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Planning location of parcel lockers using group Analytic Hierarchy Process in Spherical Fuzzy environment

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A B S T R A C T

Parcel lockers have emerged as an effective solution to address inefficiencies in last-mile delivery. However, the selection of an appropriate location plays a crucial role in ensuring optimal service and enhanced logistic performance. To address this challenge, this work aims to define the best location for parcel lockers in the capital of Ireland, Dublin by conducting a novel decision-making model. The Spherical Fuzzy Analytic Hierarchy Process (SF-AHP) has been adopted to deal with the uncertainty in the decision maker preferences, while the Euclidean Distance-Based Aggregation Method (EDBAM) has been conducted to aggregate the decision makers preferences. The proposed integrated model is an applicable approach to elude AHP deterministic disadvantages, moreover, it is the first application of SF-AHP and EDBAM to select parcel lockers' location. The findings, including the identification of the top three optimal locations, namely "Post office," "On commercial area," and "High population density area," along with their respective weight scores, provide valuable insights for policymakers making strategic decisions regarding parcel locker placements in Dublin city.

1. Introduction

The exponential growth of the e-commerce industry has led to notable changes and advancements in the last-mile delivery sector over the past two decades. This evolution has been driven by increasing consumer demand for convenient and swift deliveries. According to market analysis, the Business to Customer (B2C) sector in Ireland is projected to experience an annual growth rate of 17.16%, reaching a substantial market value of US$15,915.1 million in 2022. This growth trajectory is indicative of the significant role that e-commerce plays in modern consumer habits. In fact, the medium to long-term outlook for the B2C e-commerce market in Ireland is quite promising. The industry is expected to experience steady growth, with a compound annual growth rate of 12.80% forecasted for the period between 2022 and 2026. Over this period, the Gross Merchandise Value (GMV) of B2C e-commerce in Ireland is expected to increase from US$13,583.9 million to US$25,769.1 million by 2026. Customers increasingly demand the flexibility and convenience to purchase products at any time and from anywhere, which has complicated delivery logistics for courier, express, and parcel delivery services. Consequently, providing around-the-clock services has become a significant operational challenge for these companies (Grosman, 2018).

Logistics Service Providers (LSP) may suffer from costs and idle time as a result of missed delivery. Home delivery has several inherent limitations. For example, since goods are delivered door to door rather than Business to Business (B2B), it is not able to consolidate deliveries in optimal way. Additionally, home delivery rounds are longer and have more loading and unloading stops. All of the other drawbacks of urban freight movement, including congestion, pollution, and an increase in the likelihood of accidents, are a result of these restrictions (Browne et al., 2012).

Given that most individuals now work throughout the day and that home delivery may no longer be the optimal alternative, there is a need to create an option that will please both the customer and the delivery companies (Emeç et al., 2016). In order to highlight these issues, postal service providers have made investments in value-added services such as delivery to monitored or automated collection points over the past decade. To meet the needs and expectations of end-users, these new delivery methods offer a viable alternative to home delivery. Given the rapid growth of the e-commerce sector and the expansion of logistics services, many experts have recognized the importance of parcel locker systems as a key component of the last-mile delivery in the supply chain system. As a self-service solution, parcel locker systems offer an efficient approach to addressing the last-mile challenge, which is a critical

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bottleneck in the delivery process. By improving the quality of the delivery network and enhancing customer satisfaction, parcel lockers have the potential to significantly impact the delivery industry (Viu-Roig and Alvarez-Palau, 2020).

Yang et al. (2020) proposed the developed bilevel programming approach to evaluate the problem of parcel locker location, the proposed approach integrated with GIS data. Schaefer and Figliozzi (2021) employed the cluster analysis to ameliorate the quality of Amazon lockers by selecting optimal location for the lockers. Ghaderi et al. (2022) conducted an integrated algorithm along with a linear program approach in its simple version to locate parcel lockers locations. Iwan et al. (2016) evaluated the quality of parcel lockers system by measuring its efficiency and usability. Tang et al. (2021) applied statistical analysis and the confirmatory factor analysis to estimate the parcel lockers service quality by defining the main influenced factors and their impact on consumer satisfaction. Pan et al. (2021) proposed an integrated Genetic Algorithm with the Lin-Kernighan Heuristic to estimate and enhance the efficiency of the estimate the parcel lockers service quality. Keeling et al. (2021) evaluated parcel lockers location problem by adopting a multiple-criteria method.

The preferences for parcel locker locations are largely influenced by users' demands. In Sweden, the users group preferred the commercial places as the best location for parcel lockers (Bengtsson and Vikingson, 2015). Meanwhile, the users in Poland, neither commercial areas nor public transport stops were good options for locating parcel lockers (Iwan et al., 2016). However, Brazil's case differed from that of Poland, as the users ranked the commercial places as the best location for parcel lockers, similar to Sweden (Oliveira et al., 2019). In Korea, on the other hand, public transport stops were considered the ideal location for parcel lockers from the users' side (Lee et al., 2019). The demand of the users for parcel lockers also varied in France, where the urban places preferred public transport stops while rural places leaned towards high population density places for locating the lockers (Morganti et al., 2014). Finally, in Southeast Queensland, the most favored location the users to locate parcel lockers was in the high population density places, particularly those with public transport stops (Lachapelle et al., 2018).

Undoubtedly, placing parcel lockers in all cities to meet the demand of the hour is a complex and significant decision which needs to be supported by decision-making support models. However, the multi criteria decision making (MCDM) approaches has been widely adopted to identify and solve the challenging location selection problems (Alberto, 2000; Żak and Węgliński, 2014; Hama et al., 2019; Mihajlović et al., 2019; Anderluh et al., 2020; Zhang et al., 2021; Liang et al., 2021; Aljohani, 2023; Ortega et al., 2023; Moslem et al., 2024). Additionally, fuzzy based MCDM techniques have been successfully applied to other problems (Xu et al., 2024; Bouraima et al., 2024; Lo et al., 2024; Yüksel et al., 2024; Wang et al., 2024). In this work, we employed the most popular MCDM approach in solving location selection problems, the Analytic Hierarchy Process (AHP) with the Euclidean Distance-Based Aggregation Method (EDBAM) and Spherical Fuzzy Sets (SFS). The model has been conducted for the evaluation process to select the proper location for parcel lockers in an academic-oriented manner. The AHP in a fuzzy environment generates significant and reliable results, and several works have approved this approach in the case of location selection (Chowdhury and Haque Munim, 2022; Moslem et al., 2023; Moslem et al., 2024). However, the main advantage of using AHP with SFS is avoiding uncertainty and vagueness in decision-making processes (Kutlu Gundogdu and Kahraman, 2019), where the hesitancy can be defined severally from membership and non-membership indexes (Kutlu Gündoğdu and Kahraman, 2020).

The rationale for integrating EDBAM within this framework could have been elucidated in more depth to provide a clearer understanding of its role and significance. While the research successfully adopts EDBAM as part of the decision-making model for selecting parcel locker locations in Dublin, further elaboration would have enhanced the comprehensibility and justification of this integration. Providing insights into its advantages over alternative aggregation methods and its compatibility with the objectives of parcel locker location selection would have strengthened the methodology's rationale. Additionally, a more detailed description of how EDBAM operates, including its step-by-step process and principles, would have demystified its application for readers who may not be familiar with this method. Given that one of the primary motivations for adopting the Spherical Fuzzy Analytic Hierarchy Process (SF-AHP) is to address uncertainty in decision maker preferences, it is crucial to clarify how EDBAM contributes to managing this uncertainty. Articulating the synergies between SF-AHP and EDBAM and how they collaboratively tackle uncertainty within the aggregation process would have provided a clearer picture of their combined efficacy.

EDBAM is known for its simplicity and transparency. It involves calculating distances in a Euclidean space, a concept that is widely understood. This simplicity makes it accessible to a broad range of users, including those without advanced mathematical or statistical expertise. Decision-makers and stakeholders can easily grasp how EDBAM works, fostering better communication and understanding. Moreover, the EDBAM produces numerical results, which are objective and quantifiable. This objectivity reduces the potential for subjective biases in decision-making processes. Users can rely on the numerical output to make informed and data-driven choices.

As the e-commerce market continues to thrive, research endeavors like this not only address the immediate challenges of efficient parcel delivery but also contribute to the larger goal of developing sustainable and responsive urban systems. This paper addresses the critical challenge of selecting optimal locations for parcel lockers in Dublin, Ireland, to enhance last-mile delivery efficiency. It introduces an innovative decision-making model that combines the SF-AHP and EDBAM to overcome the limitations of traditional AHP. By doing so, it aims to provide policymakers and logistics stakeholders with valuable insights into the best parcel locker locations, thus improving the overall performance of last-mile delivery services in the city.

The remainder of this study is divided into three main sections. Section 2 presents the applied AHP in SF space with EDBAM to estimate the problem. Then, an application to parcel lockers location selection in Dublin is presented in Section 3. Finally, in Section 4, discussion and conclusion are presented.

2. Methodology

2.1. Spherical Fuzzy AHP (SFAHP)

The Analytic Hierarchy Process (AHP), initially proposed by Saaty (Saaty, 1977), has since undergone improvements and has been applied to solve complex problems in various fields (Vargas, 1990), where several scholars illustrated the undergone improvements of AHP and how it was applied to evaluate and solve the complex problems. For instance, AHP has been employed prioritize construction development projects (Darko et al., 2019), in operations management (Subramanian and Ramanathan, 2012), in the medical and health care sector (Liberatore and Nydick, 2008), in marketing (Davies, 2001), in urban transport planning ((Nassi and da Costa, 2012; Van Asch et al., 2020; Moslem et al., 2023; Moslem, 2024) and sustainable development (Dos Santos et al., 2019). These applications highlight AHP's versatility in addressing intricate decision-making challenges across diverse domains.

In our study, we selected AHP as the Multi-Criteria Decision Making (MCDM) approach for evaluating the optimal location of parcel lockers. To address the hesitancy issue of the decision maker, we proposed applying AHP in a Spherical Fuzzy environment using the Spherical Fuzzy AHP (SFAHP) model introduced by Kutlu Gundogdu and Kahraman (2019). In Fig. 1, we summarize the main steps of the SFAHP model with EDBAM for the location selection evaluation process.

The details of the evaluation process are depicted step by step in the following seven main steps:

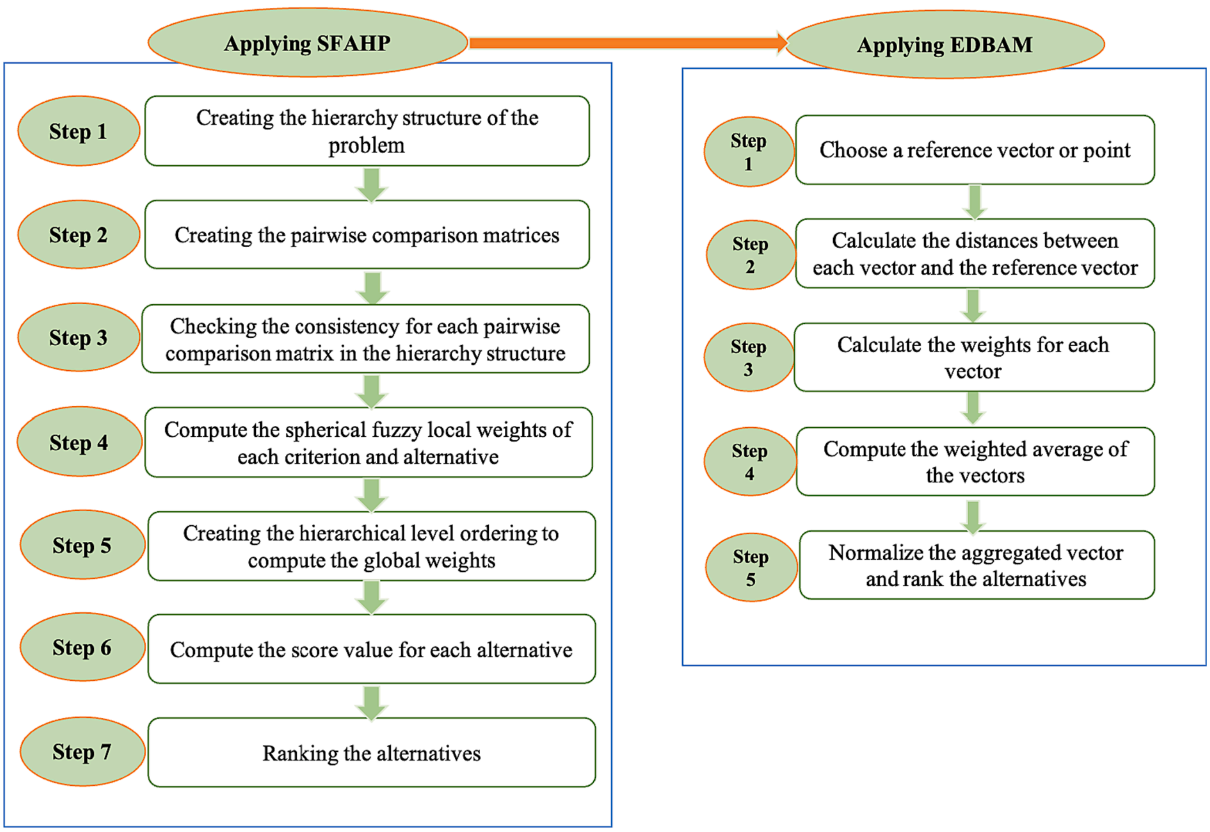

Fig. 1. The flowchart of the adopted model.

Step 1:

Structuring the hierarchy model of the location selection problem.

In the initial step, we establish a hierarchical framework founded on the views of experts and literature. This hierarchical structure typically encompasses three tiers. The first tier pertains to the target level or choosing the most suitable location. The second tier consists of criteria levels, which encompass the pertinent criteria associated with the location selection quandary. In some scenarios, this tier may feature various levels, incorporating primary and secondary criteria levels. Finally, the third tier constitutes the alternatives level (the suggested possible m alternatives $X = \{x_1, x, \cdots x\}$ $(m >= 2)$ for location selection). The set of criteria $C = \{C_1, C_2, \cdots C_n\}$ provides the weights and score index (SI).

Step 2:

Create the pairwise comparisons (PCs) and using SFSs taking in consider the linguistic terms (Table 1). Eqs. (1) and (2) are adopted to compute SI.

$$SI = \sqrt{\left|100^*\left[\left(\mu_{\tilde{A}_s} - \pi_{\tilde{A}_s}\right)^2 - \left(\nu_{\tilde{A}_s} - \nu_{\tilde{A}_s}\right)^2\right]\right|} \tag{1}$$

Table 1
The importance scale for PCs.

	(μ, ν, π)	SI
AMI	(0.9, 0.1, 0.0)	9
VHI	(0.8, 0,2, 0.1)	7
HI	(0.0, 0.0, 0.0)	5
SMI	(0.6, 0. 4, 0.3)	3
EI	(0.5, 0.4, 0.4)	1
SLI	(0.4, 0.6, 0.3)	1/3
LI	(0.3, 0.7, 0.2)	1/5
VLI	(0. 2, 0. 8, 0. 1)	1/7
ALI	(0.1, 0.9, 0.0)	1/9

where $\widetilde{A}_s$ is a spherical fuzzy set and for each x, $\mu_{\tilde{A}S(x)}$, $\nu_{\tilde{A}S(x)}$ and $\pi_{\tilde{A}S(x)}$ are degrees of membership, non-membership, and hesitancy of x to $\widetilde{AS}$, respectively.for SMI; EI; AMI; VHI; and HI

$$\frac{1}{SI} = \frac{1}{\sqrt{\left|100^*\left[\left(\mu_{\tilde{A}_s} - \pi_{\tilde{A}_s}\right)^2 - \left(\nu_{\tilde{A}_s} - \nu_{\tilde{A}_s}\right)^2\right]\right|}} \tag{2}$$

for VLI; ALI; EI; SLI and LI

Step 3:

Detect the consistency for each PC matrix (PCM) in order to omit the inconsistent outcomes. For checking the consistency, we replace the linguistic terms in the PCM to the corresponding SI. After that, we conduct the conventional process of computing the consistency ratio (CR). The CR threshold is 10% for PCM with (5×5) size matrices and smaller ones, however, it is 20% for PCM matrices which are bigger than (5×5).

The threshold values for the CR may vary depending on the specific application and the decision-maker's preferences. There isn't a universal limit on the size of the matrix itself. However, the acceptable size of the matrix depends on several factors:

- The size of the matrix should be determined based on the complexity of the decision problem. If there are many criteria or alternatives to compare, the matrix may become larger.
- The quality and availability of data play a role. If you have limited data or information for certain criteria or alternatives, it may affect the size of the matrix.
- The decision-maker's comfort and ability to handle a matrix of a certain size are important. Very large matrices can become challenging to work with, leading to fatigue and potential inconsistencies in judgments.

- The software or tools you are using for AHP may have limitations on the size of matrices they can handle efficiently.

If the size of the matrix becomes too large, it may be advisable to consider reducing the number of criteria or alternatives, if possible, to keep the analysis manageable and the judgments consistent. Additionally, using specialized software designed for AHP can assist in handling larger matrices and calculating consistency ratios efficiently (Saaty, 1977).

Step 4:

Computing the fuzzified local weights of each criterion and alternative.

The concept of “fuzzification” in the context of Fuzzy Analytic Hierarchy Process (Fuzzy AHP) refers to the process of converting crisp (precise) data or weights into fuzzy data or weights to account for uncertainty or imprecision. It’s a fundamental step in Fuzzy AHP, allowing decision-makers to express their judgments and preferences in a more flexible and nuanced manner. In essence, “fuzzification” is a way to make the decision-making process in AHP more robust and reflective of the real-world complexity where judgments are rarely entirely crisp or precise. By using fuzzy numbers and fuzzy logic, Fuzzy AHP accommodates the inherent vagueness and ambiguity in decision-making and provides a more realistic representation of decision-makers’ preferences and uncertainties. It’s particularly valuable when dealing with complex decisions involving multiple criteria and alternatives where precise judgments are hard to come by (Zadeh, 1965).

The spherical fuzzy weights are calculated by using spherical weighted geometric mean (SWGM) which is assigned as follow:

Step 7:

With respect to the defuzzified final weight scores, we rank the alternatives. The highest number refers to the best alternative.

Defuzzification is a crucial step in fuzzy logic-based decision-making processes, like the one described in this study. It involves converting fuzzy or linguistic values, which are inherently imprecise, into crisp numerical values that can be more easily understood and used for ranking or decision-making. In the context of this study, defuzzification is used to obtain crisp numerical scores from the fuzzy final weight scores of each alternative. To obtain a crisp numerical value, the centroid method calculates a weighted average of the linguistic values based on their membership in the fuzzy set. The weights used in this averaging process are the fuzzy final weight scores obtained from the step 6 using Eq. (4).

2.2. *Aggregation by Euclidean Distance-Based Aggregation Method (EDBAM)*

The EDBAM has been adopted in several studies (Miller and Osherson, 2009; Yu and Lai, 2011; Duleba and Szádoczki, 2022) and recently Szádoczki and Duleba (2022) demonstrated the efficiency of EDBAM for aggregating decision makers preferences. EDBAM involves several steps to combine and it is described in details by (Szádoczki and Duleba, 2022). However, here are the main steps of this method:

- Identify the criteria or attributes that are relevant to your decision-making process. Also, list the alternatives you want to evaluate based on these criteria.

$$= \langle \left[1 - \prod_{i=1}^{n} (1 - \mu_{\tilde{A}_s}{}^2)^{w_i}\right]^{1/2}, \prod_{i=1}^{n} v_{\tilde{A}_{si}}{}^{wi}, \left[\prod_{i=1}^{n} (1 - \mu_{\tilde{A}_s}{}^2)^{w_i} - \prod_{i=1}^{n} (1 - \mu_{\tilde{A}_s}{}^2 - \mu_{\tilde{A}_s}{}^2)^{w_i}\right]^{1/2} \rangle \tag{3}$$

with respect to spherical fuzzy weight *w*:

$$w = (w_1, w_2 \ldots, w_n);\; w_i \in [0, 1];\; \sum_{i=1}^{n} w_i = 1$$

In this step, the geometric mean is chosen because it aligns with the fundamental principles of the method, such as consistency, positivity, and scale invariance. It also ensures that the final priorities or weights reflect the relative importance of criteria or alternatives as intended by decision-makers in a way that makes logical and mathematical sense.

Step 5:

Creating the hierarchical level ordering to compute the global weights of each criterion and alternative.

The computation process is applied level wisely from lower level to top level.

The score function (S) is employed to adopt the crisp weights by using the following Eq. (4):

$$SI(\widetilde{w}_j^s) = \sqrt{\left|100^* \left[\left(3\mu_{\tilde{A}_s} - \pi_{\tilde{A}_s}/2\right)^2 - \left(\nu_{\tilde{A}_s}/2 - \nu_{\tilde{A}_s}\right)^2\right]\right|} \tag{4}$$

The Eq. (5) is applied to normalize the generated weights:

$$\overline{w}_j^s = \frac{S(\widetilde{w}_j^s)}{\sum^{nj=1} S(\widetilde{w}_j^s)} \tag{5}$$

Step 6:

The final weight score of each alternative is defuzzify by using S in Eq. (4).

- Normalize the data for each criterion and alternative to bring them to a common scale. This step ensures that all criteria are treated equally in the evaluation. Common normalization methods include min–max scaling or z-score normalization.
- Assign weights to each criterion to indicate their relative importance in the decision-making process. The sum of all weights should equal 1.
- For each alternative, calculate the Euclidean distance between the normalized values of that alternative and the ideal values for each criterion. The ideal values represent the best performance for each criterion.
- Identify the alternative(s) with the smallest and largest Euclidean distances for each criterion. These are the ideal and anti-ideal alternatives, respectively.
- For each alternative, calculate its relative closeness to the ideal solution. This step quantifies how close each alternative is to the ideal solution for all criteria.
- Rank the alternatives based on their relative closeness values. Higher closeness values indicate better performance and, therefore, a higher ranking.
- The alternative with the highest relative closeness value is considered the best choice among the available options.

The preference vector for each evaluator $w^{(E)}$ is the solution of the following formula normalized to one:

argminf $(x)$where E is the evaluated matrix and $x \in \mathrm{R}^n$ and $f(x)$ is defined as follows: $f(x) = \sum_{k=1}^{m} (a_k . d_E(w^k, x))$

where the Euclidean distance is:

$$d_E(w^k, x) = \sqrt{\sum_{i=1}^{n} (w_i^k - x_i)^2} \quad (6)$$

and $\sum_{k=1}^{m} a_k = 1$ as before. Thus, we depict the vector in R^n that is the closest one to individual priority vectors after that normalize it to 1.

3. Application to parcel lockers location selection in Dublin

Dublin, Ireland, serves as an ideal context for our research due to its urban density, economic significance, varied geography, policy relevance, and data availability. Dublin's high population density and economic activity highlight the importance of efficient last-mile delivery solutions, making it a pertinent location for our study. The city's diverse geography allows us to explore the impact of different contexts on parcel locker placements. Additionally, Dublin's transportation and environmental challenges align with our research focus, providing relevant insights for policymakers and stakeholders.

The SFAHP has been adopted to evaluate the parcel lockers location problem in Dublin city, the applied model based on a hierarchy structure which is composed of criteria and alternatives. In consonance with a comprehensive literature review and scientists' point of view in the related field, the possibilities for locating parcel lockers have been identified along with the related criteria, the specialists selecting the following six alternatives to be estimated as mostly preferred locations (*A1: "Public transport stops"; A2: "Private car parking"; A3: "Post office"; A4: "On commercial area"; A5: "High population density area"; A6: "On pedestrian area"*). The authors established the hierarchy structure of the parcel lockers location selection (Fig. 2. illustrates the alternatives) based on the for mentioned alternatives:

In the evaluation process three specialists (The three specialists involved in the evaluation process consisted of one expert from the DCC (Dublin City Council) and two experts from academia who specialize in the relevant field. Due to privacy and confidentiality considerations, the specific details and identities of these experts are not disclosed in the research report. However, it's important to note that their expertise and knowledge in the subject matter were crucial in providing evaluations and assessments for the study) estimated the PCMs (one 5 × 5 matrix for criteria level and one 6 × 6 matrix for the alternative level) employing the linguistic terms from Table 1. The consistency for each PCM was revealed by considering the corresponding values in the conventional AHP approach for the linguistic terms from Table 1. Because of the complexity of the problem and the large size of the PCM, the current evaluation considered 0.2 as CR threshold, the reason come from the limited ability of human to estimate the large size PCMs (Apostolou and Hassell, 1993).

The following tables (2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, and 18) presents the evaluated PCs, the detected CR, the computed spherical fuzzy weights $\tilde{w}^s$ and the normalized crisp weights $\overline{w}^s$.

Table 2 provides a comprehensive view of the estimated Pairwise Comparison Matrix (PCM) of the alternatives, particularly focusing on DM1's perspective regarding the second criteria (C2). The results indicate that the Consistency Ratio (CR) for this analysis was found to be acceptable, signifying the reliability of the judgments made during the pairwise comparisons. From DM1's standpoint, it's evident that alternative A3 stands out as the most favored choice based on the second criteria, reflecting its strong alignment with DM1's preferences and objectives. Following closely is alternative A4, which also garners significant attention and support from DM1, although to a slightly lesser extent. These findings shed light on the relative importance of these alternatives within the context of the second criteria and offer valuable insights into the decision-making process.

In Table 3, we delve into the estimated Pairwise Comparison Matrix (PCM) of the alternatives, specifically focusing on DM2's viewpoint concerning the second criteria (C2). The inclusion of the Consistency Ratio (CR) ensures the validity of the pairwise comparisons conducted during the analysis. From DM2's perspective, the results are enlightening. Alternative A3 emerges as the top choice, aligning closely with DM2's preferences and priorities with regard to the second criteria. This is followed closely by alternative A4, which also holds significant weight in DM2's evaluation, though with a slightly lower preference level.

Table 2
Pairwise comparison of locations caused by reliability based on DM1 evaluation.

	A_1	A_2	A_3	A_4	A_5	A_6	$\tilde{w}^s$		
A_1	EI	SMI	LI	SLI	SLI	HI	0.515	0.479	0.293
A_2	SLI	EI	VLI	VLI	LI	HI	0.443	0.564	0.254
A_3	HI	VHI	EI	EI	SLI	VHI	0.662	0.324	0.254
A_4	SMI	VHI	EI	EI	SMI	HI	0.631	0.353	0.284
A_5	SMI	HI	HI	SLI	EI	HI	0.602	0.389	0.285
A_6	LI	LI	LI	VLI	LI	EI	0.333	0.652	0.248

CR = 0.149.

Table 3
Pairwise comparison of locations caused by reliability based on DM2 evaluation.

	A_1	A_2	A_3	A_4	A_5	A_6	$\tilde{w}^s$		
A_1	EI	SMI	LI	LI	SLI	SMI	0.476	0.516	0.301
A_2	SLI	EI	VLI	LI	SLI	HI	0.455	0.550	0.268
A_3	HI	VHI	EI	SMI	SMI	VHI	0.691	0.303	0.237
A_4	HI	HI	SLI	EI	SMI	VHI	0.649	0.346	0.252
A_5	SMI	SMI	SLI	SLI	EI	VHI	0.588	0.408	0.285
A_6	SLI	LI	VLI	VLI	VLI	EI	0.327	0.664	0.248

CR = 0.094.

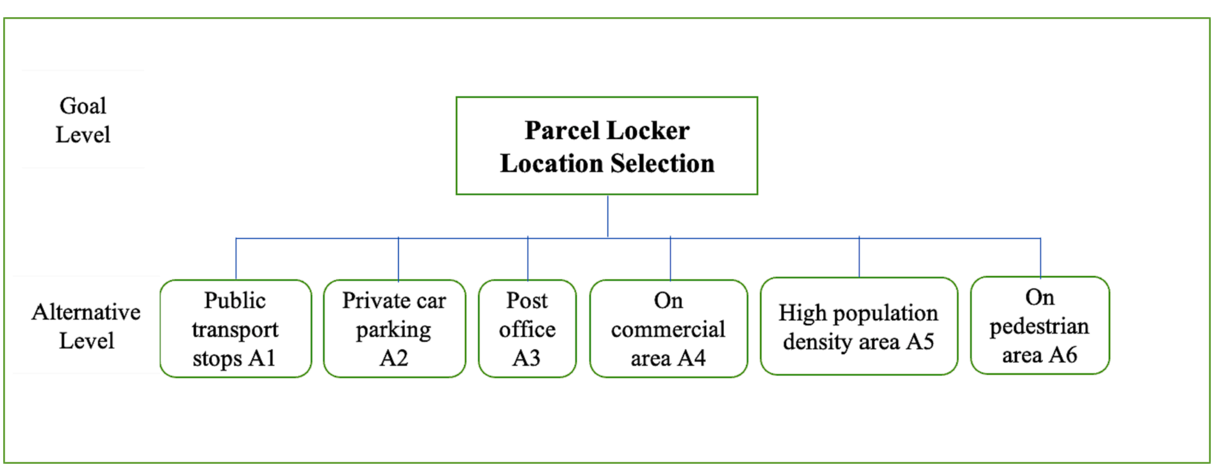

Fig. 2. The hierarchy framework for choosing parcel locker location.

Table 4
Pairwise comparison of locations caused by reliability based on DM3 evaluation.

	A_1	A_2	A_3	A_4	A_5	A_6	$\widetilde{w}^s$		
A_1	EI	SLI	LI	LI	LI	SLI	0.377	0.606	0.286
A_2	SMI	EI	SLI	SLI	SLI	SMI	0.497	0.490	0.321
A_3	HI	SMI	EI	SMI	SMI	HI	0.625	0.363	0.285
A_4	HI	SMI	SLI	EI	SMI	HI	0.602	0.389	0.285
A_5	HI	SMI	SLI	SLI	EI	HI	0.577	0.416	0.285
A_6	SMI	SLI	LI	LI	LI	EI	0.424	0.566	0.288

CR = 0.089.

These findings provide valuable insights into how DM2 perceives the alternatives in relation to the second criteria, shedding light on their relative importance in the decision-making process.

In Table 4, we shift our focus to the estimated Pairwise Comparison Matrix (PCM) of the alternatives from the viewpoint of DM3. Specifically, we're considering the fourth criteria (C4) in this analysis. The introduction of the Consistency Ratio (CR) is crucial to ensure the reliability of the pairwise comparisons made during this evaluation. From the perspective of DM3, the results provide valuable insights. Alternative A4 stands out as the most significant choice, reflecting DM3's strong preference for this option concerning the fourth criteria. Following closely, we have alternatives A3 and A2, which also hold considerable weight in DM3's evaluation, albeit with slightly lower preference levels. These findings offer a deeper understanding of how DM3 perceives the alternatives in relation to the fourth criteria, highlighting their relative significance in the decision-making process.

One reason for variability could be differences in the expertise and background of the specialists. Each expert may have a unique perspective or interpretation of the criteria and alternatives, leading to variations in their assessments. The criteria used in the study might be open to interpretation. Different specialists may weigh certain criteria differently or have varying definitions of what constitutes a favorable or unfavorable score on a criterion. Fuzzy AHP inherently involves some degree of subjectivity. The experts are asked to provide linguistic assessments, and these assessments can be influenced by their personal judgments and experiences. To address variability, consistency checks, such as the Consistency Ratio (CR), can be applied to the evaluations. If the CR exceeds an acceptable threshold, it may indicate inconsistencies in the judgments, and this should be discussed in the paper. The discussion on variability can also be an opportunity to suggest directions for future research. For example, exploring ways to reduce subjectivity, improve consistency, or conducting sensitivity analyses to assess the impact of different expert judgments.

The use of three specialists in the field for data collection may seem limited at first glance. However, the concept of "the wisdom of crowds" suggests that even with a relatively small number of participants, such as these three specialists, valuable insights and collective expertise can be harnessed (Solomon, 2006) .

Table 5 demonstrate the gained weight scores for the parcel locker location alternatives taking in consider the experts' point of views.

Table 5 appears to represent the results of a multi-criteria decision-making (MCDM) analysis, where three decision-makers (DM1, DM2, DM3) have evaluated six alternatives (A1 to A6) based on certain criteria. The table provides the weighted scores (w¯ˆs) assigned to each alternative by each decision-maker and the ranks given to the alternatives by each DM.

Table 5
The alternatives preference based on experts' evaluation.

	$\overline{w}^s$ for DM1	Rank	$\overline{w}^s$ for DM2	Rank	$\overline{w}^s$ for DM3	Rank
A_1	0.160	4	0.146	4	0.117	6
A_2	0.138	5	0.141	5	0.158	4
A_3	0.213	1	0.223	1	0.205	1
A_4	0.200	2	0.208	2	0.197	2
A_5	0.190	3	0.185	3	0.188	3
A_6	0.100	6	0.097	6	0.134	5

- **A3** has the highest weighted score (w¯ˆs) for all three decision-makers (DM1, DM2, DM3), and it is ranked first by each DM. This suggests a unanimous preference for A3 among all three DMs.
- **A4** is consistently ranked second by all three DMs and has relatively high weighted scores.
- **A5** is consistently ranked third by all three DMs and also has moderate weighted scores.
- **A1** and **A2** are consistently ranked fourth and fifth, respectively, by all three DMs. They have lower weighted scores compared to the top three alternatives.
- **A6** is consistently ranked sixth by all three DMs and has the lowest weighted scores, indicating that it is the least preferred alternative.

To perform distance-based aggregation for these three vectors, we need to follow these steps:

Step 1: Choose a reference vector or point.

We can choose the mean vector as the reference vector. The mean vector for the three vectors that represent the decision makers point of views is (0.140, 0.146, 0.214, 0.202, 0.187, 0.110).

Step 2: Calculate the distances between each vector and the reference vector.

The Euclidean distances between each vector and the reference vector are:

The Euclidean distance d_1 between v_1 and the reference vector is computed as follow:

$$\begin{aligned} d_{E1} &= sqrt((0.160-0.140)^2+(0.138-0.146)^2+(0.213-0.214)^2 \\ &\quad +(0.2-0.202)^2+(0.190-0.187)^2+(0.1-0.110)^2) \\ &= 0.095 \end{aligned}$$

The Euclidean distance between v_2 and the reference vector is

$$\begin{aligned} d_{E2} &= sqrt((0.140-0.140)^2+(0.141-0.146)^2+(0.223-0.214)^2 \\ &\quad +(0.208-0.202)^2+(0.185-0.187)^2+(0.097-0.110)^2) \\ &= 0.075 \end{aligned}$$

The Euclidean distance between v_3 and the reference vector is computed as follow:

$$\begin{aligned} d_{E3} &= sqrt((0.117-0.140)^2+(0.158-0.146)^2+(0.205-0.214)^2 \\ &\quad +(0.197-0.202)^2+(0.188-0.187)^2+(0.134-0.110)^2) \\ &= 0.070 \end{aligned}$$

Step 3: Calculate the weights for each vector.

We will use a linear function to calculate the weights. The weights for each vector are:

We adopted the linear function for computing the weights (W_1, W_2, W_3) for each vector (w_1, w_2, w),

The weight for v_1 is computed as follow:

$$\begin{aligned} W_1 &= 1-(d_{E1}/(d_{E1}+d_{E2}+d_{E3}))=1-(0.095/(0.095+0.075+0.070)) \\ &= 0.358 \end{aligned}$$

The weight for v_2 is computed as follow:

$$\begin{aligned} W_2 &= 1-(d_{E2}/(d_{E1}+d_{E2}+d_{E3}))=1-(0.075/(0.095+0.075+0.070)) \\ &= 0.291 \end{aligned}$$

The weight for v_3 is computed as follow:

$$\begin{aligned} W_3 &= 1-(d_{E3}/(d_{E1}+d_{E2}+d_{E3}))=1-(0.070/(0.095+0.075+0.070)) \\ &= 0.351 \end{aligned}$$

Step 4: Compute the weighted average of the vectors:

We compute the weighted average of the vectors using the weights as coefficients. The aggregated vector can be adopted by calculating the weighted average of the vectors (w_1, w_2, w_3),

$$\begin{aligned}&(W_1w_1 + W_2w_2 + W_3w_3)/(W_1 + W_2 + W_3)\\&= ((0.358) \times (0.160, 0.138, 0.213, 0.20, 0.190, 0.100) + (0.291)\\&\quad \times (0.140, 0.141, 0.223, 0.208, 0.185, 0.097) + (0.351)\\&\quad \times (0.117, 0.158, 0.205, 0.197, 0.188, 0.134))/(0.358 + 0.291 + 0.351)\\&= (0.1429, 0.147, 0.213, 0.201, 0.187, 0.111)\end{aligned}$$

Step 5: Normalize the aggregated vector and rank the alternatives.

The obtained final normalized aggregated vector is (0.1428, 0.146, 0.211, 0.199, 0.186, 0.110) and the priority of the alternatives is $A_3 > A_4 > A_5 > A_1 > A_2 > A_6$ and the best location for locating the parcel lockers is A_3 *"Post office"* with weight score (0.211), followed by A_4 *"On commercial area"* with weight score (0.199) and A_5 *"High population density area"* with weight score (0.186) (Fig. 3.).

The CR threshold of 0.2 has been commonly used in AHP and is based on empirical observations and practical experience. It was introduced as a rule of thumb to help decision-makers identify and rectify inconsistent judgments. However, this value was not derived from formal mathematical principles but rather from practical experience. Several recent studies have questioned the rigidity of the CR threshold and explored alternative methods to assess consistency. For instance, Chan et al. (2019) conducted a study comparing the use of traditional AHP with fuzzy AHP. They found that fuzzy AHP can handle a higher level of inconsistency in judgments, suggesting that rigid CR thresholds might not always be suitable. The appropriateness of the CR threshold may depend on the specific context of the decision problem. Some decisions may inherently involve more uncertainty and subjectivity, making it challenging to achieve high levels of consistency. In such cases, a relaxation of the CR threshold might be justified (Schmidt et al., 2016; Gutknecht et al., 2018).

The process of selecting these specific locations typically involves several steps:

1. Problem Definition
2. Identification of Alternatives.
3. Criteria Selection.
4. Data Collection.
5. Weighting of Criteria.
6. Evaluation.
7. Ranking and Selection:

Regarding whether other locations were considered and discarded, it is common in MCDM to evaluate only a subset of possible alternatives due to practical constraints, resource limitations, or to focus the analysis on the most relevant options. The reasons for discarding alternatives could include factors like:

- Infeasibility: Some locations may have been deemed infeasible due to legal, environmental, or technical reasons.
- Irrelevance: Locations that do not meet the basic requirements or objectives of the decision may be excluded.
- Resource Constraints: Data collection and evaluation for every possible location can be resource-intensive, so a representative sample is often chosen.
- Stakeholder Input: Stakeholders may have identified a specific set of locations for evaluation.

To understand why these specific locations (A1 to A6) were chosen and if other locations were considered and discarded, it would be necessary to refer to the methodology section or any additional information provided in the study. The study should ideally provide a rationale for the selection of these alternatives and the criteria used for their evaluation.

4. Discussion

The initial step in location selection is usually identifying the demand for usage and additional capacity. The analysis for optimal location is then conducted based on this. The increasing customer demand for shipping and parcel volumes has created the need for low shipping costs. However, many retailers hide the true shipping costs in order to promote sales. This study introduces a novel decision support approach using a new estimation system for the selection of parcel lockers.

The resolution of a selection dilemma necessitates a methodical approach across multiple criteria. This necessity underscores the requirement for a process of multi-criteria decision-making (MCDM), which evaluates options based on expert appraisals and arranges them according to predetermined criteria. Numerous MCDM techniques have been employed in previous research. Among these, AHP with its fuzzy

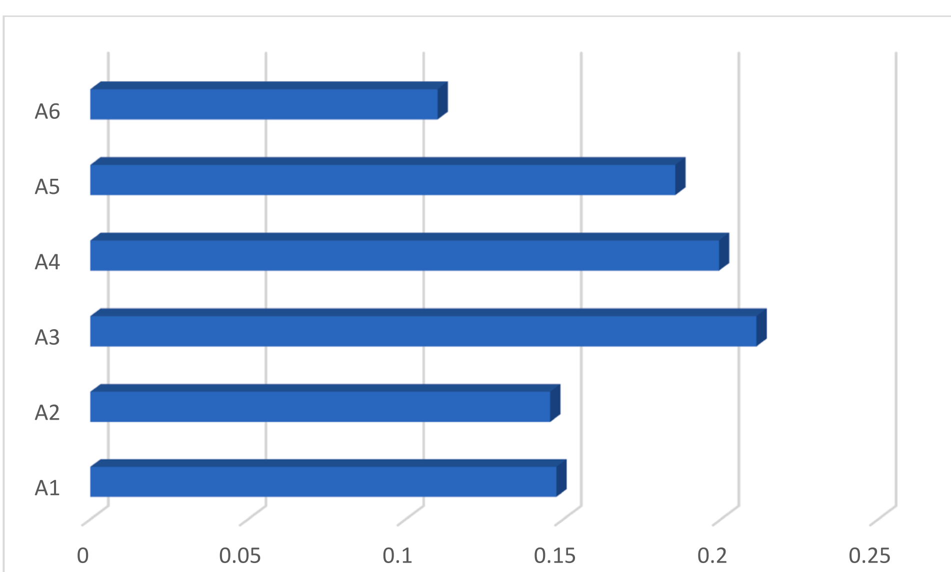

Fig. 3. The final normalized aggregated weight scores for parcel locker's location alternatives.

extensions holds a prominent position. In this regard, the incorporation of Spherical Fuzzy Sets (SFS), was innovatively applied alongside AHP for the very first time in the context of selecting parcel locker locations within this study.

Kutlu Gündoğdu and Kahraman (2020) and Dogan (2021) presented how SF-AHP is more efficient in avoiding the deterministic disadvantages of traditional AHP. To evaluate the related criteria and alternatives from specialists' point of view towards the problem, the AHP approach is usually applied, however, decision makers can be hesitant during the evaluation process. This is why the AHP has been utilized with spherical fuzzy sets to accurately estimate the impact of the factors.

In this study, five main criteria with six locations (A_1: "Public transport stops"; A_2: "Private car parking"; A_3: "Post office"; A_4: "On commercial area"; A_5: "High population density area"; A_6: "On pedestrian area") are used to select the optimal location of parcel lockers. The data are collected from three specialists in transport and logistic field, each of them has at least five years of experience, the survey was delivered in October 2022 and the evaluators completed evaluating the survey in November 2022. The convenient SFAHP model had successfully highlighted the post offices as the most suitable locations for placing parcel lockers, spherical fuzzy extent determines efficiently criteria and alternatives priorities.

The selection of post offices as the most suitable locations for parcel lockers can be attributed to several factors. Firstly, post offices are strategically dispersed throughout urban areas, providing a widespread network for efficient parcel delivery. This proximity to residential areas reduces the last-mile delivery distance, enhancing the convenience and speed of delivery. Secondly, post offices often have extended operating hours compared to other public places, allowing recipients to collect their parcels at their convenience, even after regular working hours. Lastly, post offices typically have robust security measures in place, ensuring the safety of parcels stored in lockers. The preference for post offices may also be influenced by the data collected in the survey. Specialists in the transport and logistics field are likely aware of the existing infrastructure and capabilities of post offices in handling parcels. Their responses might reflect a practical understanding of the suitability of post offices due to factors like accessibility, security, and operational efficiency.

5. Conclusion

The findings of this study have direct implications for managerial decision-making in the logistics and last-mile delivery sectors. We assessed six potential locations (A1: "Public transport stops"; A2: "Private car parking"; A3: "Post office"; A4: "On commercial area"; A5: "High population density area"; A6: "On pedestrian area") based on five key criteria to determine the optimal locations for parcel lockers. We collected data from three specialists in the transport and logistics field, each possessing a minimum of five years of experience. The survey was conducted in October 2022, with evaluators completing their assessments in November 2022. Our study successfully utilized the convenient SFAHP model, which efficiently determined the priorities of criteria and alternatives. As a result, post offices emerged as the most suitable locations for placing parcel lockers. This insight provides valuable guidance for optimizing parcel locker placement strategies, enhancing logistics efficiency, and improving last-mile delivery services.

Managers in parcel delivery companies can use the prioritized locations, with post offices at the forefront, to strategically place parcel lockers. This can lead to cost savings, improved delivery efficiency, and enhanced customer satisfaction. Additionally, understanding the factors that influence location preferences can help managers in making data-driven decisions for expanding their parcel locker networks. In terms of contributions to the existing literature, our study extends the application of the SFAHP model, showcasing its effectiveness in solving real-world logistics problems. By focusing on parcel locker placement, we contribute to the literature on last-mile delivery optimization. Moreover, this research adds to the body of knowledge regarding the integration of fuzzy logic in decision-making processes, particularly within the context of logistics and transportation. From a policymaking perspective, these results can inform urban planning and logistics policies. City planners and policymakers can consider the importance of post offices and other factors identified in this study when making decisions about urban development and transportation infrastructure. Policymakers may also explore incentives for parcel delivery companies to collaborate with post offices, potentially leading to mutually beneficial arrangements.

In the context of a multi-criteria decision-making (MCDM) selection issue, the incorporation of individually stipulated weights introduces notable constraints. Initially, diverse personally stipulated weights for performance assessment led to fluctuating decision outputs, resulting in incongruent outcomes. Consequently, the findings of a study may give rise to misleading interpretations when attempting to generalize the results. Secondly, quantifying evaluations proves to be a formidable task for decision-makers. Lastly, the allocation of weights becomes intricate with the escalation of criteria and alternative options.

In future, we will focus on involving different stakeholder groups in order to deliver more sustainable solutions for parcel lockers locations selection problem. The success of any logistics optimization strategy is contingent on the collaboration of various stakeholders. Future research could focus on the practical implementation of our findings by involving key stakeholders such as parcel delivery companies, post offices, city planners, and local authorities. Engaging these stakeholders in discussions and workshops could lead to a more comprehensive and context-specific model. Additionally, gathering feedback from end-users, the recipients of parcels, can provide valuable insights into the effectiveness of parcel locker placement in enhancing their delivery experience. While our study provides a generalized model for parcel locker placement, the nuances of each district within Dublin may require tailored approaches. Further research could delve into the specifics of individual districts, considering local factors such as population density, traffic patterns, and infrastructure. This district-level analysis would offer a more fine-grained perspective, allowing for more precise decisions regarding parcel locker placement in each area.

While AHP is a widely used decision-making tool with notable strengths, it does have limitations. AHP relies on subjective judgments, which can introduce bias. Sensitivity to changes in input data or criteria weights can also affect outcomes. Additionally, managing complex decision hierarchies can become unwieldy, and the process can be time-consuming. AHP's reliance on precise numerical inputs may not always align with real-world imprecisions. Finally, interpreting the results can sometimes be challenging, and the method may not fully account for dynamic, time-sensitive decisions. In addition to the mentioned limitations, another critical aspect is the potential exclusion of end-users in the AHP process. AHP often involves experts and stakeholders, but the perspectives and preferences of the actual users of the final decision may not be adequately incorporated. This omission can be a significant limitation, as it may not fully represent the practical implications and user satisfaction associated with the decision outcomes.

Moreover, extend the work by applying it for each district in Dublin to get the real demand-based district. As methodology, the Parsimonious extension can be adopted in future studies. Since in AHP, one of the critical steps involves comparing each element in a decision hierarchy with every other element to establish their relative importance. This process can become cumbersome and time-consuming as the number of elements grows. The Parsimonious extension addresses this challenge by intelligently minimizing the number of necessary comparisons without sacrificing the quality of the decision-making process. By reducing the pairwise comparison workload, the Parsimonious extension streamlines the decision-making process (Moslem, 2023). This not only saves valuable time and effort for evaluators but also enhances the overall efficiency of the AHP methodology.

Contributions

All authors contributed equally in preparing this manuscript.

Ethical approval

This article does not contain any studies with human participants or animals performed by the author.

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CRediT authorship contribution statement

Sarbast Moslem: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Francesco Pilla:** Validation, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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