Soft Computing (2021) 25:4525–4544
https://doi.org/10.1007/s00500-020-05461-y

METHODOLOGIES AND APPLICATION

Decision-making from multiple uncertain experts: case of distribution center location selection

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Published online: 23 November 2020

Abstract

The location selection of distribution center covers one of the important strategic decision issues for the logistics system managers. In view of the inherent uncertainty and inaccuracy of human decision-making, the future behavior of the market and companies, this paper adopts the improved multi-attribute and multi-Actor decision-making (MAADM) method as a fuzzy multi-attribute and multi-actor decision-making (FMAADM) method for solving the selection problem under an uncertain environment. The great strengths of our proposed method are: first, the integration of the decision-makers group preferences into the decision-making process, second, the consideration of the informations related to the alternatives and the criteria weights which are inaccurate, uncertain or incomplete, third, the verification of the obtained solution by both tests of concordance and non-discordance. To validate the FMAADM method, a decision support system was developed. Different experiments were provided based on comparative analysis of results and the sensitivity analysis. These experiments demonstrate the efficiency of our proposed method and its superiority over another existing methods.

Keywords Distribution center location selection · Multi-attribute decision-making · Multiple uncertain experts · Uncertain preferences · Fuzzy set theory

1 Introduction

In an urban context, the city functioning means an important rate of freight transportation. This functioning relies on various physical facilities, as shown in Fig. 1. These facilities are considered as real drivers of logistics systems. Therefore, the location selection of logistics facilities is viewed as one of the main strategic issues of distribution system for the logistics systems managers (Agrebi et al. 2016; Klose and Drexl 2005). Indeed, the best location of logistics facilities contributes to the logistics service quality and plays a key role for operation in the future (Lee 2014). In terms of logistical system design, location selection decisions are of high priority, since such decisions involve long-term commitment of resources and generally represent a substantial investment, which may affect the long-term profitability and sustainability of the firm. Besides, these decisions are usually irreversible (Cagri Tolga et al. 2013).

The distribution center location, as a special case of logistics facilities location, plays an important role not only in minimizing traffic congestion and pollution, but also in decreasing transport cost and maximizing of profit (Eldemir and Onden 2016). Moreover, a good location of distribution center may contribute in maximizing customers' satisfaction, as well as maximizing the acceptability by inhabitants, who live near the logistics platforms and are impacted by vehicle movements (Agrebi et al. 2016, 2017). In addition, knowing that higher load factor in the city can decrease harmful effects associated with city logistics (van Duin et al. 2012), a good location of distribution center allows reductions in the number of kilometers vehicle and better utilization rates for vehicles (Huschebeck and Allen 2005).

In fact, select the best distribution center location from a set of potential locations (alternatives) is difficult, especially in a context of decision-making from multiple uncertain experts (He et al. 2017; Sopha et al. 2018). In this context, the aim of this paper is to treat this problem as a fuzzy multi-

Communicated by V. Loia.

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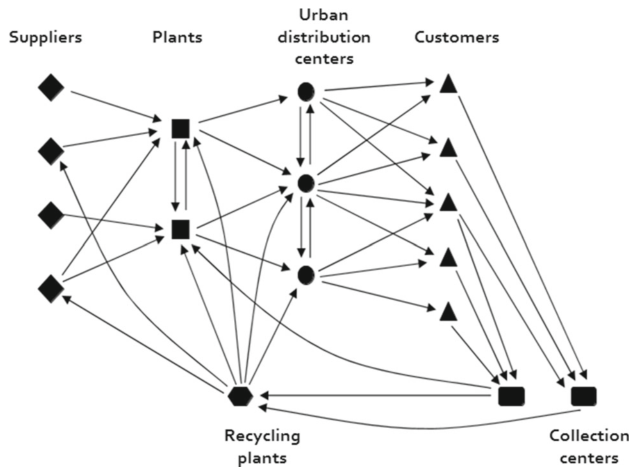


Fig. 1 Generic supply chain network (Melo et al. 2009)

criteria decision-making problem (FMCDM). The expected decision must respect decision-makers group preferences and existing evaluation criteria (e.g., the investment cost, the possibility of expansion, the availability of acquisition hardware, the human resources, the proximity to suppliers, etc.).

In the literature, a number of studies have been conducted on location selection problem of distribution center under uncertain environment (Pamucar et al. 2020; Deveci et al. 2020). However, the existing methods represent main limitations (Wolf 2011; Manav et al. 2013; Agrebi et al. 2017; Chen et al. 2018; Agrebi 2018):

– The multi-criteria aspect for the selection of the location of distribution centers is important. However, most of the existing methods seek to convert qualitative criteria and sometimes even quantitative criteria to cost.
– The majority of methods do not consider the impact of the overall strategy of the company on decisions taking into account qualitative criteria.
– The selection of distribution centers location requires the participation of several company departments, including distribution, quality and sustainable development, etc. However, most of the methods developed rely on a single decision-maker and therefore, only on their preferences.
– The location of distribution centers is based on maximizing certain criteria and minimizing others. However, many methods do not consider these two aspects at the same time, for example maximizing quality of service and minimizing congestion at the same time.
– Metaheuristics for the fuzzy multi-objective decision-making methods and fuzzy multi-objective decision-making methods can deal with only quantitative criteria. The consequence is that qualitative criteria are neglected in the decision-making process.

In order to overcome the limitations and satisfy more the distribution center location decision requirements as well as the expectations of decision-makers, in this paper, a new Fuzzy Multi-attribute and Multi-actor Decision-Making (FMAADM) method is proposed. FMAADM method combines the Multi-Attribute and Multi-Actor Decision-Making (MAADM) method (Agrebi et al. 2017) based on ELECTRE I method and the multiple criteria decision-making method (Chen 2001) based on the fuzzy set theory (Yager 1996; Zadeh 1975a, b, c; Zadeh et al. 1965). Although the MAADM method has proved its strengths and robustness in the issue of the distribution location selection (Agrebi et al. 2017), it is not able to treat this problem under an uncertain environment. Thus, we combine the MAADM method with the fuzzy set theory. Indeed, the fuzzy set theory is an important paradigm given its ability to treat uncertainty and imprecision associated with information (Alias et al. 2019; Garg and Rani 2019) and reduce its complexity (Awasthi et al. 2018).

The strengths of the FMAADM method are as follows:

– First, the integration of the decision-makers group preferences into the decision-making process, knowing that the human preferences are often ambiguous and uncertain,
– Second, the consideration of the informations related to the alternatives and the criteria weights which are inaccurate, uncertain or incomplete (Arora and Garg 2018),
– Third, the verification of the obtained solution by both tests of concordance and non-discordance.

The main contributions of this paper are threefold:

– We propose a novel method, FMAADM method, and a novel decision support system to treat the decision-making problem from multiple uncertain experts;
– We experimentally valid that our proposed method provides the expected results by using real data and that our method when confronted with the decision process acts as expected within distribution center location selection process;
– We demonstrate not only the stability and the robustness of the FMAADM method, but also its superiority over two other existing methods, by applying the Sensitivity analysis based on the simulation of scenarios.

The rest of paper is organized as follows. The literature about the location selection of distribution center is presented in Sect. 2. In Sect. 3, the FMAADM method is developed. Sect. 4 presents the experimental and operational validation of our proposed method. Finally, Sect. 5 concludes the paper and presents the future research directions.

2 Literature review

To arrange the survey of the problem of distribution center location selection in various aspects, we will divide it into the following parts: nature of the problem, existing methods, and discussion.

2.1 Nature of the problem

In the literature, several studies have been conducted by researchers on location selection problem of distribution center under not only a certain environment but also an uncertain environment. This depends on the nature of the used parameters in the decision-making process, notably the criteria values, the desired value and importance weight of criteria and the rating of each alternative location.

Regarding the certain environment, the used parameters are known and fixed in advance and the problem in question is characterized as static and deterministic problem (Agrebi et al. 2017). On the contrary case, under an uncertain environment, the real data and the information pertaining, mainly the informations related to the alternatives and the criteria weights, are imprecisely because of the inherent vagueness of human preferences.

2.2 Existing methods

According to the application environment, the existing methods, for dealing with the location selection problem of distribution center under uncertainty, can be mainly classified, as indicated in Table 1, into:

– Metaheuristics for the fuzzy multi-objective decision-making (FMMODM) methods,
– Fuzzy multi-criteria decision-making (FMCDM) methods categorized into Fuzzy multi-objective decision-making (FMODM) methods and Fuzzy multi-attribute decision-making (FMADM) methods.

The common point between the FMCDM and the FMMODM methods is the development and the application of fuzzy theory. Table 2 presents the most proposed methods in this issue.

2.2.1 Existing metaheuristics for the fuzzy multi-objective decision-making methods

Wang et al. (2005) developed a method combining quantitative heuristic arithmetic, qualitative analytic hierarchy process and fuzzy comprehensive evaluation. Their objective is to realize the minimum expenses of distribution center and system. Yang et al. (2007) proposed a hybrid method combining Tabu search algorithm, genetic algorithm and fuzzy simulation algorithm to seek the approximate best solution of the model. Their objective is to minimize the total relevant cost. Xu et al. (2011) developed a method based on Tabu search algorithm, genetic algorithm and fuzzy simulation algorithm. The objective is to minimize the total relevant cost comprising of fixed costs of the distribution center and transport costs and minimize the transportation time. Liu et al. (2011) proposed a hybrid heuristic algorithm to deal with the problem, which combines rough set methods and fuzzy logic. The objective is to optimize the cost and combined earnings. Zhou et al. (2015) proposed a solution model termed as rough multi-objective synthesis effect model. This constitutes a series of crisp multi-objective programming models that reflect different decision consciousness for each decision maker. The optimal solutions of the proposed model can be obtained by using the genetic algorithm. Zhuge et al. (2016) proposed a stochastic programming model on locating distribution centers determining their suitable scales, as well as adjusting distribution centers so as to adapt to the dynamically changing demands at the sites of retailers. Xiyang et al. (2018) established a fuzzy multiobjective model to solve the location problem. This model is based on two-stage supply chain, taking into account the inventory status of the tight front and rear nodes involved in the location of the distribution center. The core of this model is the impact of inventory fluctuations on the supply chain.

In this first category, the metaheuristics for the fuzzy multi-objective decision-making methods, the proposed methods attempt to convert the multi-objective problem into a single objective problem and then optimize this new single objective problem (Chen et al. 2018; Manav et al. 2013). In fact, optimizing this single objective problem yields a single solution. But, the decision-makers need diverse options in the real condition (Wolf 2011). However, there are some classical methods that require knowing the optimal solution of each objective but acquiring this information is expensive and time-consuming (Wolf 2011). In addition, it is difficult, especially in the case of the non-deterministic situation, to choose weights for which these methods are dependent.

2.2.2 Existing fuzzy multi-criteria decision-making methods

Chen (2001) proposed a multi-attribute decision-making method based on fuzzy set theory. In this method, the weights of the criteria and the evaluations of the alternatives are described by linguistic variables expressed in triangular fuzzy numbers. The final evaluation value of each distribution center location is also expressed in a triangular fuzzy number. Lee (2005) addressed the problem of selecting the location of distribution centers in a fuzzy environment by proposing a fuzzy multi-criteria decision-making method based on fuzzy set theory and SWOT analysis. The goal is to refine the imprecision of decision data by using alternative scores and criteria

Table 1 Comparison of some characteristics between existing methods

	FMCDM		FMMODM
	FMADM	FMODM	
Alternatives	Limited	Limited	Unlimited
Solution(s)	One or more	One or more	One
Criteria	Qualitative and/or quantitative	Quantitative	Quantitative

Table 2 Existing methods

Methods	Proposed by
FMCDM methods	
FMCDM method based on Fuzzy Set Theory (FST)	Chen (2001)
FMCDM method based on fuzzy logic and SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis	Lee (2005)
Improved FMCDM approach	Chu and Lai (2005)
Fuzzy Analytic Hierarchy Process (AHP)	Fan et al. (2006)
Multidimensional FMCDM method based on fuzzy quality function deployment and fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	Zhang et al. (2006)
Fuzzy integrated hierarchical decision-making approach	Chan et al. (2007)
FMCDM method based on fuzzy Analytic Network Process (ANP)	Wei and Wang (2009)
Weighted fuzzy factor rating system	Ou and Chou (2009)
FMCDM model	Chou and Chang (2009)
Model of multi-level fuzzy optimization based on information entropy and AHP	Zhang et al. (2009)
Fuzzy decision-making model based on engineering FST	Yu et al. (2009)
Fuzzy TOPSIS method based on FST, the factor rating system and simple additive weighting	Hu et al. (2009)
FMCDM method based on fuzzy Decision Making Trial and Evaluation Laboratory (DEMATEL) and AHP/ANP	Kuo (2011)
FMCDM method based on fuzzy TOPSIS	Awasthi et al. (2011)
Approach based on FST, fuzzy integration method, axiomatic fuzzy set approach based fuzzy clustering algorithm and fuzzy TOPSIS	Wang et al. (2012)
Hybrid FMCDM method based on fuzzy Entropy Weight (EW), fuzzy AHP and fuzzy TOPSIS	He et al. (2017)
Framework of hybrid spatial-fuzzy multi-criteria decision-making based on weighted Geographical Information System data and fuzzy TOPSIS	Sopha et al. (2018)
Metaheuristics for FMODM	
Method combines the quantitative heuristic arithmetic, the qualitative AHP and the fuzzy comprehensive evaluation	Wang et al. (2005)
Method based on fuzzy chance-constrained programming, tabu search algorithm + genetic algorithm + fuzzy simulation algorithm	Yang et al. (2007)
Multi-objective approach based on fuzzy AHP method and LP-metric method	Jafari et al. (2010)
Heuristic Algorithm combines rough set methods and fuzzy logic	Liu et al. (2011)
Multi-objective programming model with random fuzzy coefficients, chance-constrained programming, the spanning tree-based genetic algorithm	Xu et al. (2011)
Fuzzy neural network method	Li and Liu (2013)
Method based on cluster analysis, Floyd algorithm and fuzzy AHP	Guo-qin and Hong-yan (2014)
Rough model based on crisp multi-objective programming models and genetic algorithm	Zhou et al. (2015)
Method based on AHP and fuzzy comprehensive evaluation method	Cheng and Zhou (2016)
Stochastic programming model	Zhuge et al. (2016)
Fuzzy multi-objective model	Xiyang et al. (2018)

weights which are assigned as linguistic variables represented by fuzzy triangular numbers. Chan et al. (2007) developed fuzzy integrated hierarchical decision-making approach which is the combination of the hierarchical decision-making technique and the fuzzy decision making technique. Wei and Wang (2009) applied fuzzy-ANP methodology to select the location of distribution center. This methodology is a method combined ANP, fuzzy theory, and fuzzy AHP. The relationship between the criteria is established using the ANP, while the criteria weights as well as the evaluations of the alternatives according to the various criteria are determined using the fuzzy ANP. Ou and Chou (2009) are interested to treat the problem of international distribution center selection under uncertain environment. On this subject, they developed weighted fuzzy factor rating system. Chou and Chang (2009) proposed a fuzzy multiple criteria decision making model. Zhang et al. (2009) proposed model of multilevel fuzzy optimization into location decision on distribution center of emergency logistics for emergency event and used information entropy and analytical hierarchy process to determine the combined weight of the indexes. Yu et al. (2009) presented the new optimal selection for alternative programs of logistics center using the fuzzy decision-making model based on engineering fuzzy set theory. Hu et al. (2009) proposed a fuzzy TOPSIS method integrating fuzzy set theory, the factor rating system and simple additive weighting to evaluate facility locations alternatives. Jafari et al. (2010) treat the problem of distribution center location as a multiobjective problem. Cost minimization is the primary objective in this area. Then, they proposed a method for the uncapacitated single stage facility location problem in which a fuzzy AHP method is used to achieving these importances. Awasthi et al. (2011) presented a multi-criteria decision making approach for location planning for urban distribution centers under uncertainty. Their proposed approach involves identification of potential locations, selection of evaluation criteria, using of fuzzy theory to quantify criteria values under uncertainty and application of fuzzy TOPSIS to evaluate and select the best location for implementing an urban distribution center. Kuo (2011) proposed an hybrid method combining the concepts of fuzzy DEMATEL and a method of fuzzy multiple criteria decision-making in a fuzzy environment. The fuzzy DEMATEL is proposed to arrange a suitable structure between criteria, and the analytic hierarchy/network process (AHP/ANP) is used to construct weights of all criteria. The linguistic terms characterized by triangular fuzzy numbers are used to denote the evaluation values of all alternatives versus various criteria. Finally, the aggregation fuzzy assessments of different alternatives are ranked to determine the best selection. Wang et al. (2012) proposed fuzzy integration and clustering approach using the improved axiomatic fuzzy set theory developed for location clustering based on multiple hierarchical evaluation criteria. Then, they applied the technique for order preference by similarity to ideal solution for evaluating and selecting the best candidate for each cluster. Guo-qin and Hong-yan (2014) employed the cluster analysis method and Floyd algorithm to achieve minimization of all paths to get the Shanghai agricultural product logistics distribution center alternatives. Combined with the Fuzzy AHP, an analysis of Shanghai agricultural products logistics distribution center alternatives is performed. Cheng and Zhou (2016), to improve the efficiency of decision-making, proposed a method combining AHP and fuzzy and comprehensive evaluation method. He et al. (2017) proposed an hybrid fuzzy multiple-criteria decision-making method, in order to achieve operational efficiency and reduce operational cost. Their method combines fuzzy AHP method, fuzzy-entropy method, and fuzzy TOPSIS method. Sopha et al. (2018) proposed a framework of hybrid spatial fuzzy multi-criteria decision-making based on weighted Geographical Information System data and fuzzy TOPSIS.

In this second category, the fuzzy multicriteria decision-making methods, existing methods cited above are used in the case where the number of predetermined alternatives is limited. This set of alternatives satisfies each objective in a specified level (Wolf 2011). Then, the best solution is selected according to the priority of each objective and the interaction between them. However, these methods neglect the aspects of concordance and non-concordance to verify that a sufficient majority of criteria, represented by their weight, are in favor of the assertion Ai outclass Ak, and, to make it possible to refuse the outclass of an alternative over another when there is too much opposition on at least one criterion. Indeed, most existing methods not consider qualitative criteria in the process decision. Besides, many methods consider only one objective, maximization or minimization, for example maximizing quality of service or minimizing congestion but not the both.

2.3 Discussion

In order to satisfy more distribution center location decision requirements, this paper presents a new Fuzzy Multi-Attribute and Multi-Actor Decision-Making (FMAADM) method. The proposed method combines the Multi-Attribute and Multi-Actor Decision-Making (MAADM) method (Agrebi et al. 2017) based on ELECTRE I method (Milosavljević et al. 2018; Collette and Siarry 2011; Roy 1968) and the multiple criteria decision-making method (Chen 2001) based on the fuzzy set theory (Si et al. 2019; Yager 1996; Zadeh 1975a, b, c; Zadeh et al. 1965). Although the MAADM method has proved its strengths and robustness in the issue of the distribution location selection (Agrebi et al. 2017), it is not able to treat this problem under an uncertain environment. Thus, we combine the MAADM method with the fuzzy set theory. We argue below the choice of MAADM method and fuzzy set theory.

Table 3 Advantages/disadvantages of a number of MADM methods (Ayadi 2010; Agrebi et al. 2017; Agrebi 2018)

Method	Advantages	Disadvantages
AHP	The hierarchical structure of the decision problem	The explosion of the number of pairwise comparisons in the case of processing a large number of elements
	The semantic scale used to express the preferences of the decision-maker	The reversal of the alternatives rank following the deletion/addition of one or more alternatives
		The association of a numerical scale with the semantic scale is restrictive
TOPSIS	The introduction of the notions of ideal and anti-ideal	The requirement that attributes must be cardinal in nature
	Easy to apply	In the event of the alternatives are bad, TOPSIS offers the best alternative among the bad ones
		The arbitrariness of the distance choice to the ideal point and to the anti-ideal point
ELECTRE I	The introduction of the kernel notion makes it possible to narrow the field of study to focus only on the best alternatives	The requirement to translate the performance of alternatives into scores can lead to loss of control over data
		The non-consideration of group decision-makers
MAADM	The non-need to translate the performance of alternatives into scores	The absence of fuzzy notion in the choices of the decision maker
ELECTRE II	The alternatives' outranking from the best to the worst	The requirement of cardinal evaluations and the a priori articulation of preferences
ELECTRE III	The alternatives' outranking from the best to the worst	The need for a large number of technical parameters
	The admission of the fuzzy notion in the choices of the decision maker and the introduction of the veto threshold	Complex and sometimes difficult to interpret
ELECTRE IV	The association with each criterion of the preference thresholds and the overpressure of the criteria weighting	The need for a large number of technical parameters
ELECTRE TRI	The ability to process a large number of alternatives	The need for a large number of technical parameters
		The inability in some cases to compare each alternative with the alternatives limiting the different categories
		The definition of categories linked to the choice of benchmark alternatives
PROMETHEE I	The construction of the valued outranking relationship reflecting an intensity of preference	Indifference is in practice very rare given the numerous calculations to obtain the flows
PROMETHEE II	The construction of a total preorder excluding incomparability and greatly reducing indifference	Pairwise comparison are only used to hide the calculation of the final score for each alternative
PROMETHEE III	The introduction of indifference thresholds, which minimizes numerous calculations	The indifference thresholds have no concrete interpretation for the decision maker These thresholds are the subject of statistical calculations which make POMETHEE III less accessible

2.3.1 ELECTRE method

ELECTRE method and its different derivatives (ELECTRE I, ELECTRE II, ELECTRE III, ELECTRE IV, and ELECTRE TRI) are considered to be the most preferred methods among several outranking methods like PROMETHEE and its derivatives (PROMETHEE I and II), ORESTE, QUALIFLES, MELCHIOR, MAPPACC, PRAGMA, and TACTIC (Zandi and Roghanian 2013; Agrebi et al. 2017) as shown in Table 3. Furthermore, ELECTRE method is considered as one of the best methods which take into account both desirable directions (Min and Max) (Farahani and Asgari 2007; Agrebi 2018)

ELECTRE I method, as a derivative of ELECTRE method, is suitable for solving the location selection problem distribution centers as a multi-criteria selection problem under certain environment. This method allows to select the best locations among a limited set of alternatives by respecting of qualitative and quantitative criteria (Kumar et al. 2017). Moreover, it includes the decision-makers and their preferences into the decision-making process. Besides, the obtained results are validated using concordance and non-discordance tests. However, it does not consider neither several decision makers, nor the information uncertainty and imprecision. MAADM method (Agrebi et al. 2017; Agrebi 2018) as an extension of ELECTRE I takes into account several decision-makers into the decision process. Thus, the fuzzy set theory is used to address this limitation.

2.3.2 Fuzzy set theory

Fuzzy set theory is an extension of ordinary set theory was introduced by Zadeh et al. (1965) for dealing with uncertainty and imprecision which are inherent to human judgment in decision making processes through the use of linguistic terms and degrees of membership (Alias et al. 2019; Garg and Rani 2019; Tayal et al. 2014; Zouggari and Benyoucef 2012). Indeed, a fuzzy set is a class of objects with grades of membership. These grades present the degree of stability to which certain element belongs to a fuzzy set (Zadeh et al. 1965). Therefore, it is economically sensible for an enterprise decision maker to use fuzzy set theory, one of the artificial intelligence techniques (Simić et al. 2017).

In the multi-criteria environment, fuzzy set theory had an impact on classification techniques and contributed to the proposal of new decision-making methods (Awasthi et al. 2018; Bashiri and Hosseininezhad 2009; Chen 2000, 2001; Chu and Lai 2005; Ertuğrul 2011; Hwang and Thill 2005; Kahraman et al. 2006; Kaya and Çinar 2006; Li et al. 2011; Rebaa 2003; Takači et al. 2012; Trivedi and Singh 2017; Zhou and Liu 2007). These methods make it possible to treat uncertainty based on the idea of order. In addition, they are based on a methodology of representation and use of vague and uncertain knowledge, called the theory of approximate reasoning, better known as fuzzy logic. In addition, they consider classes of objects whose boundaries are not clearly defined by introducing a membership function taking values between zero and one.

In short, fuzzy set theory offers a mathematically precise way of modeling vague preferences, for example setting weights of performance scores on criteria. Simply stated, fuzzy set theory makes it possible to mathematically describe statements like: “criterion X should have a weight of around 0.8”. Besides, fuzzy set theory can be combined with other techniques to improve the quality of results (Simić et al. 2017) and improve the decision-making process by making it more realistic.

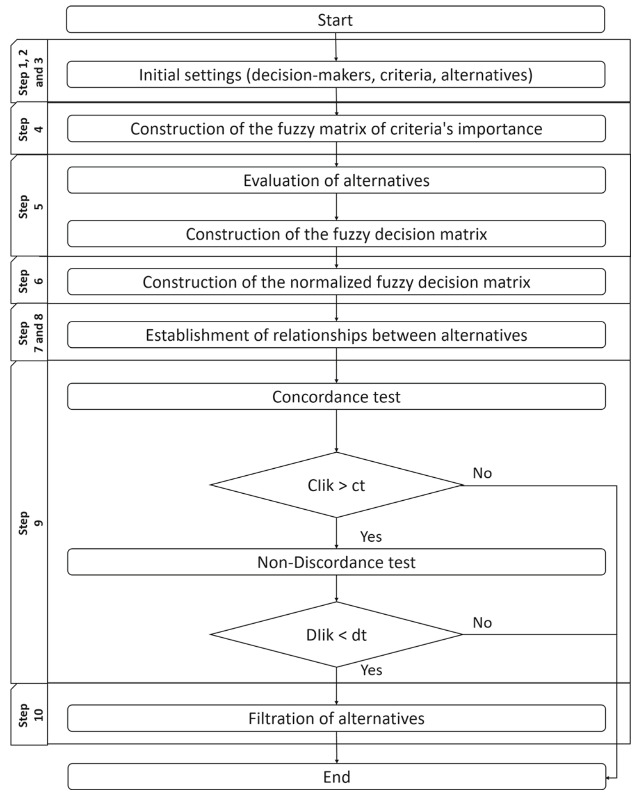


Fig. 2 Flowchart of FMAADM method

3 The multi-attribute and multi-actor decision-making (FMAADM) method

The Multi-Attribute and Multi-Actor Decision-Making (FMAADM) method is described in this section. First, Sect. 3.1 details the procedure of the FMAADM, second, Sect. 3.2 represents its architecture, and third, Sect. 3.3 shows the proposed decision support system based on FMAADM method.

3.1 FMAADM method procedure

The FMAADM method comprises, essentially, the ten steps described as follows. The flowchart of this method is presented as shown in Fig. 2.

Step 1. Constitution of decision-makers’ committee: This step consists in forming a committee of decision-makers (K) from various departments (distribution, quality, sustainable development, etc.) in order to defend the departments interests that represents each decision-maker. The goal is to reflect the general case of the request and to treat the selection problem in a broad perspective by including different points of view (Turkoglu and Genevois 2017).

Step 2. Identification of potential locations: This step consists in identifying a set of potential locations (alternatives) of distribution centers ($A_i = 1, \ldots, m$) based on sustainable freight regulations, decision-makers' preferences and knowledge conditions of freight transportation. The potential locations are those that cater to the interest of all city stakeholders, that is, city residents, logistics operators, municipal administrations, and so forth (Awasthi et al. 2011).

Step 3. Selection of evaluation criteria: This step consists in selecting n criteria (C_j, where $j = 1, \ldots, n$) such as connectivity to multimodal transport, proximity to customers and transportation cost, etc. Compared with the selected criteria, the alternatives will be evaluated.

Step 4. Determination of the fuzzy weight of criteria: This step consists in assigning the importance of n criteria by K decision-makers. The goal is to establish the matrix criteria's importance (W) based on Eq. (1) expressed as follows:

$$W = \left[w_1\ w_2\ \ldots\ w_n\right].$$
$$W = \frac{1}{K}\left[w_j^1 + w_j^2 + \cdots + w_j^K\right], \tag{1}$$

where w_j ($j = 1, 2, 3, \ldots, n$) is the weight of criterion (C_j).

Step 5. Evaluations of alternatives and determination of the fuzzy decision matrix: This step consists, first, in evaluating m alternatives by K decision-makers with respect to the criteria (C_j, where $j = 1, \ldots, n$) and then in constructing the fuzzy decision matrix (D) based on Eq. (2) and expressed as follows:

$$D = \begin{bmatrix} x_{11} & x_{12} & \ldots & x_{1n} \\ x_{21} & x_{22} & \ldots & x_{2n} \\ . & . & & . \\ . & . & & . \\ . & . & \ldots & . \\ x_{m1} & x_{m2} & \ldots & x_{mn} \end{bmatrix},$$

where x_{ij}, $\forall\, i,j$ is the rating of alternative A_i (i=1,2,…,m) with respect to criterion C_j.

$$x_{ij} = \frac{1}{K}\left[x_{ij}^1 + x_{ij}^2 + \cdots + x_{ij}^K\right]. \tag{2}$$

Step 6: Construction of the normalized fuzzy decision matrix: This step is based on the normalization of the fuzzy decision matrix (D) by using the linear scale transformation. The aim is to ensure that the evaluations above preserve the property that the ranges of normalized fuzzy numbers belong to [0, 1]. Then, the normalized fuzzy decision matrix is obtained and denoted by R.

$$\begin{aligned} R &= \left[r_{ij}\right]_{m*n}, \\ r_{ij} &= \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), j \in B, \\ r_{ij} &= \left(\frac{\bar{a}}{c_{ij}}, \frac{\bar{a}}{b_{ij}}, \frac{\bar{a}}{a_{ij}}\right), j \in C, \\ c_j^* &= \max_i c_{ij} if j \in B, \\ \bar{a}_j &= \min_i \bar{a}_{ij} if j \in C, \end{aligned} \tag{3}$$

where r_{ij} is the normalized value of x_{ij}, B and C are the set of benefit criteria and cost criteria, respectively.

Considering the different importance of each criterion, the final fuzzy evaluation value of each alternative is calculated as:

$$P_i = r_{ij}.w_j, i = 1, 2, \ldots, m, \tag{4}$$

where P_i is the final fuzzy evaluation value of alternative A_i.

Step 7. Establishment relations between alternatives with respect to each criterion: By respecting to each criterion, the pairwise comparisons of the alternatives A_i and A_k (where $k \in [i, \ldots, m]$ and $k \neq i$) are established as follows:

$$J^+{}_{(A_i,A_k)} = \{j | C_j(A_i) > C_j(A_k)\}, \tag{5}$$

where $J^+{}_{(A_i,A_k)}$ the set of criteria for which the alternative A_i is preferred over A_k.

$$J^={}_{(A_i,A_k)} = \{j | C_j(A_i) = C_j(A_k)\}, \tag{6}$$

where $J^={}_{(A_i,A_k)}$ the set of criteria for which the alternative A_i is equal in preference to alternative A_k.

$$J^-{}_{(A_i,A_k)} = \{j | C_j(A_i) < C_j(A_k)\}, \tag{7}$$

where $J^-{}_{(A_i,A_k)}$ the set of criteria for which the alternative A_k is preferred over A_i.

Step 8. Conversion of relations between alternatives in numerical values: In this step, the sum of the criteria weights is determined in each set of criteria as follows:

$$P^+{}_{(A_i,A_k)} = \sum_j w_j\ \forall j \in J^+{}_{(A_i,A_k)}. \tag{8}$$
$$P^={}_{(A_i,A_k)} = \sum_j w_j\ \forall j \in J^={}_{(A_i,A_k)}. \tag{9}$$
$$P^-{}_{(A_i,A_k)} = \sum_j w_j\ \forall j \in J^-{}_{(A_i,A_k)}. \tag{10}$$

Step 9. Merger the numerical values: This step consists in merging the numerical values by calculating the Concordance Index (CI) and the Disconcordance Index (DI).

– Concordance index (CI): This index expresses how much the hypothesis (A_i outclasses A_k) is consistent with the reality represented by the evaluations of alternatives.

$$CI_{ik} = \frac{P^{+}(A_i, A_k) + P^{=}(A_i, A_k)}{P(A_i, A_k)}, \quad (11)$$

where $P_{(A_i,A_k)} = P^{+}{}_{(A_i,A_k)} + P^{=}{}_{(A_i,A_k)} + P^{-}{}_{(A_i,A_k)}$.

– Set of concordance:

$$J(A_i, A_k) = J^{+}(A_i, A_k) \cup J^{=}(A_i, A_k). \quad (12)$$

– Disconcordance index (DI):

$$DI_{ik} = \begin{cases} (0,0,0) \quad if\ J^{-}(A_i, A_k) = \emptyset \\ \frac{(1,1,1)}{\partial_j} \times \max(C_j(A_k) - C_j(A_i)) \quad \text{where } j \in J^{-}(A_i, A_k), \text{ otherwise} \end{cases} \quad (13)$$

where ∂_j is the amplitude of the scale associated with criterion j.

Step 10. Filtration of alternatives: This step allows to extract from the set of the potential alternatives A_i (where $i = 1, \ldots, m$) the set of alternatives which respect Eq. (14). From this set, one alternative will finally be retained. It is the alternative that outclasses more alternatives.

$$\left.\begin{aligned} CI_{ik} \geq ct \\ DI_{ik} \leq dt \end{aligned}\right\} \Leftrightarrow A_i\ S\ A_k, \quad (14)$$

where:

– ct is the threshold of concordance beyond which the hypothesis $A_i\ S\ A_k$ is considered as valid.
– dt is the threshold of discordance below which the hypothesis $A_i\ S\ A_k$ is no longer valid.

We remind that S is the outranking relation ($A_i\ S\ A_k$ means that A_i is at least as good as A_k).

3.2 FMAADM method architecture

The architecture of FMAADM method consists of three levels notably users level, user-application interface level and application level. Fig. 3 gives a general view of the interactions between levels.

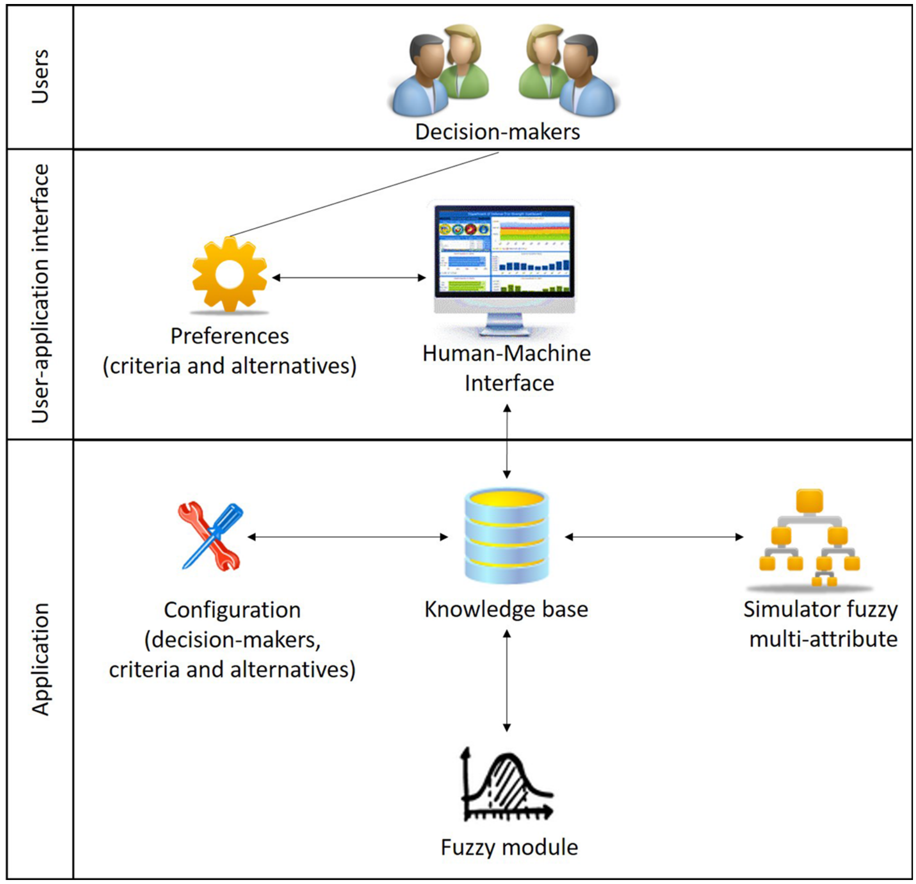
– User level: The users are the involved decision-makers into the decision-making process. They are invited to express their preferences by regarding the importance of each criterion and each alternative. From these preferences, the matrix criteria's importance (W) and the decision matrix (D) are determined. The goal is to store them into the knowledge base in order to use them for selecting the best alternative.
– User–application interface: This level regroups the communication interfaces between the decision-makers and the application.
– Application level: Configuration module: This module ensures the configuration of the decision-making process in accordance with the selection policy of the enterprise such as the number of alternatives to choose, and the decision-makers.
Simulator fuzzy multi-attribute : This simulator is based on FMAADM method. It is developed for generating the decision-makers preferences based on linguistic variables represented by triangular fuzzy number. The aim is to find the best alternative among the set of potential alternatives.
Fuzzy module : The role of this module is to accommodate the uncertain parameters of the selection process. The decision-maker communicates the linguistic variables in order to express his point of view about the criteria importance and alternatives. Subsequently, the fuzzy module translates the equivalence in triangular fuzzy number.

3.3 Proposed decision support system

In order to find an appropriate solution to users' needs and specificities, we developed the decision support system based on FMAADM method. The interface and the functionality of our system are implemented in Java 8. Netbeans[1] has been selected as the appropriate development environment. Also, the system uses XML[2] format for information transmission and storage (saving performed studies or projects). In addition, we made use of some APIs such as Apache POI,[3] JDBC[4] in order to manage data, which may be extracted from excel files. Users can generate data automatically based on a random generator or existing data source and manually. We note that the random generator is basically used for testing purpose. Fig. 4 presents the architecture of our S-SSD.

1 https://netbeans.org/.
2 https://www.w3.org/XML/.
3 https://poi.apache.org/.
4 http://www.oracle.com/technetwork/java/javase/jdbc/index.html.

Fig. 3 FMAADM method architecture



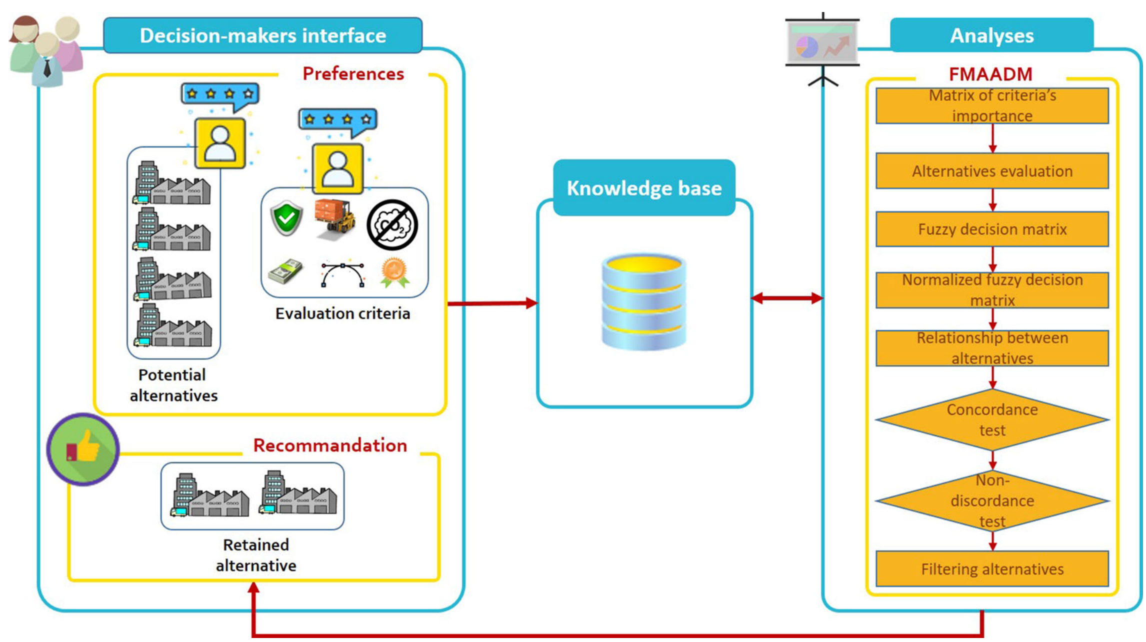


Fig. 4 Architecture of the proposed decision support system

Table 4 Evaluation criteria for location selection

Criteria	Illustrations	Units	Types
Accessibility ($C1$)	Access by public and private transport modes to the location	Quantitative	Benefit
Security ($C2$)	Security of the location from accidents	Qualitative	Benefit
Connectivity to multimodal transport ($C3$)	Connectivity of the distribution center with other modes of transport	Quantitative	Benefit
Costs ($C4$)	Costs combining land cost, vehicle resources cost, policy cost and taxes	Quantitative	Cost
Environmental impact ($C5$)	Impact of the implementation of the distribution center on the environment	Quantitative	Cost
Proximity to customers ($C6$)	Distance of location to customer	Quantitative	Benefit
Proximity to suppliers (C_7)	Distance of location to suppliers	Quantitative	Benefit
Resource availability (C_8)	Availability of resources to various uses	Quantitative	Benefit
Conformance to sustainable freight regulations (C_9)	Ability to conform to sustainable freight restriction imposed by public authorities.	Qualitative	Benefit
Possibility of expansion (C_{10})	Capability to augment the size to accommodate increasing demands	Quantitative	Benefit
Quality of service (C_{11})	Ability to assure timely and reliable service to clients	Qualitative	Benefit

4 Experimental validation

In order to establish the necessary consensus between the decision-making problem and a proposed method, Bisdorff et al. (2015) present four kinds of validation:

- Conceptual validation: verify on what each precise concept represents and how this is useful for the decision-making's problem.
- Logical validation: verify whether the concepts are logically consistent and meaningful.
- Experimental validation: test the method using experimental data in order to show that the method provides the expected results and possibly check formal requirements such as convergence of an algorithm, accuracy of a classification, and sensitivity to small variations of the parameters.
- Operational validation: show that the method when confronted with the decision process acts as expected within such a decision-making process.

To this end, in this section, performance of our proposed method is validated by a case of an accompany, which is interested in selecting a new distribution center location. The selection of the best location is done by a committee of three decision-makers D_1, D_2 and D_3. The aim of which is to select a best location among three alternatives A_1, A_2 and A_3. The selection decision is made based on eleven main evaluation criteria $C_1, \ldots, C_{11}$. As shown in Table 4, C_4 and C_5 are cost criteria and the remaining of criteria are the benefit criteria. The hierarchical structure of this case study is illustrated as shown in Fig. 5.

4.1 Application of the FMAADM method

The computational procedure of the FMAADM method is summarized as the following steps.

Foremost, using the linguistic variables (Awasthi et al. 2016, 2011; He et al. 2017) presented in Tables 5 and 6 , the criteria and the alternatives are evaluated by the decision-makers. Table 7 presents the importance of criteria and the weight of each criterion calculated using Eq. (1). Table 8 summarizes the evaluations of the alternatives. Then, the fuzzy decision matrix (D) is constructed using Eq. (2) as shown in Table 9. The normalized fuzzy decision matrix (R) is determined using Eq. (3) and presented in Table 10.

Afterward, considering the criteria, the final fuzzy evaluation value (P) of each alternative is determined using Eq. (4) as shown in Table 11. Therefore, the relationship (J^+, $J^=$, J^-) between the alternatives is established as shown in Table 12, by calculating the difference between two final fuzzy evaluation value of each alternative using Eqs. (5), (6) and (7). These relations are converted subsequently, using Eqs. (8), (9) and (10) , in numerical values (P^+, $P^=$, P^-) by calculating the set of concordance J as shown in Tables 12 and 13 . The merge of the numerical values is obtained, using Eqs. (11), (12) and (13) , by calculating of the coefficients of concordance C_{ik} and the coefficients of disconcordance D_{ik} as shown in Table 14.

Finally, the test of concordance and the test of non-disconcordance are done using Eq. (14) in order to filter the

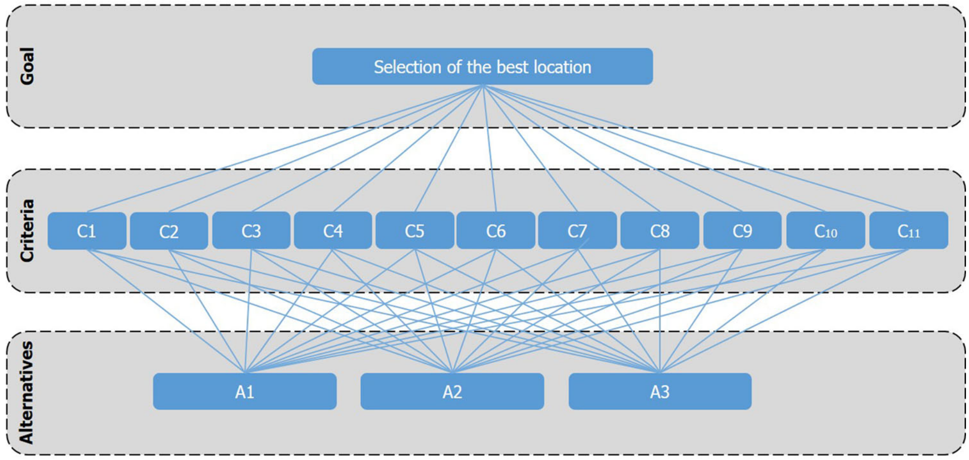


Fig. 5 Hierarchical structure of the distribution center's location selection

Table 5 Linguistic variables for the importance weight of criteria

Linguistic term	Membership function
Very low (VL)	(1, 1, 3)
Low (L)	(1, 3, 5)
Medium (M)	(3, 5, 7)
High (H)	(5, 7, 9)
Very high (H)	(7, 9, 9)

Table 6 Linguistic variables for the ratings

Linguistic term	Membership function
Very poor (VP)	(1, 1, 3)
Poor (P)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Good (G)	(5, 7, 9)
Very good (VG)	(7, 9, 9)

alternatives. For that, the threshold ct is fixed to (0.5, 0.7, 0.9). This test is satisfied if $CI_{ik} \geq (0.5, 0.7, 0.9)$. The threshold dt is fixed to (0.3, 0.5, 0.7). Then, the test is satisfied if $DI_{ik} \leq (0.3, 0.5, 0.7)$.

The CI_{ik} which satisfied the test of concordance are CI_{21}, CI_{31} and CI_{32}. The DI_{ik} which satisfied the test of non-disconcordance are DI_{12}, DI_{13} and DI_{23}. Therefore, based on both tests, we found that : the alternative A_1 outclasses the alternatives A_2 and A_3. Then, we can infer that the alternative A_1 is the best alternative.

To validate experimentally our proposed method, an application of FMAADM by using real data was presented. The obtained results show that FMAADM method when confronted with the decision process acts as expected within distribution center location selection process. In the following Sect. 4.2, a comparative analysis of the obtained results by our method and two existing methods will be detailed.

Table 7 Importance and weight of criteria

C_j	Decision-makers			Weight
	D_1	D_2	D_3	
C_1	VH (7, 9, 9)	VH (7, 9, 9)	VH (7, 9, 9)	(7, 9, 9)
C_2	VH (7, 9, 9)	H (5, 7, 9)	VH (7, 9, 9)	(6.33, 8.33, 9)
C_3	VH (7, 9, 9)	H (5, 7, 9)	VH (7, 9, 9)	(6.33, 8.33, 9)
C_4	H (5, 7, 9)	VH (7, 9, 9)	VH (7, 9, 9)	(6.33, 8.33, 9)
C_5	M (3, 5, 7)	H (5, 7, 9)	M (3, 5, 7)	(3.66, 5.66, 7.66)
C_6	VH (7, 9, 9)	H (5, 7, 9)	VH (7, 9, 9)	(6.33, 8.33, 9)
C_7	H (5, 7, 9)	VH (7, 9, 9)	H (5, 7, 9)	(5.66, 7.66, 9)
C_8	M (3, 5, 7)	H (5, 7, 9)	H (5, 7, 9)	(4.33, 6.33, 8.33)
C_9	H (5, 7, 9)	H (5, 7, 9)	VH (7, 9, 9)	(5.66, 7.66, 9)
C_{10}	VH (7, 9, 9)	H (5, 7, 9)	VH (7, 9, 9)	(6.33, 8.33, 9)
C_{11}	VH (7, 9, 9)	VH (7, 9, 9)	VH (7, 9, 9)	(7, 9, 9)

Table 8 Evaluations of alternatives

C_j	A_i	Decision-makers		
		D_1	D_2	D_3
C_1	A_1	VG (7, 9, 9)	G (5, 7, 9)	VG (7, 9, 9)
	A_2	G (5, 7, 9)	VG (7, 9, 9)	VG (7, 9, 9)
	A_3	VG (7, 9, 9)	VG (7, 9, 9)	VG (7, 9, 9)
C_2	A_1	G (5, 7, 9)	VG (7, 9, 9)	G (5, 7, 9)
	A_2	F (3, 5, 7)	G (5, 7, 9)	F (3, 5, 7)
	A_3	P (1, 3, 5)	P (1, 3, 5)	F (3, 5, 7)
C_3	A_1	F (3, 5, 7)	G (5, 7, 9)	F (3, 5, 7)
	A_2	F (3, 5, 7)	F (3, 5, 7)	F (3, 5, 7)
	A_3	F (3, 5, 7)	G (5, 7, 9)	G (5, 7, 9)
C_4	A_1	G (5, 7, 9)	G (5, 7, 9)	F (3, 5, 7)
	A_2	F (3, 5, 7)	G (5, 7, 9)	F (3, 5, 7)
	A_3	F (3, 5, 7)	G (5, 7, 9)	G (5, 7, 9)
C_5	A_1	G (5, 7,9)	F (3, 5, 7)	G (5, 7, 9)
	A_2	G (5, 7, 9)	F (3, 5, 7)	F (3, 5, 7)
	A_3	G (5, 7, 9)	P (1, 3, 5)	G (5, 7, 9)
C_6	A_1	G(5, 7, 9)	VG (7, 9, 9)	VG (7, 9, 9)
	A_2	VG (7, 9, 9)	VG (7, 9, 9)	G (5, 7, 9)
	A_3	VG (7, 9, 9)	VG (7, 9, 9)	G (5, 7, 9)
C_7	A_1	F (3, 5, 7)	VG (7, 9, 9)	F (3, 5, 7)
	A_2	G (5, 7, 9)	G (5, 7, 9)	F (3, 5, 7)
	A_3	G (5, 7, 9)	G(5, 7, 9)	(5, 7,9)
C_8	A_1	F (3, 5, 7)	F (3, 5, 7)	G (5, 7, 9)
	A_2	G (5, 7, 9)	F (3, 5, 7)	F (3, 5, 7)
	A_3	F (3, 5, 7)	F (3, 5, 7)	F (3, 5, 7)
C_9	A_1	F (3, 5, 7)	F (3, 5, 7)	F (3, 5, 7)
	A_2	F (3, 5, 7)	P (1, 3, 5)	P (1, 3, 5)
	A_3	VP (1, 3, 5)	VP (1, 1, 3)	VP (1, 1, 3)
C_{10}	A_1	G (5, 7, 9)	G (5, 7, 9)	VG (7, 9, 9)
	A_2	VG (7, 9, 9)	G (5, 7, 9)	VG (7, 9, 9)
	A_3	G (5, 7, 9)	G (5, 7, 9)	G (5, 7, 9)
C_{11}	A_1	VG (7, 9, 9)	G (5, 7,9)	VG (7, 9, 9)
	A_2	VG (7, 9, 9)	G (5, 7, 9)	G (5, 7, 9)
	A_3	G (5, 7, 9)	VG (7, 9, 9)	VG (7, 9, 9)

4.2 Comparative analysis of the results

In this section, we compare the results of our proposed method with two other existing methods under fuzzy environment so that the consistency of the aforesaid results can be justified: the first method, the hybrid FMCDM method based on fuzzy Entropy Weight (EW), fuzzy AHP and fuzzy TOPSIS, is proposed by He et al. (2017) and, the second method, the framework of hybrid spatial-fuzzy multi-criteria decision-making based on weighted Geographical Information System data and fuzzy TOPSIS, is invented by Sopha et al. (2018). Table 15 recapitulates the obtained outranking and selected location by applying the different methods.

Table 9 Fuzzy decision matrix

	A_1	A_2	A_3
C$_1$	(6.33, 8.33, 9)	(6.33, 8.33, 9)	(7, 9, 9)
C$_2$	(5.66, 7.66, 9)	(3.66, 5.66, 7.66)	(1.66, 3.66, 5.66)
C$_3$	(3.66, 5.66, 7.66)	(3, 5, 7)	(4.33, 6.33, 8.33)
C$_4$	(4.33, 6.33, 8.33)	(3.66, 5.66, 7.66)	(4.33, 6.33, 8.33)
C$_5$	(4.33, 6.33, 8.33)	(3.66, 5.66, 7.66)	(3.66, 5.66, 7.66)
C$_6$	(6.33, 8.33, 9)	(6.33, 8.33, 9)	(6.33, 8.33, 9)
C$_7$	(4.33, 6.33, 7.66)	(4.33, 6.33, 8.33)	(5, 7, 9)
C$_8$	(3.66, 5.66, 7.66)	(3.66, 5.66, 7.66)	(3, 5, 7)
C$_9$	(3, 5, 7)	(1.66, 3.66, 5.66)	(1, 1.66, 3.66)
C$_{10}$	(5.66, 7.66, 9)	(6.33, 8.33, 9)	(5, 7, 9)
C$_{11}$	(6.33, 8.33, 9)	(5.66, 7.66, 9)	(6.33, 8.33, 9)

In fact, to evaluate the goodness of a result produced by any method, we need to make a comparison with the true result which is of course unknown (Munier et al. 2019). If it was known, we would not need multi-criteria decision-making, as we do when we use the Linear Programming, because if there is an optimum solution it will find it. However, the Linear Programming works with only one objective and with only quantitative criteria, and these conditions are generally not present in real life scenarios. Since it is impossible to realize if a result is good or bad, common sense says that the practitioner has to consider a method that fits his needs, and consequently it is expected that its result must be better that a one that does not (Agrebi 2018; Munier 2011).

According to the afore-given discussion and analysis, compared with the group decision-making methods from the literature (He et al. 2017; Sopha et al. 2018), our proposed method in this paper has the following three major characteristics:

- Our proposed method applies both tests of concordance and non-discordance. On the one hand, to ensure that a sufficient majority of criteria, represented by their weight, are in favor of the assertion A_i S A_k, and, on the other hand, to make it possible to refuse the outclass of an alternative over another when there is too much opposition on at least one criterion,
- The FMAADM method makes it possible to restrict the field of study to focus only on the best alternatives based in the kernel concept. Contrariwise, He et al.'s method and Sopha et al.'s method, if all alternatives are bad, they offer the best alternative among the bad ones,
- And compared with the He et al.'s method our proposed method possesses the ability to treat a large number of alternatives.

Table 10 Normalized fuzzy decision matrix

C_j	a_j^-	c_j^*	Decision-makers		
			A_1	A_2	A_3
C_1	6.33	9	(0.7, 0.75, 1)	(0.7, 0.75, 1)	(0.7, 0.7, 0.9)
C_2	1.66	9	(0.18, 0.21, 0.29)	(0.21, 0.29, 0.45)	(0.29, 0.45, 1)
C_3	3	8.33	(0.43, 0.67, 0.91)	(0.36, 0.60, 0.84)	(0.51, 0.75, 1)
C_4	3.66	8.33	(0.51, 0.75, 1)	(0.43, 0.67, 0.91)	(0.51, 0.75, 1)
C_5	3.66	8.33	(0.51, 0.75, 1)	(0.43, 0.67, 0.91)	(0.43, 0.67, 0.91)
C_6	6.33	9	(0.7, 0.92, 1)	(0.7, 0.92, 1)	(0.7, 0.92, 1)
C_7	4.33	9	(0.48, 0.7, 0.85)	(0.48, 0.7, 0.92)	(0.55, 0.77, 1)
C_8	3	7.66	(0.52, 0.73, 1)	(0.52, 0.73, 1)	(0.39, 0.65, 0.91)
C_9	1	7	(0.42, 0.71, 1)	(0.23, 0.52, 0.8)	(0.14, 0.23, 0.52)
C_{10}	5	9	(0.62, 0.85, 1)	(0.7, 0.92, 1)	(0.55, 0.77 , 1)
C_{11}	5.66	9	(0.7, 0.92, 1)	(0.62, 0.85, 1)	(0.7, 0.92, 1)

Table 11 Final fuzzy evaluation value of alternatives

	A_1	A_2	A_3
C_1	(4.9, 6.75, 9)	(4.9, 6.75, 9)	(4.9, 6.3, 8.1)
C_2	(1.13, 1.74, 2.61)	(1.32, 2.41, 4.05)	(1.83, 3.74, 9)
C_3	(2.72, 5.58, 8.19)	(2.27, 4.99, 7.56)	(3.22, 6.24, 9)
C_4	(3.22, 6.24, 9)	(2.72, 5.58, 8.19)	(3.22, 6.24, 9)
C_5	(1.86, 4.24, 7.66)	(1.57, 3.79, 6.97)	(1.57, 3.79, 6.97)
C_6	(4.43, 7.66, 9)	(4.43, 7.66, 9)	(4.43, 7.66, 9)
C_7	(2.71, 5.36, 7.65)	(2.71, 5.36, 8.28)	(3.11, 5.89, 9)
C_8	(2.25, 4.62, 8.33)	(2.25, 4.62, 8.33)	(1.68, 4.11, 7.58)
C_9	(2.37, 5.43, 9)	(1.30, 3.98, 7.2)	(0.79, 1.76, 4.68)
C_{10}	(3.92, 7.08, 9)	(4.43, 7.66, 9)	(3.48, 6.41, 9)
C_{11}	(4.9, 8.28, 9)	(4.34, 7.65, 9)	(3.48, 6.41, 9)

Table 12 Summary of relations between alternatives

	A_i	A_1	A_2	A_3
	A_1	–	{2, 7, 10}	{2, 3, 7}
J^-	A_2	{3, 4, 5, 9, 11}	–	{2, 3, 4, 7}
	A_3	{1, 5, 8, 9, 10, 11}	{1, 8, 9, 10, 11}	–
	A_1	–	{1, 6, 8}	{4, 6}
$J^=$	A_2	{1, 6, 8}	–	{5, 6}
	A_3	{4, 6}	{5, 6}	–
	A_1	–	{3, 4, 5, 9, 11}	{1, 5, 8, 9, 10, 11}
J^+	A_2	{2, 7, 10}	–	{1, 8, 9, 10, 11}
	A_3	{2, 3, 7}	{2, 3, 4, 7}	–

In the following Sect. 4.3, the Sensitivity analysis will be applied to verify the stability of outranking obtained by FMAADM and two existing methods.

4.3 Sensitivity analysis

In order to verify the stability of the outranking of alternatives (A_1, A_2 and A_3) shown above in Sect. 4.1, the Sensitivity analysis based on the simulation of scenarios was applied by using: (1) the hybrid FMCDM method based on fuzzy Entropy Weight (EW), fuzzy AHP and fuzzy TOPSIS (He et al.'s method He et al. 2017), (2) the framework of hybrid spatial-fuzzy multi-criteria decision-making based on weighted Geographical Information System data and fuzzy TOPSIS (Sopha et al.'s method Sopha et al. 2018) and (3) the FMAADM method. The objective is to test the stability of

Table 13 Summary of converted relations between alternatives in numerical values

	A_i	A_1	A_2	A_3
P_{ik}^{-}	A_1	–	{18.32, 24.32, 27}	{18.32, 24.32, 27}
	A_2	{28.98, 38.98, 43.66}	–	{24.65, 32.65, 36}
	A_3	{33.98, 45.98, 51.99}	{30.32, 40.32, 44.33}	–
$P_{ik}^{=}$	A_1	–	{17.66, 23.66, 26.33}	{12.66, 16.66, 18}
	A_2	{17.66, 23.66, 26.33}	–	{9.99, 13.99, 16.66}
	A_3	{12.66, 16.66, 18}	{9.99, 13.99, 16.66}	–
P_{ik}^{+}	A_1	–	{28.98, 38.98, 43.66}	{33.98, 45.98, 51.99}
	A_2	{18.32, 24.32, 27}	–	{30.32, 40.32, 44.33}
	A_3	{18.32, 24.32, 27}	{24.65, 32.65, 36}	–

Table 14 Concordance and discordance index

	A_i	A_1	A_2	A_3
CI_{ik}	A_1	–	(0.71, 0.72, 0.72)	(0.71, 0.72, 0.72)
	A_2	(0.55, 0.55, 0.55)	–	(0.62, 0.62, 0.62)
	A_3	(0.47, 0.47, 0.47)	(0.53, 0.53, 0.54)	–
DI_{ik}	A_1	–	(−0.47, 0, 0.44)	(−0.38, 0.14, 0.51)
	A_2	(−0.38, 0.14, 0.59)	–	(−0.38, 0.14, 0.59)
	A_3	(−0.47, 0.07, 0.51)	(−0.28, 0.22, 0.51)	–

Table 15 Comparative outranking

Literature	Main method	l Outranking	Selected location
He et al. (2017)	Hybrid FMCDM method based on fuzzy Entropy Weight (EW), fuzzy AHP and fuzzy TOPSIS	A_1 S A_2 S A_3	A_1
Sopha et al. (2018)	Framework of hybrid spatial-fuzzy multi-criteria decision-making based on weighted Geographical Information System data and fuzzy TOPSIS	A_1 S A_3 S A_2	A_1
This paper	FMAADM method	A_1 S A_2 and A_1 S A_3	A_1

the obtained results vis-a-vis variations' weight of the eleven criteria used to evaluate the different potential alternatives, since the criteria weight significantly affects the rank (Agrebi et al. 2017; Lee and Chang 2018).

To this end, 18 experiments by each method were conducted. Table 16 summarizes the obtained location in each experiment. It can be seen, in the 5 first experiments, that the weights of all criteria are set equal to (1, 1, 3), (1, 3, 5), (3, 5, 7), (5, 7, 9) and (7, 9, 9). In experiment 6 to 16, the weight of one criterion is set as the highest weight (7, 9, 9) and the remaining criteria are set to the lowest weight (1, 1, 3). In experiment 17 and 18, the weight of the cost category criteria (C_4) and (C_5) is the lowest weight equal to (1, 1, 3) and the weights of the benefit category criteria (C_1–C_3 and C_6–C_{11}) are set as the highest weight equal to (7, 9, 9).

Among the 18 experiments by each method:

- By using He et al.' method, as shown in Fig. 6, for 9 experiments (1–5, 11, 14, 15 and 17), the best location is A_1. The location A_2 has appeared as the winner for 3 experiments (6, 8 and 9). As for the location A_3 has emerged as the winner for 6 experiments (7, 10, 12, 13, 16 and 18).
- By using Sopha et al.' method, as shown in Fig. 7, in 9 experiments (1–5, 8, 12, 15 and 18), the selected location is A_1. The alternative A_2 has emerged as the best location in 2 experiments (7 and 14) and in the rest of experiments (6, 9, 10, 11, 13, 16 and 17) the best location is A_3.
- By using the FMAADM method, as shown in Fig. 8, for 13 experiments (1–7, 9, 10, 13, 14 and 16–18), the alternative A_1 has emerged as the best location. Contrariwise, in experiment 11, the alternative A_3 has appeared as the winner. In the rest of experiments (8, 12, and 15), both the alternatives A_1 and A_3 have emerged as the best locations. Therefore, we can say that the location decision is relatively insensitive to cost criteria weight. It can be seen where the weight of cost criteria C_4 and C_5 is set as the highest (experiments 9 and 10) or lowest (experiments 17 and 18), then the best solution is always the alternative A_1. In the opposite case, when the weight of benefit

Table 16 Experimental results under different experiments

N	Description	Selected location by three methods		
		He et al. (2017)	Sopha et al. (2018)	FMAADM
1	All criteria weights = (1, 1, 3)	A_1	A_1	A_1
2	All criteria weights = (1, 3, 5)	A_1	A_1	A_1
3	All criteria weights = (3, 5, 7)	A_1	A_1	A_1
4	All criteria weights = (5, 7, 9)	A_1	A_1	A_1
5	All criteria weights = (7, 9, 9)	A_1	A_1	A_1
6	Weight of criteria 1 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)	A_2	A_3	A_1
7	Weight of criteria 2 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)	A_3	A_2	A_1
8	Weight of criteria 3 = (7, 9 , 9) Weight of remaining criteria = (1, 1, 3)	A_2	A_1	A_1 and A_3
9	Weight of criteria 4 = (7, 9, 9) Weight of remaining criteria =(1, 1, 3)	A_2	A_3	A_1
10	Weight of criteria 5 = (7, 9, 9) Weight of remaining criteria =(1, 1, 3)	A_3	A_3	A_1
11	Weight of criteria 6= (7, 9, 9) Weight of remaining criteria = (1, 1, 3)	A_1	A_3	A_3
12	Weight of criteria 7 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)	A_3	A_1	A_1 and A_3
13	Weight of criteria 8 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)	A_3	A_3	A_1
14	Weight of criteria 9 =(7, 9, 9) Weight of remaining criteria = (1, 1, 3)	A_1	A_2	A_1
15	Weight of criteria 10 = (7, 9, 9) Weight of remaining criteria= (1, 1, 3)	A_1	A_1	A_1 and A_3
16	Weight of criteria 11 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)	A_3	A_3	A_1
17	Weight of criteria 4 = (1, 1, 3) Weight of remaining criteria = (7, 9, 9)	A_1	A_3	A_1
18	Weight of criteria 5 = (1, 1, 3) Weight of remaining criteria = (7, 9, 9)	A_3	A_1	A_1

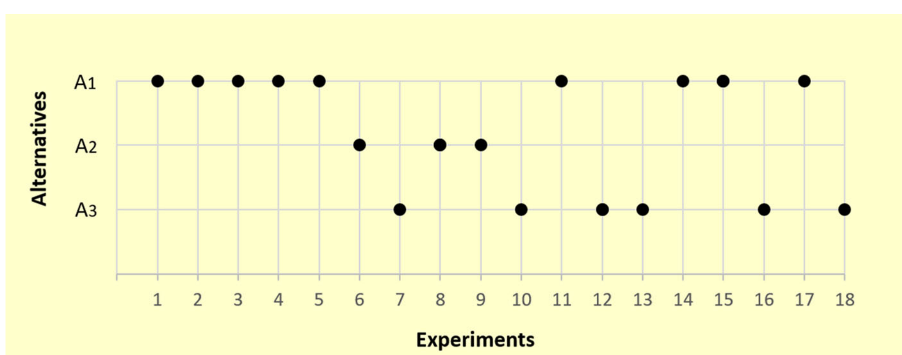


Fig. 6 Sensitivity analysis results by using He et al.'s method

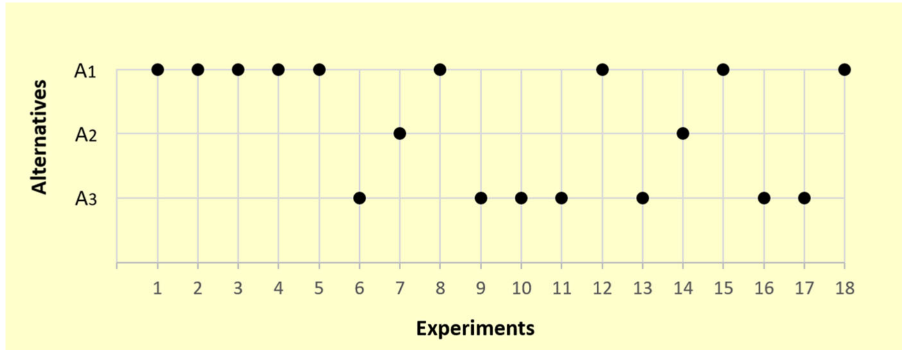


Fig. 7 Sensitivity analysis results by using Sopha et al.'s method

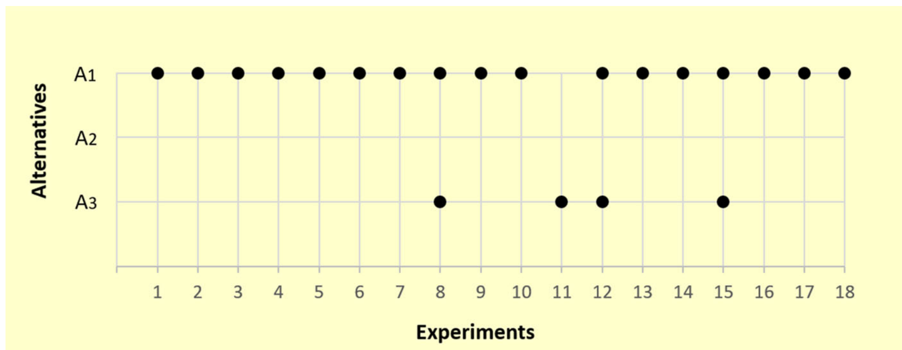


Fig. 8 Sensitivity analysis results by using FMAADM method

criteria C_1–C_3 and C_6–C_{11} is set as the highest (experiments 6, 7, 9, 10, 13, 14 and 16), then the best solution is changed from the alternative A_1 to A_3 (experiment 11) and to both the alternatives A_1 and A_3 in experiments 8, 12, and 15.

In short, compared with He et al.' method and Sopha et al.' method, the FMAADM method, as proposed in this paper, is rather stable and robust under an uncertain environment. Thus, it can be recommended to decision makers for the purpose of distribution center location selection.

5 Conclusion and future work

The aim of this paper is to help decision-makers group to select, under uncertainty, the best location of distribution center among a set of potential locations. The expected decision must respect not only a set of criteria which are often contradictory but also the decision-makers preferences.

For this purpose, the FMAADM method is proposed. This fuzzy method possesses three great strengths: first, the integration of the decision-makers group preferences into the decision-making process, knowing that the human preferences are often ambiguous and uncertain, second, the consideration of the informations related to the alternatives and the criteria weights which are inaccurate, uncertain or incomplete, third, the verification of the obtained solution by both tests of concordance and non-discordance.

In order to validate the FMAADM method, the S-SSD system is developed. Then, we conducted a case study whose objective is to select the best location among three potential locations under uncertainty. These three alternatives are evaluated by three decision-makers according to eleven criteria. The obtained results by our FMAADM method were compared by the results obtained by two other recent methods. This comparison proves that the FMAADM method meets the desired objective and thus retained for the selection of the best location of distribution center under an uncertain context of the multi-attribute and the multi-actor. Moreover, the sensitivity analysis was conducted in order to verify the stability of our method. 54 experiments were provided. The comparative analysis demonstrates not only the stability and the robustness of the FMAADM method, but also its superiority over the two other methods.

Based on the obtained results of FMAADM method and its validation, our study advances the knowledge in the issue of multicriteria decision making problem. This through the treatment of the problem from multiple uncertain experts while ensuring that a sufficient majority of criteria are in favor of the outranking, and, on the other hand, to make it possible to refuse the outclass of an alternative over an other when there is too much opposition on at least one criterion. Besides, based in the kernel concept, it is possible to restrict the field of study to focus only on the best alternatives. Contrariwise of a number of methods, if all alternatives are bad, they offer the best alternative among the bad ones.

Despite the case studies carried out in this paper, it would be relevant to test our method on other real business issues in order to validate its generalization, and if possible in various fields: logistics, biomedical, tourism, etc. Furthermore, future researches may focus on the exploitation of decision-makers preferences through similarity analysis to build virtual experts communities. Moreover, we expect to propose adaptations in the Big Data context by proposing an approach to build ontologies from a large amount of data and extend experiments to support the contribution of the proposal. Besides, we count improve our system to be able to extract the important criteria according to the studied case, and this, automatically. Finally, we expect integrate a results visualization module with an explanation sub-system.

Compliance with ethical standards

Conflict of interest The authors declare no potential conflict of interests

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