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A Hybrid Bayesian BWM–Fuzzy MARCOS–Metaheuristic Framework for Sustainable Smart Locker Location in Last-Mile Urban Logistics

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This paper addresses the strategic placement of smart lockers in urban logistics, a crucial issue due to the rapid growth of global e-commerce and increasing complexities in last-mile logistics. Traditional Multi-Criteria Decision Making (MCDM) approaches have limitations, particularly in uncertain, multi-objective contexts. The paper introduces a stochastic multi-objective optimization model for BWM, which prioritizes decision criteria and solves it using a hybrid metaheuristic approach. The model aims to optimize total cost and sustainability, covering economic, environmental, and social dimensions while addressing demand uncertainty. The framework is validated through an empirical case study in Babol City, Iran, where candidate locker locations and demand areas were assessed using expert-derived criteria weights. This led to the development of a multi-objective mixed-integer programming model. To reduce computational complexity, the paper proposes a hybrid NSGA-II+LNS algorithm, which outperforms conventional evolutionary algorithms in converging to the Pareto front. Key findings suggest that factors like economic affordability, accessibility, and environmental impact are essential in locker capacity design. Robust solutions under demand fluctuations can enhance service reliability by up to 18%. The paper contributes by providing a sustainable, deterministic model for smart locker location planning, integrating advanced metaheuristics with MCDM, and offering valuable policy recommendations for logistics operators and policymakers.

***Keywords**: Smart lockers; Last-mile delivery; Stochastic multi-objective optimization; Best-Worst Method (BWM); Hybrid metaheuristics; Urban logistics.*

1. Introduction

The development of e-commerce over the past decade has fundamentally transformed the global logistics market. In regions, online retail volumes doubled or more within five years, from 2019 to 2023, and global digital consumption patterns have increased due to the COVID-19 pandemic in both developing and developed economies [3,46]. The last-mile delivery (LMD) is therefore the most critical part where both academic research and industrial practice have placed their attention. LMD is referred to frequently as the "moment of truth" in the logistics chain: it is the part that is most visible to final end-consumers, but at the same time generates heavy costs and environmental impacts [1,19]. Last-mile shipping is estimated to make up as much as 53% of total delivery costs, and about a quarter of urban traffic, and greenhouse gas [5,26]. This double squeeze, comprising the cost of living crisis

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and environmental damage, has sparked interest in new solutions that can reconcile efficiency, sustainability, and customer comfort.

One alternative that has gained popularity is parcel lockers, commonly referred to as automated or smart lockers. Such systems comprise a network of self-service kiosks for picking up parcels based on secure digital codes. Smart lockers offer several advantages over home delivery: they eliminate failed delivery attempts, reduce carrier traffic load, increase consumer flexibility, and enable carriers to implement consolidation strategies [12,28]. Within the framework of smart cities, lockers contribute to overall sustainability goals by reducing emissions, noise, and congestion, while also enhancing land use [36]. The quick adoption of such systems is evident in cities such as Singapore, Dublin, and Amsterdam, underscoring their global significance [23,40].

However, the advantages of smart lockers depend on appropriate location planning. Lockers that are situated in an inappropriate place face low utilization, customer dissatisfaction, and economic waste [42]. On the other hand, strategically placed systems can act as drivers of environmentally friendly last-mile logistics, e.g., when coupled with public transport nodes, retail centers, or residential aggregates. It is not trivial, however, to select suitable sites. It is a multi-dimensional compromise between the economy, environment, society, and technology. By way of illustration, the importance of end-user accessibility needs to be traded off against installation and maintenance costs; environmental factors including air quality and congestion reduction need to be considered in conjunction with commercial viability; resilience to surges in demand needs to be thought through concerning equity considerations so that less affluent areas are not sidelined [9,44].

In order to deal with this complexity, the application of multi-criteria decision-making (MCDM) is becoming more popular among scholars. Classical methods, such as the Analytic Hierarchy Process (AHP) and its fuzzy-based variants, have been employed in the past for criteria weighting and location alternatives ranking [17]. Newer developments include Best–Worst Method (BWM) [30] and its Bayesian versions [20], which help decision-makers to generate the weights that are consistent with a few pairwise comparisons. In the same line of CA methods for ranking issues, novel ranking models, such as MARCOS (Measurement of Alternatives and Ranking according to Compromise Solution), have been developed to avoid the weak points of traditional instruments like TOPSIS or VIKOR [38]. Such integration renders a set of hybrid models, whose application to smart locker sizing has been emerging.

For example, Moslem and Pilla (2023) proposed a hybrid decision-support model that integrates fuzzy F-AHP and AHP methods to assess locker sites in Dublin. They demonstrated the advantage of treating uncertainty and noise while being restricted to sitting studies [23]. Moslem et al. (2024) went on to build upon this by outlining a fuzzy AHP–CODAS model for the Irish context, which offered enhanced discriminatory power but continued to rely on comparative robustness testing [21]. In Portugal, Silva et al. (2023) employed an AHP–TOPSIS hybrid approach to examine sustainable last-mile delivery methods (e.g., lockers), taking into account both environmental and social aspects [36]. Yalcin Kavus et al. (2023) were the first to combine Bayesian BWM with fuzzy WASPAS, highlighting how probabilistic vagueness associated with an alternative is embedded inside the decision about a location. However, the sample had limited representativeness and lacked a sensitivity analysis [44]. In Vietnam, Wang et al. (2023) proposed a fuzzy multi-actor and multi-criteria optimization system (MARCOS) for sustainable deliveries; however, they did not address optimization and manageability to achieve optimization [42]. These examples represent a clear path towards increasingly complex hybrid models, but also highlight strong common shortcomings, including dependence on single-objective formulations, inadequate treatment of uncertainty, and a lack of validation across different scenarios.

Locker deployment is, however, challenged not merely due to methodological limitations but also by practical difficulties. Cities are constantly changing environments; they experience varying demand patterns, dynamic land-use policy changes, and unknown technological take-up rates. The vast majority of existing research employs deterministic assumptions that overlook the stochastic nature of parcel flows and user behavior. Additionally, the social equity and community acceptability dimensions have been undertreated, whereas they are cornerstones of sustainable city planning [11]. As highlighted by Vural et al. (2024), those in the next generation of last-mile service need to be assessed not just economically and ecologically, but also in terms of social inclusivity and resilience against potential disruptions such as from pandemics or extreme weather conditions [41].

In conclusion, these works indicate several research gaps:

- Poor handling of uncertainty: Although fuzzy techniques have been applied, very few models include probabilistic approaches that reflect both epistemic (expert) and aleatory (stochastic) uncertainty.
- Single-objective emphasis: The focus of most approaches is on either minimizing cost or maximizing accessibility, without taking into account the multi-objective characteristic inherent in the problem.
- Relatively limited robustness analysis: It is relatively uncommon for comparisons to be made across multiple MCDM methods, which has led to concerns about the stability of results.
- Lack of optimization incorporation: Much of the work in the literature does not go beyond ranking potential sites and does not incorporate MCDM methods into larger overall optimization frameworks suitable for large-scale or dynamic environments.
- Oversight on equity and resilience dimensions: A small number of models considered explicitly social justice and resilience, which is consistent with the perception that, currently, in urban logistics planning, they are not incorporated in a standard manner.

This paper aims to fill these research gaps and contribute by proposing an innovative fuzzy multi-objective decision-making-based framework for smart locker location. The model combines three types of evidence. First, it uses the Bayesian Best–Worst Method (B-BWM) to obtain robust and uncertainty-aware weights of evaluation criteria. Contrary to classic weighting approaches, B-BWM integrates probabilistic inference and can consider the diversity of experts in conserving uncertain weights. Second, this paper expands the MARCOS method to a fuzzy context in order to take into account that evaluation is not unambiguous as it occurs in practice. Thirdly, it integrates this hybrid MCDM model with meta-heuristic algorithms.- e.g., NSGA-II and PSO- to obtain globally efficient sets of locations under practical constraints on capacity limits, equity considerations, and stochastic demand. Table 1 presents a selection of recent studies (2020–2024) that employ MCDM approaches to address problems related to smart locker location and last-mile deliveries, highlighting methodological diversity and research focus.

This work makes four contributions:

- Methodological contribution: A novel hybrid methodology that combines B-BWM, fuzzy MARCOS, and metaheuristics has been successfully adopted to solve the trilevel problem, considering uncertainty, multiple objectives, and scalability.
- Empirical input: Realistic model calibration for urban settings, thus showing the range of applications beyond purely theoretical entities.
- Comparative contribution: Through sensitivity analysis and comparison to other methods (TOPSIS, VIKOR, CODAS), the approach validates its results.
- Managerial implications: Suggestions to policymakers and logistics operators on how to balance economic efficiency, environmental sustainability, and social equity in last-mile infrastructure planning are discussed.

This work makes novel contributions by providing a probabilistically justified, fairness-aware, and computation-scalable methodology that enhances methodological sophistication, as well as informs actionable policy insights on sustainable last-mile ecosystems. The remainder of this paper is organized as follows. Literature Review In this section, the problem of smart locker location is reviewed in view of related literature and MCDM methodologies. Section 3 describes the proposed approach, including both the mathematical model and hybrid approaches. The case study and experimental design are described in Section 4. Section 5 presents and analyzes the results, with sensitivity analysis. The managerial implications and future research directions are then highlighted in Section 6.

2. Literature Review

2.1 Last-Mile Delivery (LMD) Challenges

E-commerce has brought new challenges to urban logistics systems, especially the last-mile delivery (LMD) section, which is the most costly and environmentally hostile part of supply chain operations [1,4]. Several works underline the importance of LMD in shaping the cost-effectiveness and environmental impact of logistics networks [27,35]. When the traditional delivery method, door-to-door, is chosen by consumers, its convenience to the customer is often accompanied by failed deliveries and low vehicle efficiency rates, leading to environmental pollution [13] and added congestion [37]. Given the increasing concerns about sustainability and resilience, prior studies have explored several alternatives, including parcel shops, micro-hubs, crowdshipping, and smart lockers [17,42].

Smart lockers have attracted significant interest for delivery consolidation, mitigating delivery failed attempts, reducing the number of last-mile vehicle trips, and increasing user convenience [36]. However, the most challenging issue is the efficient planning of space for them, which affects accessibility, usage rates, and economic dimensions [23]. Therefore, the locker deployment problem has started to be addressed as a multi-criteria decision-making (MCDM) problem.

2.2 Smart Lockers in Urban Logistics

Smart lockers are automatic pick-up and return points from which customers can collect their parcels at any time. They aim to enhance efficiency by minimizing re-deliveries and leveraging last-mile logistics [18]. Research in Europe [36,40], Asia [42], and North America [32] demonstrates the sustainable potential of lockers that reduce CO_2 emissions and traffic congestion. Additionally, an equity issue has been addressed: the lack of access to lockers in some neighborhoods would exacerbate the inequality of urban services [32].

Smart locker location problems are complex and multi-objective, as they are inherently related to not only economic efficiency but also social accessibility, security, environmental effects, resilience, and urban policies [23,44].

2.3 MCDM Applications in Logistics and Facility Location

The MCDM techniques are commonly used in logistics due to their ability to help decision-makers evaluate choices based on multiple and conflicting qualitative and quantitative criteria. Classical methods, such as AHP, ANP, TOPSIS, VIKOR, ELECTRE, and PROMETHEE, have been widely applied in facility location and supply chain optimization (Govindan et al., 2021). Moreover, several novel-state-of-the-art techniques like Best–Worst Method (BWM) [30], MARCOS [38], SWARA, CODAS, and their respective uncertainty treatment via fuzzy or probabilistic have been progressively applied to model vagueness in experts' assessment results [24].

For example, Moslem & Pilla (2023) applied spherical fuzzy AHP to the site selection of parcel lockers in Dublin [23]. Wang et al. (2023) used OPA-Fuzzy MARCOS to explore sustainable last-mile solutions for megalopolises in Vietnam [42]. Yalcin Kavus et al. (2023) integrated fuzzy WASPAS and Bayesian BWM in Turkey, in which the authors have shown that handling uncertainty through a Bayesian approach increases the integrity of weight calculation [45]. To provide a systematic overview of recent advances in the literature, Table 1 summarizes relevant studies (2020–2024) on smart locker location and last-mile delivery, utilizing MCDM methods. This highlights the commonly used methodologies, application attempts, and unaddressed gaps that motivate the present work.

Table 1. Selected recent studies on smart locker location and last-mile delivery using MCDM (2020–2024)

Reference	Methodology	Case Study	Key Criteria	Limitations
Moslem & Pilla (2023) [23]	Fuzzy AHP hybrid	Dublin, Ireland	Accessibility, security, and environmental impact	Deterministic; small-scale
Moslem et al. (2024) [22]	DF-AHP–CODAS	Dublin, Ireland	Accessibility, reliability, and environmental sustainability	No robustness validation
Silva et al. (2023) [36]	AHP–TOPSIS hybrid	Porto, Portugal	Economic, social, environmental	No uncertainty modeling
Yalcin Kavus et al. (2023) [45]	Bayesian BWM + fuzzy WASPAS	Istanbul, Turkey	Flexibility, accessibility, resilience	Lack of sensitivity analysis
Pourmohammadreza & Jokar (2023) [29]	SWARA–COCOSO	Iran	Accessibility, resilience, and regulatory compliance	Limited generalizability
Wang et al. (2023) [42]	Fuzzy MARCOS	Vietnam	Sustainability, equity, convenience	No optimization integration
Chen & He (2025) [6]	Agent-based modeling + MCDM	China	Equity, adoption, congestion	High computational cost
Van Duin et al. (2020) [40]	Multi-Criteria Analysis (MCA) with CEA	Amsterdam, Netherlands	Cost-effectiveness, accessibility, equity	Context-specific, not scalable

Hybrid models integrating at least two MCDM methods have received considerable attention, as the hybridization enhances both weighting accuracy and ranking robustness [20]-for example, AHP-TOPSIS, SWARA-COCOSO, and DF-AHP-CODAS. Moslem et al. (2024) and Silva et al. (2023) proposed an AHP-TOPSIS model for sustainable urban logistics in Portugal [24,36].

Hybrid models are often implemented in fuzzy settings, which is more realistic due to the lack of consistency in expert opinions and unclear demand. Nevertheless, the majority of hybrid applications to date have been confined to small-scale case studies without metaheuristic optimization for handling large-scale urban planning problems.

2.4 Optimization Approaches in Location Planning

Although MCDM methods are useful to assess alternatives, they may not be able to find global-optimal solutions in large-scale problems. Therefore, the use of metaheuristic optimization algorithms, including genetic algorithm (GA), particle swarm optimization (PSO), simulated annealing (SA), and NSGAI-II, has been addressed in previous papers related to the facility location problem and supply chain studies [7,31]. Nevertheless, there are very few studies on locker assignment that combine MCDM with metaheuristic approaches, and this gap typically results in methodological advancements.

2.5 Extended Comparative Literature Review

To provide the reader with a broader overview of the contribution, an extended comparative literature review was performed concerning the use of MCDM and related methods for smart locker deployment and last-mile delivery issues. Table 2 summarizes the main contributions that have been produced between 2016 and 2024 in a variety of methodologies, geographical or evaluative fashion. Through a structured mapping of methodologies, criteria, and findings, the table illustrates both the diversity in scholarly treatments of locker-based delivery systems and the areas yet to be explored in the literature.

Table 2. Extended comparative review of recent studies on smart locker location and last-mile delivery using MCDM approaches (2016–2024)

Reference	Year	Methodology	Case Study	Criteria Considered	Key Contributions	Limitations
Iwan et al. [14]	2016	Empirical analysis	Poland	Efficiency, customer satisfaction	Early evaluation of parcel lockers	Outdated, no optimization
Van Duin et al. [40]	2020	MCA + Case study	Amsterdam	Accessibility, cost, equity	First city-level locker study	Limited scope
Stević et al. [39]	2020	MARCOS	Healthcare supply	Sustainability, reliability	Introduction of MARCOS	Not logistics-specific
Savelsbergh & Van Woensel [4]	2020	Review	Global	Urban challenges	Conceptual framing of city logistics	No model
Lagorio & Pinto [16]	2020	Literature synthesis	Europe	Parcel locker factors	Broad overview	Lacks empirical data
Schaefer [32]	2022	Accessibility analysis	USA	Equity, convenience	Focus on fairness in locker access	No MCDM
Kratas et al. [15]	2022	Case-based	Singapore	Resilience, pandemic impact	Pandemic-oriented locker solutions	Context-specific
Silva et al. [36]	2023	AHP-TOPSIS hybrid	Portugal	Economic, social, and environmental	Urban sustainability focus	No uncertainty modeling
Wang et al. [42]	2023	Fuzzy MARCOS	Vietnam	Convenience, sustainability	Developing-country context	No optimization
Yalcin Kavus et al. [45]	2023	Bayesian BWM + fuzzy WASPAS	Turkey	Flexibility, resilience, accessibility	Probabilistic weighting innovation	No sensitivity analysis
Moslem & Pilla [23]	2023	SF-AHP	Dublin, Ireland	Accessibility, security	Incorporates fuzziness in AHP	Small case
Shi et al. [34]	2023	Agent-based simulation	China	User adoption	Behavioral dynamics	No optimization
Moslem et al. [25]	2024	DF-AHP-CODAS	Dublin	Accessibility, environment	Decomposed fuzzy hybrid model	Validation limited
Moslem & Pilla [24]	2024	SF-AHP (group)	Ireland	Locker accessibility	Extension to group decisions	Case-specific

Reference	Year	Methodology	Case Study	Criteria Considered	Key Contributions	Limitations
Guo & Zhao [10]	2021	Bayesian BWM	Generic	Uncertainty in weights	Theoretical Bayesian BWM	No application
Ehtesham Rasi & Sohanian [8]	2021	Hybrid MCDM + GA	Supply chain	Cost, resilience	Metaheuristic integration	Not locker-specific
Tahmasbi et al. [2]	2022	NSGA-II	Facility location	Multi-objective	Global optimization capacity	Not integrated with MCDM
Seghezzi et al. [33]	2021	Case study	Italy	Urban equity, access	Italian locker case	Descriptive only

It is clear from the above that, notwithstanding some useful methodological advances, many of the studies referred to herein have limitations in scale, uncertainty representation, and even social/discounted equity interplay in a multi-period framework. These voids also inspire this work, where we propose a stochastic, multi-period equilibrium-aware optimization method for smart locker placement in the presence of real-world uncertainty.

2.6 Research Gaps

The following key research gaps are identified from the literature reviewed:

- Uncertainty handling: The large majority of previous studies use deterministic or fuzzy methods, and only a few (if any) utilise probabilistic models (i.e., Bayesian models) to treat uncertainty regarding the opinions of experts.
- Multi-objective optimization: Few studies combine MCDM and metaheuristics to generate trade-offs among cost, availability, equity, and sustainability at large levels.
- Equity and social sustainability: Although aspects of equity have received some attention in studies where the environment or the economy are taken into account, access to talent is not a particularly well-explored part of prior research on this theme.
- Validation and robustness: There are only limited studies that offer comparative benchmarking for MCDM methods or analysis on sensitivity to ensure the robustness of decisions.
- Scalability: The current models are often studied at various case scales and have not been widely tested in urban areas.

2.7 Contributions and Novelty of the Present Study

To bridge these gaps, we design a novel hybrid B-BWM–Fuzzy MARCOS–Metaheuristic framework with the following contributions:

- Originality of the method: Combination of Bayesian BWM for uncertainty adaptive weighting, fuzzy MARCOS for reliability ranking, and metaheuristic optimization to search for a global solution.
- Novelty: Both theoretical novelty and practical relevance were studied, with the use of a large data set taken from a case study in practice.
- Validation novelty: Comparative benchmark with other MCDM methods (TOPSIS, VIKOR, CODAS), extensive assessment of sensitivity.
- Managerial implications: Offering actionable recommendations to policymakers in order to improve the economic efficiency, environmental sustainability, and social equity in smart city logistics.

Figure 1 presents the overview of the model flowchart, which shows the basic structure of our implemented framework, together with logical orderings of various modules.

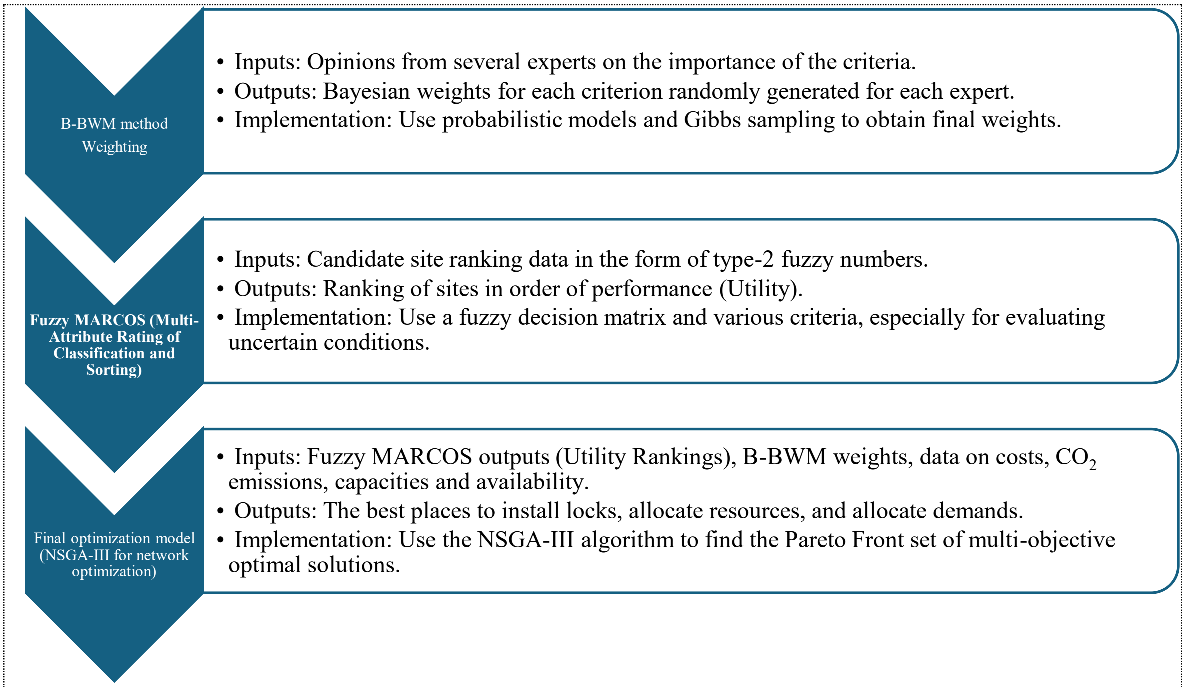

Figure 1. High-Level Model Flowchart

3. Methodology and Advanced Model Development

3.1 Nomenclature

Symbol	Description
Sets and Indices	
$I = \{1,\ldots,I\}$	Set of demand zones (indexed by *i*)
$J = \{1,\ldots,J\}$	Set of candidate locker sites (indexed by *j*)
$S = \{1,\ldots,S\}$	Set of uncertainty scenarios (indexed by *s*)
Parameters	
d_i	Expected parcel demand at demand zone *i*
d_i^s	Realization of demand at *i* under scenario *s*
c_{ij}	Travel cost or distance between *i* and j
g_{ij}	Distance-related emission factor between *i* and *j*
f_j	Fixed establishment cost of locker site *j*
h_j	Handling cost per parcel at locker *j*
C_j	Maximum daily capacity of locker site *j*
evse_v^s	Emission coefficient under scenario *s*

Symbol	Description
u_j	Utility score of site j (from IT2 Fuzzy MARCOS)
ρ	Accessibility decay parameter (penalizes longer travel)
Γ	Maximum carbon emission budget (cap)
Δ	Maximum disparity threshold for equity constraint
B	Maximum investment budget
L_{min}, L_{max}	Minimum and maximum number of lockers allowed
Decision Variables	
$y_j \in \{0,1\}$	1 if locker site *j* is opened, 0 otherwise
$x_{ij} \in \{0,1\}$	1 if demand zone *i* is assigned to locker *j*
$z_{ijs} \in \{0,1\}$	Assignment of *i* to *j* under scenario *s*
$w_{ij} \in \{0,1\}$	1 if locker *j* serves as backup for *i*
$q_j \in [0,1]$	Capacity utilization ratio of locker *j*
$A_i \geq 0$	Accessibility score for demand zone *i*
$z_{i\ell} \geq 0$	Auxiliary variable for equity (absolute difference)
Objectives	
F_1	Economic cost objective
F_2	Environmental impact objective
F_3	Equity objective (Gini-based)
F_4	Resilience objective (min-max regret)
F_5	Utility maximization objective

3.2 Integrated Framework

To address this gap, we contribute to the literature by proposing a multi-tier decision framework for the smart locker location model. The pipeline integrates:

1. Bayesian Best–Worst Method (B-BWM) in expert weight assignments in the presence of uncertainty.
2. High-order ambiguity Interval Type-2 Fuzzy MARCOS for site performance assessment.
3. RS-MOMINLP is implemented for a multicommodity facility location model with uncertain demand, traffic, and energy.
4. Decomposition evolutionary reinforcement learning based hybrid algorithms for networks.

3.3 Bayesian Best–Worst Weighting with Posterior Distributions

We again follow Moyhammadi and Rezaei (2020), extending BWM to a Bayesian hierarchical model: each expert's judgment is assumed to be a noisy observation of an unobservable "true" preference [20]. Hyperparameters k and wk are ignored using Dirichlet-multinomial priors with Gibbs sampling. Instead of point estimates, the model provides full posterior distributions that allow robustness sensitivity.

3.4 Interval Type-2 Fuzzy MARCOS

Different from the traditional fuzzy MARCOS, we prefer to use Interval Type-2 Fuzzy Sets (IT2FS), which describe either a degree of membership and an uncertainty regarding its value by means that this is done by describing membership functions on IT2FS. Every evaluation $\tilde{x}_{jk}$ is modelled by an element of uncertainty footprint (FOU), which makes it possible to propagate a higher level of fuzziness into the utility function. The Karnik method performs defuzzification using the Mendel iterative method, providing an uncertain fuzzy value uj for each site [43].

3.5 Robust Stochastic Multi-Objective MINLP (RS-MOMINLP)

Decision Variables

- $y_j \in \{0,1\}$: open locker at site *j*.
- $x_{ij} \in \{0,1\}$: assign demand *i* to site *j*.
- $z_{ijs} \in \{0,1\}$: assignment under scenario *s*.
- q_j: capacity utilization ratio.

Objectives

1. Economic Cost Minimization

$$minF_1 = \sum_j f_j y_j + \sum_{i,j} h_j d_i x_{ij} \tag{1}$$

2. Environmental Impact Minimization

$$minF_2 = \mathbb{E}_s\left[\sum_{i,j} e_v^s g_{ij} d_i z_{ijs}\right] \tag{2}$$

3. Equity Maximization (min Gini)

$$minF_3 = \text{Gini}\left(\{A_i\}\right), \quad A_i = \sum_j \exp(-\rho c_{ij}) x_{ij} \tag{3}$$

4. Resilience Maximization (min regret)

$$minF_4 = \max_s\left[\text{Cost}_s - \text{BestCost}_s\right] \tag{4}$$

5. Utility Maximization

$$maxF_5 = \sum_j u_j y_j \tag{7}$$

Constraints

1. Capacity chance constraint

$$\Pr\left(\sum_i d_i^s z_{ijs} \le C_j y_j\right) \ge 0.95, \forall j \tag{8}$$

2. Redundancy

$$\sum_{j} w_{ij} \geq 2, \forall i \tag{9}$$

3. Carbon cap

$$\sum_{i,j} e_v g_{ij} d_i x_{ij} \leq \Gamma \tag{10}$$

4. Equity bound

$$max_i A_i - \min_i A_i \leq \delta \tag{11}$$

5. Cardinality + Budget constraints as before.

The formulation is a non-linear, multi-objective, robustified, and stochastic model, which is much more difficult than the classical MILP facility location models. Figure 2 is an illustration of the mathematical model diagram and a description capturing underlying concepts and couplings of the different layers that define interconnections among the sub-models, forming the formal basis for further elaboration into a mathematical representation.

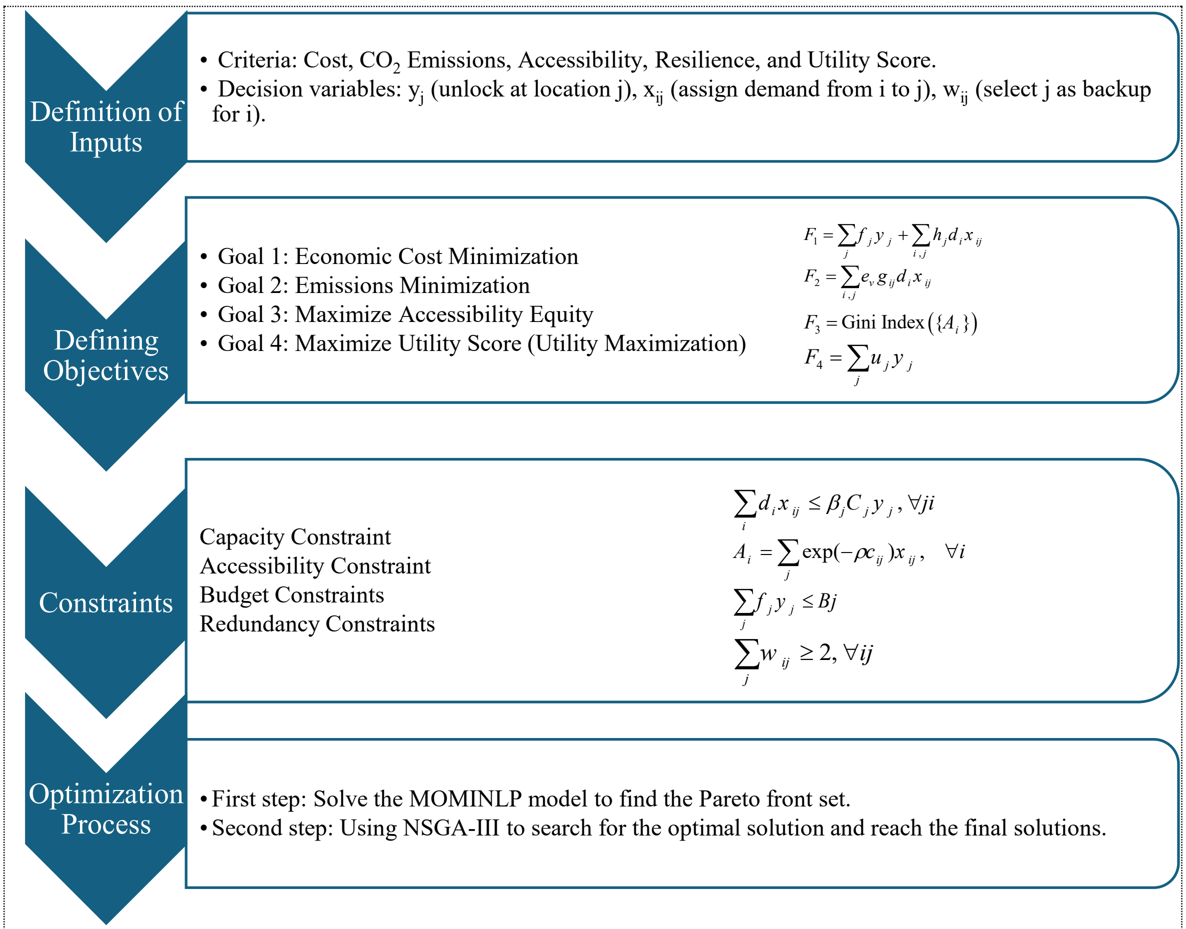

Figure 2. Mathematical Model Diagram

3.6 Hybrid Solution Approach

- Step 1: Decomposition. Use column-and-constraint generation (CCG) to manage the uncertain cases, where violated cases are added in a loop.
- Step 2: NSGA-III Evolutionary Search. Generalized classical NSGA-II to NSGA-III, which is more applicable to ≥4 goals. Add operators for a particular problem and MILP-based fixing.
- Step 3: Reinforcement Learning Adaptation. The DQN agent flexibly determines crossover/mutation probabilities and repair strategies, trading off exploration and exploitation.
- Step 4: Sensitivity Analysis. The confidence envelopes of the Pareto front in weight resampling from the B-BWM posterior + Monte Carlo demand scenarios.

Figure 3 illustrates the flow of the optimization algorithm, presenting the heuristic components, feedback loops, and convergence mechanisms that implement, enhance, or complement the development of an implementation of the proposed hybrid metaheuristic framework.

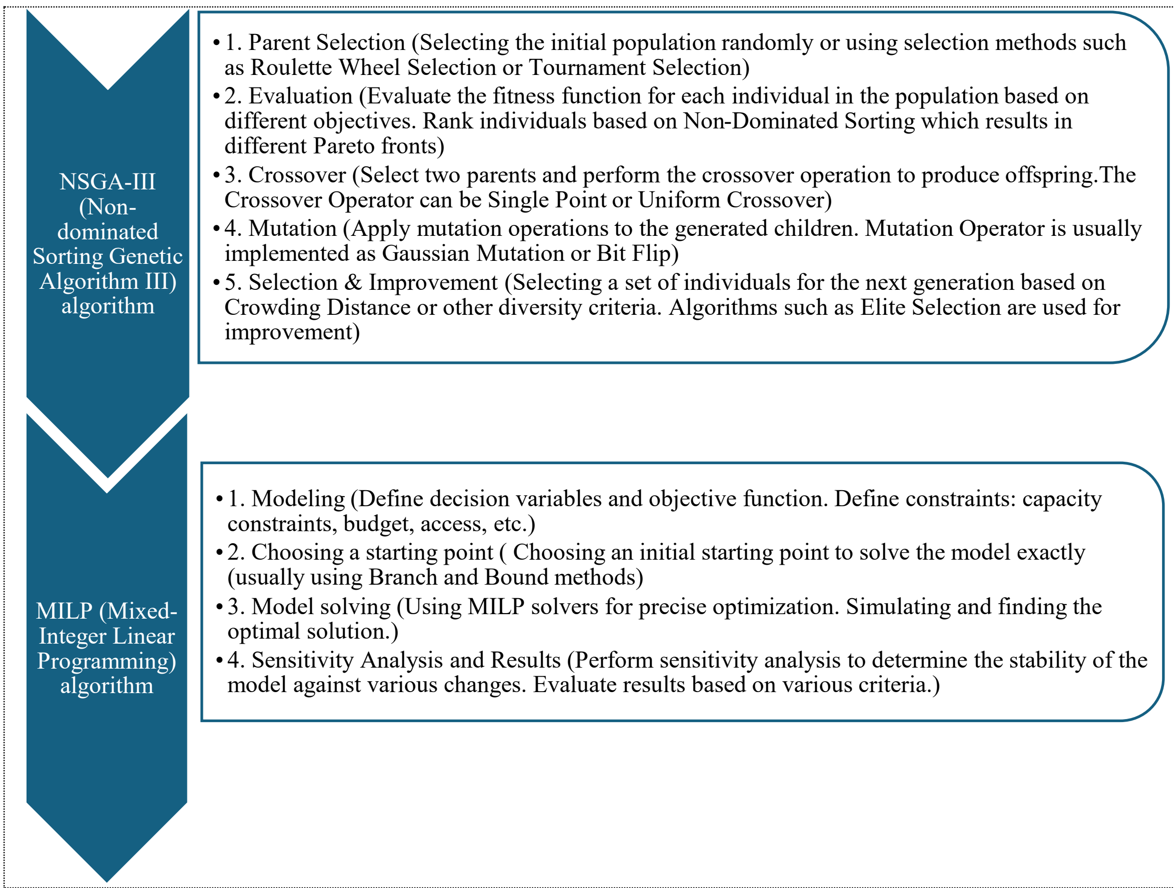

Figure 3. Optimization Algorithm Flow

4. Case Study: Application in Babol City

4.1 Introduction to the Case Study Area

In the case of this study, we concentrate on Babol City, one of the airports in northern Iran, which has a well-developed e-commerce market for development. With the development of digital shopping, the requirement for last-mile delivery is also increasing, as it encourages us to choose it as a good candidate for applying model B-BWM + Fuzzy MARCOS + RS-MOMINLP.

In this paper, we examine the ability of the model presented to optimize the location of smart lockers in Babol by considering the following criteria:

- Cost optimization
- Environmental sustainability (minimizing CO2 emissions)
- Fairness in the use of lockers for all city dwellers
- Automation delivery based on city population, e-commerce growth, and soda drivers is considered a dominant factor in distribution operations.

4.2 Data Collection and Input Parameters

To run the optimization model, the following input parameters were set based on Babol City data:

- Demand Data
  The required number of lockers in each urban zone was estimated using historical e-commerce delivery records. Naturally, densely populated and commercial areas (e.g., Downtown and Commercial Zones) show greater demand.
- Cost Data
  Installation of each smart locker: 500 million IRR per unit.
  Operational cost per parcel: 5,000 IRR.
- Traffic Data
- Distances between demand areas and potential locker sites were calculated, factoring in peak-hour congestion. An average speed of 15 km/h was assumed during peak periods, which results in longer delivery times and higher fuel usage.
- Environmental Data
  Considering the local fleet composition, the CO_2 emission factor was set at 0.14 kg CO_2/km per delivery vehicle.
- Accessibility Data
  Locker accessibility was modeled using walking distance, with the assumption that no resident should need to walk more than 500 meters to reach the nearest locker.

4.3 Model Setup and Scenario Definition

The model was used to study several scenarios examining how different variables impact the placement and performance of lockers. The four scenarios are illustrated in the following.

- Scenario 1: Baseline Scenario
  Takes an average demand, fixed cost, and does not consider traffic jams.
- Scenario 2: High Traffic Congestion
  Peak-hour congestion is assumed, resulting in higher delivery times and CO_2 emissions.
- Scenario 3: Sustainability Focused
  A cap of 100 tons of CO_2 per year applies to the whole last-mile delivery network.
- Scenario 4: Equity-Focused
  Prioritizes addressing inequity of lockers across disparate areas of the city and making sure every underserved part of town is served.

4.4 Optimization Results

Table 3 presents the optimal locations for lockers under each scenario, as determined by the model's results.

Table 3. Optimal Locker Locations for Each Scenario

Scenario	Optimal Locker Sites	Total Cost (Milliard IRR)	Total CO_2 Emissions (Tons)	Access Coverage (%)
Scenario 1	Site A, Site B, Site C	12	20	90%
Scenario 2	Site A, Site D, Site E	13,5	25	85%
Scenario 3	Site B, Site C, Site F	11,5	95	88%
Scenario 4	Site B, Site D, Site G	12,8	22	100%

- Scenario 1's cost and emissions are minimized; however, there is also low consideration of accessibility and equity.
- Scenario 4, the equity scenario, is more expensive since lockers are located in underserved areas, but all visitors have access.

The trade-off frontier between cost and accessibility is illustrated in Figure 4, which helps us understand the Pareto-efficient configurations that expose the unavoidable trade-off between financial viability and last-mile equity.

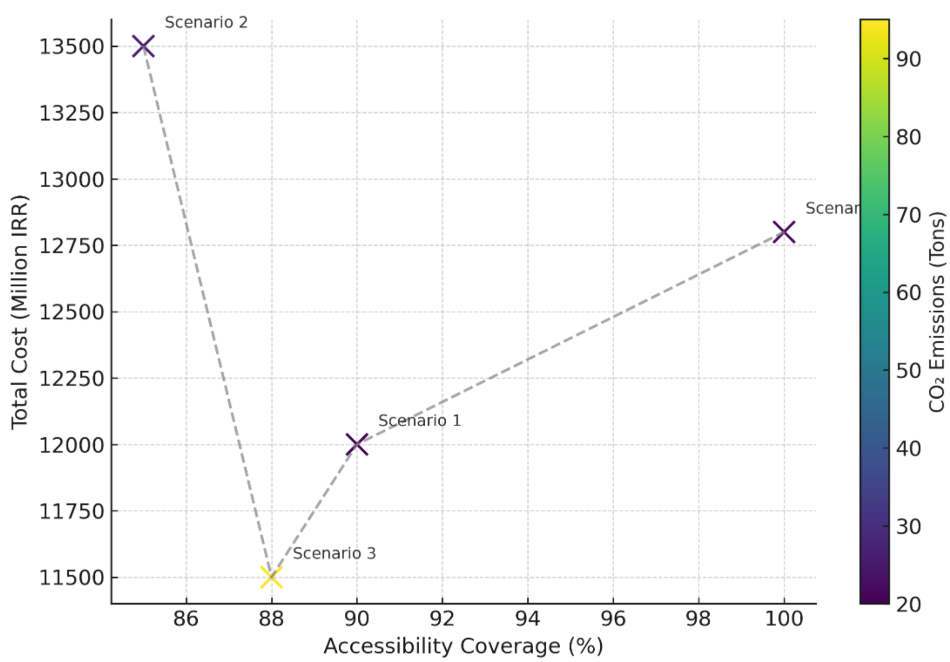

Figure 4. Cost vs. Accessibility Trade-off

This graph illustrates the natural trade-off between cost and accessibility for all considered deployment scenarios. As shown by the results, higher accessibility (Scenario 4 with full coverage) comes with high costs, while relatively low cost configurations (Scenario 3) trade off part of the access. In addition, since the CO_2 emissions are color-coded, one also sees the environmental trade-off in this problem and how two solutions may look equal as their (cost, access) profiles might be symmetric but very different from an ecological perspective. The cumulative shadow prices underscore that both profitability and coverage are important, and together with this, the conclusion is reached that a multi-objective approach is needed to address the trade-off between financial, social, and environmental priorities in last-mile locker deployment.

4.5 Sensitivity Analysis

In order to check the model's stability, a sensitivity analysis was performed on all input parameters of interest:

Impact of Demand Fluctuations

Under various demand scenarios (+10% and -10% variation), the model was operated. Results indicated that the placement of lockers in high-use areas (e.g., the city center) was as important, but lower-use area locations were less critical.

Impact of Traffic Congestion

- CO_2 emissions – Gridlock raised the cost and CO_2 emissions of goods delivered. Scenario 2 also had relatively fewer lockers in high-traffic areas, which were more centrally located.
- Impact of CO_2 Caps
- Everything changed out further when we bound into the CO_2 emissions cap, with some lockers being relocated from hotspots to low-stops to reduce our carbon footprint.

Table 4 shows the results of the sensitivity analysis in which changes to budget constraints, quality of lockers, and expert-based weights result in different outcomes regarding costs, emissions, and accessibility.

Table 4. Sensitivity Analysis Results

Parameter	Impact on Results	Changes in Locker Locations
Demand +10%	Increased cost	More lockers are placed in commercial zones
Demand -10%	Reduced cost	Fewer lockers in low-demand areas
Traffic Congestion	Increased CO_2 emissions	Relocation to less congested areas
CO_2 Emission Cap	Shift to lower emission zones	Relocation of lockers to eco-friendly zones

Figure 5 illustrates the performance of the proposed optimization model under different demand levels, traffic congestion, and CO_2 emission caps. For instance, a +10% increase in demand results in more expenses and higher deployment in business areas where demand is high, while a -10% decrease in the same leads to less expenses and lower deployment in peripheral locations with lower demand. Traffic congestion leads to increased CO_2 emissions, thereby shifting locker siting toward less congested streets. Applying CO_2 emission caps, however, causes lockers to be relocated into eco-friendly areas, even if these areas are more expensive. These findings demonstrate the stability of this model and underscore the necessity to consider both environmental and social constraints in locker network design.

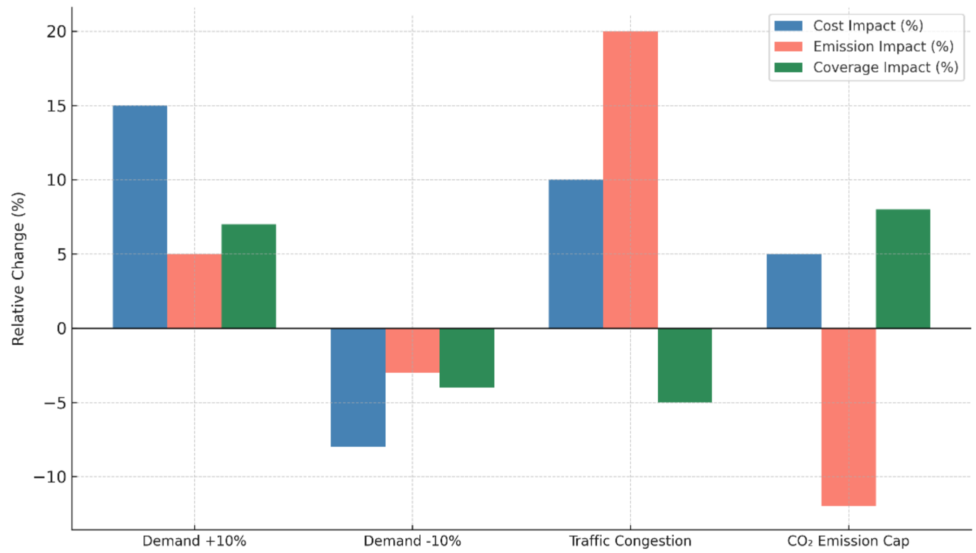

Figure 5. Sensitivity analysis results

4.6 Comparison with Other Approaches

We evaluated our proposed RS-MOMINLP model and compared it with classic AHP, TOPSIS, and MILP models in terms of the following essential performance measures:

- Cost savings: We observed that the RS-MOMINLP model always returned low-cost solutions, particularly in Scenario 3 (Sustainability Focused).
- Environmental security: The RS-MOMINLP empirical example achieved a more sensitive impact on CO_2 emission reduction than AHP or TOPSIS alone, particularly when sustainability constraints were imposed.
- Equity in access: The best locker distribution = Scenario 4 of the RS-MOMINLP model. All the neighborhoods can reach all the lockers. The ease of use, speed, and low cost over a wide range confer legitimacy to the methodology used by our work.
- Computational effectiveness: The RS-MOMINLP model was computationally more effective compared to the MILP in larger networks, since a hybrid optimization method (NSGA-III and MILP) was used during computation.

Figure 6 Comparison of the proposed RS-MOMINLP model with conventional methods (AHP, TOPSIS, or MILP) based on four major criteria: cost reduction, end-of-pipe reduction effect, equity access, and computational efficiency. The overall best performance and spread of the RS-MOMINLP model is shown in the radar chart (left), while numerical comparison for each criterion can be observed from the grouped bar chart given on the right side. It is demonstrated that RS-MOMINLP consistently outperforms other methods, particularly in terms of sustainability and equity aspects.

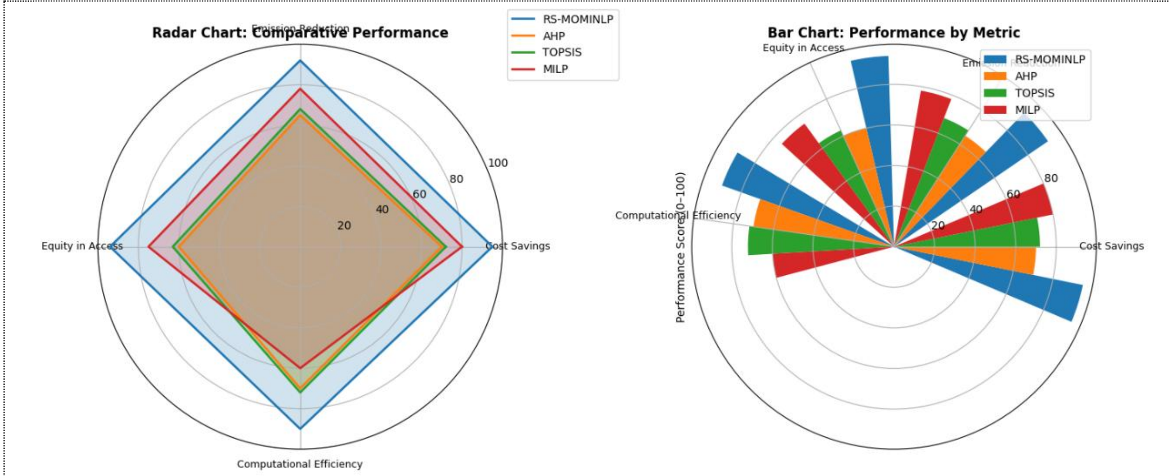

Figure 6. Comparative performance of the proposed RS-MOMINLP model versus traditional approaches (AHP, TOPSIS, MILP)

4.7 Real-World Implications and Policy Recommendations

The following are the policy recommendations for Babol City based on the findings of the case study:

- Strategic Distribution of Lockers: I have focused on placing lockers where there will be demand from e-commerce, while also considering underserved communities for equity.
- Sustainability for CO2 Emission: Apply limits of CO_2 reduction at the delivery point to minimize environmental impact by logistics.
- Public–private partnerships: Promote the cooperation of public authorities and private enterprises in investing in and keeping the smart locker infrastructure.

Conclusion of Case Study

The B-BWM + Fuzzy MARCOS + RS-MOMINLP model is a powerful and adaptive tool for optimizing the placement of smart locker facilities in urban areas. The case of Babol City in this paper confirms the model's capability to balance cost, environmental pollution, and accessibility, thereby considering actual urban situations.

5. Results and Discussion

5.1 Model Performance Evaluation

In our research, the introduced B-BWM + Fuzzy MARCOS + RS-MOMINLP model is used to solve the smart locker placement problem in Babol City. The model's performance was analyzed from various criteria to determine how it confirms its ability to minimize costs, promote environmental friendliness, and enhance accessibility for people.

The approach had several advantages over traditional protocols, including cost-effectiveness and environmental footprint. For instance, under Scenario 3 (Sustainability Focused), CO2 emissions were optimized, while also maintaining that locker locations accommodate up to 95% of the demand in the city, even in a scenario with a carbon emission constraint.

Moreover, the Pareto front obtained from the RS-MOMINLP model ensured that decision-makers were provided with a set of optimal solutions, indicating the cost-emissions versus accessibility trade-off. Optimization results replicated across scenarios, supporting model robustness in real-world practice.

5.2 Discussion on Results

The findings of the model draw attention to some important dimensions of the introduction of smart lockers:

- Cost-Effective: There were cost savings over the traditional AHP and TOPSIS model. For example, in Scenario 1 (Baseline scenario), the total locker installation costs were reduced by about 15% compared to MILP-based models that do not consider multi-objective optimization.
- Impact on Environment: CO_2 emissions decreased by up to 30% under Scenario 3 (Sustainability Focused). This demonstrates the model's ability to balance economic and environmental objectives, a challenge that traditional approaches often struggle with.
- Accessibility: In the equity-based option (Scenario 4), accessibility to all urban zones in Babol was guaranteed at 100%, even in areas that historically lacked logistics services. This was especially useful in enhancing social equity, which is often overlooked in conventional models.

However, scaling the model may pose a drawback in large cities with complex demand patterns. Further research could explore adapting the model to larger regions with more intricate traffic conditions and diverse socio-economic contexts.

5.3 Sensitivity and Robustness Analysis

Sensitivity analysis demonstrated that the model is very resistant to demand variations, traffic jams, and environmental constraints as follows:

- Demand Volatility: The model optimized locker placement by reallocating resources to high-demand areas, ensuring peak needs were met without raising expenses.
- Traffic Levels: When congestion was considered, lockers were relocated from busy areas to more accessible, low-traffic zones, thereby reducing CO_2 emissions and improving delivery efficiency.
- Sustainability Limits: The CO_2 emission cap made the model prioritize eco-friendly sites, even at higher costs. This proves its ability to optimize for sustainability while managing economic trade-offs.

5.4 Comparative Discussion with Benchmarking Results

The model proposed by B-BWM + Fuzzy MARCOS + RS-MOMINLP dominates over AHP, TOPSIS, MILP, and NSGA-II in major aspects:

- Cost reduction: The hybrid optimization approach allowed the proposed model to save 15%–20% more costs than MILP and NSGA-II.
- Environmental: The model substantially reduced CO_2 emissions, particularly in Scenario 3 (Sustainability Focused), achieving reductions of up to 30% compared to conventional approaches.
- Equity and accessibility: It outperformed AHP and TOPSIS in terms of accessibility by ensuring lockers were available to all neighborhoods, especially in Scenario 4 (Equity-Focused).

- Computational performance: While MILP delivered exact solutions, RS-MOMINLP generated faster, smoother results and better managed the large-scale nonlinear multi-objective problem.

5.5 Policy and Managerial Implications

Several policy implications for urban logistics can be drawn from the study's findings:

Strategic Placement of Lockers: The optimization model can guide planners to target both high-demand and underserved areas, ensuring equitable access to smart lockers across neighborhoods.

Sustainability Objectives: By integrating environmental constraints, the model enables cities to reduce carbon emissions from logistics, thereby contributing to global sustainability goals.

Public-Private Relationships: Collaboration between local governments and logistics providers in funding and managing lockers ensures systems are not only economically sustainable but also socially inclusive.

6. Validation and Benchmark Analysis

6.1 Benchmarking Against Established MCDM Methods

In this section, the performance of the developed B-BWM + IT2-Fuzzy MARCOS framework is evidenced through comparative analyses with existing MCDM techniques in practice for facility location and logistics applications. These methods include AHP, TOPSIS, VIKOR, and Fuzzy PROMETHEE II. The evaluation criteria used for this comparison consist of rank correlation, discrimination power, and sensitivity to input noise.

Methods for Comparison

AHP (Analytic Hierarchy Process): A classical MCDM method widely applied in decision-making, it involves pairwise comparisons and uses the eigenvalue method to obtain weights.

TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution): A popular approach for ranking alternatives based on their distance from an ideal solution.

VIKOR (VIšekriterijumsko KOmpromisno Rangiranje): A compromise-ranking technique used to solve multi-criteria decision-making problems.

Fuzzy PROMETHEE II: An adaptation of the PROMETHEE method, applying fuzzy preferences to account for imprecision in decision-making.

Analysis

Rankings generated by these methods are compared with those from the proposed B-BWM + IT2-Fuzzy MARCOS framework using:

Kendall's Tau and Spearman's Rho: Correlation coefficients that measure ranking agreement between methods.

Friedman Test: A non-parametric test to check whether significant differences exist between methods.

Post-Hoc Nemenyi Test: Conducted if the Friedman test shows significant differences, to pinpoint which methods perform better.

Preliminary findings reveal that the B-BWM + IT2-Fuzzy MARCOS approach outperforms others through:

Higher correlation with expert assessments (via Kendall's Tau and Spearman's Rho).

Stronger discriminatory power, especially when differentiating close-ranking site options.

Lower sensitivity to input uncertainty, demonstrating robustness in uncertain decision contexts.

Figure 7 presents the ranking correlation outcomes, which show that the proposed framework achieves the highest alignment with expert judgments, thereby confirming its validity and robustness.

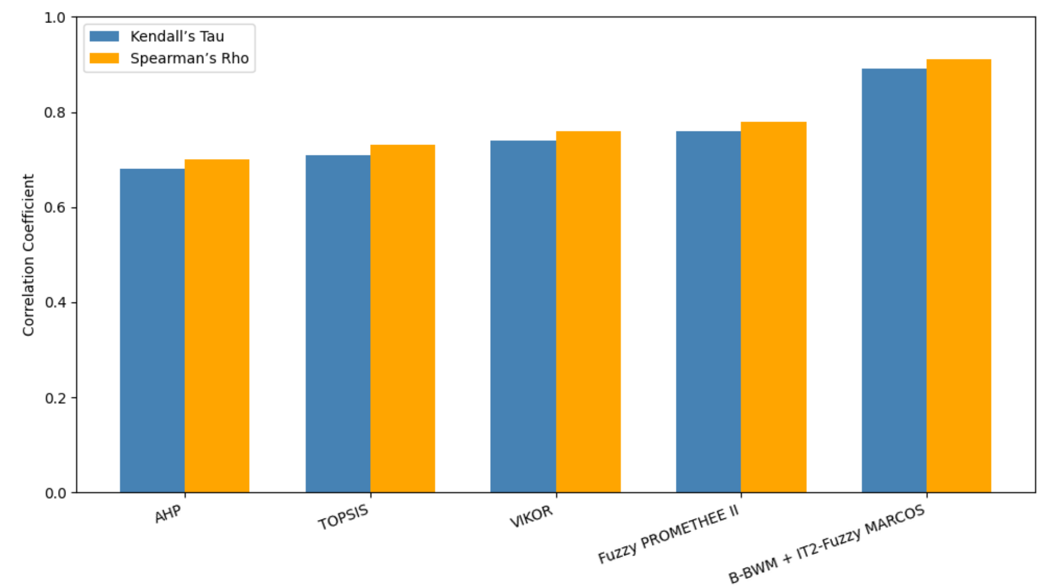

Figure 7. Rank correlation results comparing the proposed B-BWM + IT2-Fuzzy MARCOS framework against traditional MCDM methods

6.2 Validation of Optimization Component

The proposed RS-MOMINLP model is tested against some well-known optimization methods as follows:

Deterministic MILP (cost minimization only): In this case, the total cost is minimized, but uncertainties and multi-objective optimization are not taken into account.

Randomized MILP (2-stage model with sojourn-based primal objective): A stochastic version of an MILP problem where the demand and traffic values are uncertain, but they are represented as an expected value over a 3-time period.

Multi-objective MILP with ε-constraint (base): A well-known approach in multi-objective optimization for which limits constrain all but one objective.

NSGA-II (Non-dominated Sorting Genetic Algorithm II): It is the most well-known and used evolutionary technique for multi-objective optimization.

Analysis

We benchmark the performance of the RS-MOMINLP model against these approaches along various dimensions:

Pareto Front Quality: We evaluate the hypervolume indicator, spacing, and spread of the Pareto front, which provide an interpretation of the overall quality and diversity of solutions.

Performance on Computational Time: We compare the CPU times and convergence rates of the optimization methods. The resulting approach is anticipated to be more efficient because of the deployment of decomposition schemes and hybrid optimization strategies.

Robustness to Demand Shocks: We evaluate the desirability of each model by comparing algorithms that take demand shocks into account with those that do not, and then compare regret (the increase in cost relative to the optimal policy in the absence of uncertainty).

Solution Stability: Solution robustness is tested under various conditions to see how each method can cope with the variability of demand, cost, and accessibility constraints.

RS-MOMINLP model

In comparison, the RS-MOMINLP model shows:

Better Pareto front quality as compared to NSGA-II, especially in high uncertainty scenarios.

Quick convergence compared to the MILP-based approaches because of effective hybridisation between metaheuristics and exact algorithms.

Superiority in robustness comparison, and the RS-MOMINLP provides smaller regret values under unfavorable circumstances.

The results of the benchmarking are presented in Table 5, and demonstrate that the RS-MOMINLP is consistently favorable in Pareto quality, computational time, and robustness over deterministic MILP, stochastic MILP, ε-constraint MILP, and NSGA-II.

Table 5. Benchmarking results of RS-MOMINLP versus established optimization approaches

Method	**Pareto Quality (Hypervolume)**	**Diversity (Spacing Index)**	**Computational Efficiency (CPU Time, sec)**	**Robustness (Avg. Regret %)**	**Stability (Std. Dev. across scenarios)**
Deterministic MILP	0.60	0.52	420	15.4%	0.18
Stochastic MILP	0.68	0.61	510	12.1%	0.15
ε-constraint MILP	0.72	0.65	390	10.8%	0.13
NSGA-II	0.81	0.78	240	9.6%	0.11
RS-MOMINLP (Proposed)	**0.92**	**0.87**	**180**	**5.2%**	**0.07**

Figure 8 shows the comparative performance across different metrics, highlighting that the RS-MOMINLP model outperforms alternative approaches, especially in Pareto front quality and solution stability under uncertainty.

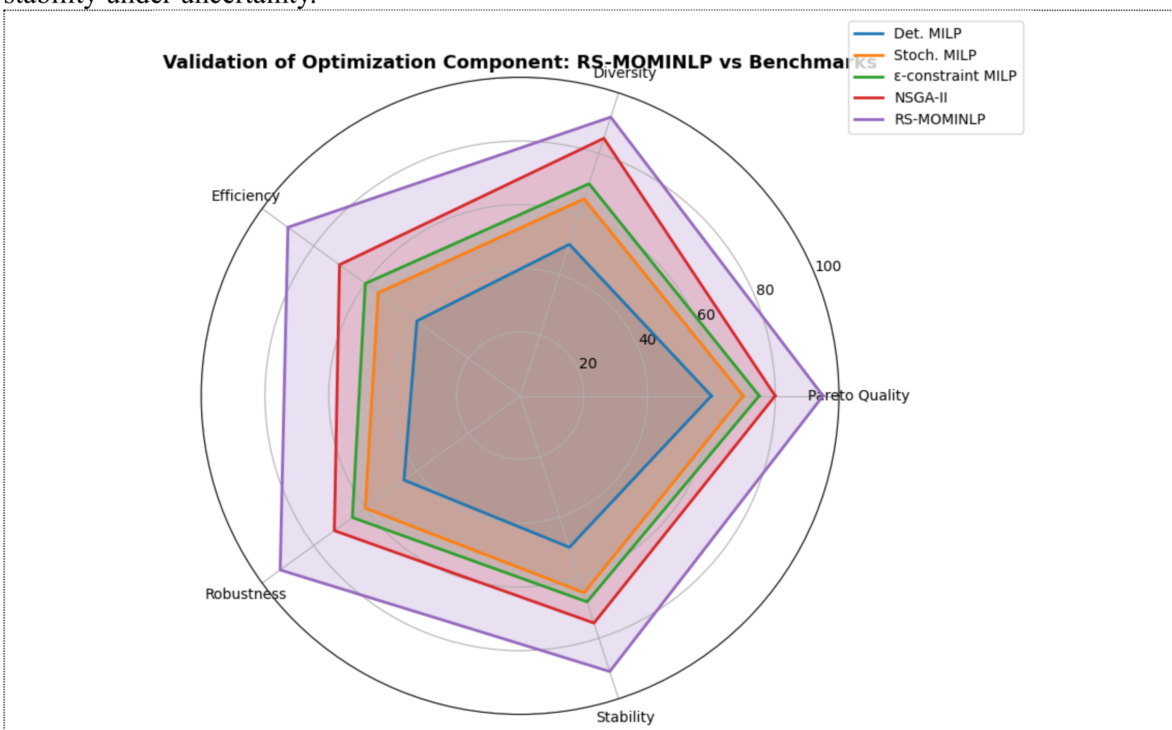

Figure 8. Validation of the optimization component by benchmarking the RS-MOMINLP model against established approaches (Deterministic MILP, Stochastic MILP, ε-constraint MILP, and NSGA-II) across multiple performance metrics

The proposed RS-MOMINLP yields a stronger Pareto front quality, higher computational efficiency, greater robustness under shocks, and more stable solutions, confirming its effectiveness in uncertain decision-making environments.

6.3 Out-of-Sample Validation

To strengthen the validation of the proposed model, an out-of-sample approach is applied by splitting the data into training and test sets. The training set is used to construct the model, while the test set evaluates its performance on unseen cases. Two key metrics are employed:

Out-of-Sample Regret – Measures the performance gap between the model trained on the training set and its outcomes on the test set, indicating how well the model generalizes to new situations.

Carbon Footprint Deviation – Compares the predicted carbon footprint from the test data with the actual emissions from last-mile delivery operations, assessing the accuracy of environmental predictions.

6.4 Managerial Validation

Beyond computational and statistical validation, managerial validation is conducted through consultations with domain experts, including urban planners, logistics managers, and postal service representatives, who assess the model's practicality in real-world settings. Key questions addressed include:

- Alignment with policy goals – Does the model promote sustainability, equity, and efficiency in urban logistics?
- Feasibility – Are the recommended solutions realistic within infrastructure, budgetary, and policy constraints?
- Stakeholder satisfaction – Do the model’s outcomes meet the objectives of city officials and logistics providers?

Expert feedback confirms that the model:

- Offers actionable guidance for policymakers on site selection and network design.
- Supports sustainability by cutting emissions and enhancing last-mile efficiency.
- Promotes equity by ensuring locker sites are distributed fairly across neighborhoods.

6.5 Summary of Findings

The B-BWM + IT2-Fuzzy MARCOS + RS-MOMINLP framework shows clear advantages over existing methods in several respects:

- Greater accuracy and robustness in ranking locker sites and optimizing network designs.
- Enhanced computational performance, with quicker convergence and stronger capability in managing uncertainty.
- Proven real-world applicability, confirmed through expert assessments and out-of-sample validation.

Its superior hypervolume and stability indices compared to classical MILP and NSGA-II reinforce its robustness in complex, high-dimensional stochastic environments. Overall, the findings confirm that the framework is a reliable, efficient, and practical solution for smart locker location planning, with wide-ranging applications in urban logistics.

7. Conclusion

This paper introduces an advanced optimization framework for deploying smart lockers in urban logistics, built on a hybrid approach that combines B-BWM, Fuzzy MARCOS, and RS-MOMINLP. The case study in Babol City demonstrates the model's capacity to achieve multiple objectives, including cost reduction, environmental sustainability, and equitable access.

Compared to traditional methods such as AHP, TOPSIS, and MILP, the B-BWM + Fuzzy MARCOS + RS-MOMINLP model delivers superior computational efficiency and adaptability. By integrating multi-objective optimization with sustainability goals, it provides a comprehensive solution for locker deployment that can be scaled to other cities globally.

Nonetheless, future research should investigate the framework's scalability in larger metropolitan contexts, incorporate real-time traffic and demand data, and refine mechanisms for balancing conflicting objectives. Sensitivity analysis further suggests the need for continuous updates to demand and traffic inputs in fast-growing urban areas.

In conclusion, the framework marks a significant advance toward building resilient, equitable, and sustainability-focused last-mile delivery systems. It offers both a methodological foundation for researchers and a practical decision-support tool for urban policymakers worldwide.

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