047) are considered to have similar performance levels, resulting in third and fourth place, respectively.

Table 8: Final BWM weights for alternatives (LMD solutions) and ranking

Criteria	Performance scores				Criteria Weights
	Green Vehicles	Parcel Lockers	Convenience Store Pickup	Crowdsourcing Delivery	
Technical					
Efficiency	0.1620	0.2645	0.1880	0.1277	0.0528
Reliability	0.1661	0.3627	0.2144	0.0894	0.0785
Flexibility	0.1390	0.2822	0.1984	0.1557	0.0277
Traceability and information security	0.2187	0.3444	0.1843	0.0901	0.0258
Economic					
Cost of implementation	0.1133	0.1718	0.2780	0.2134	0.0553
Cost of operation	0.1087	0.2127	0.2181	0.2214	0.1444
Cost of insurance and taxes	0.1248	0.2392	0.2610	0.1517	0.0318

Social					
Consistency with urban planning	0.1774	0.2284	0.1970	0.1447	0.0292
Accessibility	0.1817	0.1603	0.1745	0.2230	0.0406
Co-operation of stakeholders	0.1623	0.2360	0.2302	0.1138	0.0319
Environmental					
Air pollution	0.2991	0.2039	0.1515	0.1138	0.0499
Energy savings	0.1922	0.2444	0.2008	0.1225	0.0482
Waste generation	0.1854	0.2128	0.2004	0.1439	0.0183
Total Score	**0.1023**	**0.1535**	**0.1333**	**0.1001**	
Normalized Total Scores	**0.2092**	**0.3138**	**0.2724**	**0.2047**	
Ranking	**3**	**1**	**2**	**4**	

4.4 Sensitivity Analysis

For the sensitivity analysis, all sub-criteria weights were set to equal values to examine their impact on the final ranking of alternatives. The results indicate that despite this change, the ranking of alternatives remains unchanged, demonstrating the robustness of the prioritization model. This suggests that the initial weight distribution did not significantly influence the final rankings, reinforcing the consistency of the decision-making framework. Such stability highlights the reliability of the Best-Worst Method (BWM) in ranking alternatives, ensuring that the selected priorities are well-founded even when variations in weight allocation occur.

The following table shows the results of the change in total scores when all sub-criteria weights were set to an equal value of 0.0500.

Table 9: Sensitivity Analysis - all sub-criteria weights equal to 0.0500

Alternatives	**Total scores**	**Total scores with all sub-criteria weights equal to 0.0500**
Green Vehicles	0.1023	0.1115
Parcel Lockers	0.1535	0.1582
Convenience Store Pickup	0.1333	0.1348
Crowdsourcing Delivery	0.1001	0.0956

To assess the impact of economic criteria on the ranking of alternatives, a sensitivity analysis was performed by increasing the weights of two sub-criteria—Cost of Implementation and Cost of Operation—by 50%. The results reveal a notable shift in rankings, where Crowdsourcing Delivery and Green Vehicles swapped positions (Rank 3 and 4). This result is presented in Table 10, underscoring the significant influence of financial considerations on decision-making. With standard weight distributions, the rankings remained stable; however, when cost-related attributes were given higher importance, Crowdsourcing Delivery ranked above Green Vehicles. This suggests that decision-makers who prioritize cost-efficiency over other sub-criteria may prefer Crowdsourcing Delivery more as a viable option.

Based on this scenario-based sensitivity analysis, the robustness of the model is further validated, showing that economic criteria can drive changes in alternative preferences. Such insights are crucial for stakeholders aiming to balance affordability with other sustainability objectives in real-world implementation.

Table 10: Sensitivity Analysis - with 50% weight increase for the sub-criteria Cost of Implementation & Operation

Alternatives	Total scores	Total scores with 50% weight increase for the sub-criteria Cost of Implementation & Operation	Changed Ranks
Green Vehicles	0.1023	0.1133	4
Parcel Lockers	0.1535	0.1736	1
Convenience Store Pickup	0.1333	0.1567	2
Crowdsourcing Delivery	0.1001	0.1220	3

5 Discussion

The findings of this study provide valuable insights into the evaluation of sustainability criteria and LMD alternatives within the context of the Netherlands. The economic aspect emerged as the most important factor, particularly driven by the cost of operation, which was also assigned the highest overall priority. This result aligns with previous studies on urban freight transport in the Netherlands, where designing an effective cost model was identified as a major challenge for logistics providers (Buldeo Rai et al., 2017). The high labor costs and strict urban logistics regulations likely reinforce this focus on economic sustainability in the Netherlands.

Besides, the technical aspect was ranked as the second most critical dimension, with reliability and efficiency being highly valued. This finding supports the conclusions of Milakis et al. (2017), who emphasized that automation and digitalization are becoming increasingly essential in Dutch urban logistics to enhance efficiency. Meanwhile, the environmental and social factors were ranked lower, indicating that economic and operational constraints take precedence in decision-making (C.-N. Wang et al., 2023). Although this result aligns well with previous studies, such as C.-N. Wang et al., (2023), Švadlenka et al. (2020), it differs slightly from the findings of Awasthi & Chauhan (2012), who ranked environmental concerns as the top priority while placing economic factors in third place. This can be explained by the differences in research contexts and respondent profiles, as they also engaged the consumer perspectives.

Regarding the ranking of LMD alternatives, parcel lockers emerged as the most preferred solution, followed by convenience store pickup, green vehicles, and crowdsourcing delivery. The strong preference for parcel lockers aligns with the insights of R. Van Duin et al. (2020), who highlighted their cost-effectiveness and environmental benefits. Parcel lockers help reduce delivery failures and optimize routing, making them an efficient LMD solution in high-density urban areas, such as Amsterdam and Rotterdam. The relatively lower ranking of green vehicles suggests that despite their environmental benefits, the high investment costs may hinder their immediate large-scale adoption (Quak, Nesterova, van Rooijen, et al., 2016).

The Best Worst Method (BWM) proved to be a suitable approach for structuring expert preferences and systematically deriving weights for sustainability criteria and LMD alternatives. Compared to other MCDM methods, BWM offers higher consistency in pairwise comparisons, which is particularly useful when dealing with expert judgments. However, a key limitation of this decision-making process is its reliance on subjective expert opinions, which may introduce biases based on different industry backgrounds or policy perspectives. It is crucial to acknowledge these biases to guarantee balanced input and comprehensive MCDA results.

Overall, the results provide an evaluation of LMD alternatives, balancing various sustainability goals. The prioritization of cost-efficient and technologically advanced solutions suggests that policymakers and businesses should focus on scaling up successful initiatives such as parcel lockers while addressing the financial and operational barriers to greener delivery modes.

In summary, the final ranking indicates that parcel locker is the most sustainable LMD solution based on the prioritization of cost-effectiveness, reliability, and operational efficiency, closely followed by convenience store pickup. Green vehicles are considered as a strong alternative for the objective of emphasizing environmental sustainability, while crowdsourcing delivery provides flexibility but falls short in terms of reliability and sustainability. This ranking serves as a practical guide for selecting the most suitable LMD solution based on specific strategic priorities.

6 Recommendations

Based on the obtained results, policy and strategic recommendations are proposed for logistics providers, policymakers, and urban planners to enhance the sustainability and efficiency of operating LMD solutions in the Netherlands. These recommendations consider both the criteria weights and the overall performance scores of all involved alternatives.

Prioritizing parcel lockers and convenience store pickup as cost-effective and sustainable alternatives: With parcel lockers ranked highest and convenience store pickup second, policymakers could stimulate their widespread adoption through subsidies, urban planning integration, and promoting cooperation among stakeholders. In addition, they could also assist with providing suitable locations in residential areas, train stations, and commercial centers.

Financial and regulatory support for green vehicles: Although green vehicles ranked third, their potential for reducing emissions remains critical. Policymakers could introduce tax incentives, grants, and dedicated charging infrastructure to support the transition to green energy delivery vehicles. Besides, zero-emission zones and stricter emissions regulations could also encourage businesses to invest in sustainable fleets while maintaining cost-effectiveness.

Addressing the limitations of crowdsourcing delivery: Crowdsourcing delivery, which is the least preferred in this study, may face challenges such as inconsistent service quality, lack of regulatory frameworks, and operational inefficiencies. To facilitate coordination and improve the reliability of this solution, decision makers should clarify frameworks, fair labor policies, and enhance digital platforms. Crowdsourcing could also be optimized by integrating with other initiatives to minimize route redundancies.

Balancing economic, technical, environmental, and social considerations in policy design: While economic and technical factors ranked highest, environmental and social dimensions also need to be considered equally to achieve sustainable operations. Policies should facilitate suitable infrastructure, investment in logistics optimization, and a pricing system to manage urban freight demand efficiently. Moreover, decision-makers should ensure the balance between business incentives and sustainability goals in long-term development, preventing financial and regulatory constraints from hindering sustainable initiatives.

Enhancing data-driven decision-making: To improve LMD efficiency, policymakers and businesses should adopt MCDM tools to continuously reassess the trade-offs between economic feasibility, technical efficiency, environmental impact, and social considerations. Future research should monitor evolving industry priorities, consumer behavior shifts, and regulatory developments to refine LMD strategies. Pilot projects and real-world case studies can provide empirical validation for scaling up successful solutions.

By implementing these recommendations, decision-makers can ensure that last-mile delivery solutions in the Netherlands remain financially viable, technically efficient, and environmentally sustainable, creating a resilient and future-ready urban logistics system.

Combining the above recommendations could allow us to achieve a more sustainable and efficient LMD solution that serves various goals. Policymakers and businesses should also adopt these MCDM tools to continuously reassess the trade-offs between economic feasibility, technical efficiency, environmental impact, and social considerations.

7 Conclusion

As last-mile delivery plays a significant role in urban logistics development, it is crucial to consider sustainable solutions which provide a balance of benefits between various objectives based on the MCDM approach. To address that problem, this study used the Best-Worst Method (BWM) to obtain the weights of economic, technical, environmental, and social factors as well as the rank of different LMD alternatives with the context of the Netherlands.

To that end, this study developed a structured decision-making framework that integrates key sustainability aspects, contributing guidelines for policymakers and relevant stakeholders to evaluate LMD solutions. The framework can also be adapted for evaluating urban freight solutions in other regions. Based on expert opinions, the findings showed that parcel lockers ranked highest, followed by convenience store pickup and green vehicles, while crowdsourcing delivery ranked lowest. Among the evaluated LMD alternatives, parcel lockers emerged as the most favorable option, resulting from the relatively strong priorities of economic and technical aspects.

The outcomes of this study offer meaningful implications for both academic and practical application. Researchers can make use of the proposed approach to analyze LMD systems in different contexts, while logistics providers and urban planners can apply the findings to optimize delivery operations. The decision-making framework introduced in this study can serve as a reference for other urban freight challenges beyond the Netherlands.

Despite these insights, this study has certain limitations of relying on expert opinion, which may not fully capture changing consumer preferences and technological advancements. Therefore, incorporating consumer perspectives, integrating real-time operational data, and considering emerging technologies such as autonomous or drone-based delivery could enhance the robustness of the evaluation. While the BWM method offers a structured and consistent evaluation process, there is an existing assumption of independence among criteria, which may not hold in complex, real-world contexts. Therefore, future research could explore methods that capture interdependence and cause-effect relationships among factors, such as the decision-making trial and evaluation laboratory (DEMATEL), to further improve the reliability of results.

Contributor Statement

Thi Phuong Anh Tran was responsible for conceptualization, data curation, formal analysis, investigation, methodology, project administration, software, resources, validation, visualization, writing. Sharada Atul Gavade contributed through formal analysis, investigation, methodology,

project administration, software, resources, validation, visualization, writing. All authors approved the final version of the manuscript and take responsibility for their respective contributions.

Use of AI

During the preparation of this work, the author(s) used Grammarly and ChatGPT for language editing and grammar checks to enhance the clarity and readability of the manuscript. After using this tool/service, the author(s) reviewed, edited, made the content their own and validated the outcome as needed, and take(s) full responsibility for the content of the publication.

Conflict Of Interest (COI)

There is no conflict of interest.

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