Information Fusion 51 (2019) 145–177

Contents lists available at ScienceDirect

Information Fusion

journal homepage: www.elsevier.com/locate/inffus

An overview of MULTIMOORA for multi-criteria decision-making: Theory, developments, applications, and challenges

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ARTICLE INFO

Keywords:
Multi-criteria decision-making
MULTIMOORA
Uncertainty theories
Fuzzy set theory
Linguistic term theory
Bibliometric analysis

ABSTRACT

MULTIMOORA is a useful multi-criteria decision-making technique. The output of the MULTIMOORA is a ranking obtained by aggregating the results of the ternary ranking methods: Ratio System, Reference Point Approach, and Full Multiplicative Form. In the literature of MULTIMOORA, there is not a comprehensive review study. In this paper, we conduct an overview of MULTIMOORA by categorizing and analyzing main researches, theoretically and practically. First, we go through an theoretical survey of MULTIMOORA in terms of the subordinate ranking methods, ranking aggregation tools, weighting methods, group decision-making, combination with other models, and the robustness of the method. We scrutinize the developments of MULTIMOORA based on uncertainty theories accompanied by analyzing the mathematical formulations of breakthrough models. Practical problems of MULTIMOORA are categorized into application sectors concerning industries, economics, civil services and environmental policy-making, healthcare management, and information and communications technologies. Bibliometric analyses are implemented into all studies. Also, we pose major theoretical and practical challenges. From the theoretical viewpoint, extensions of Reference Point Approach, cooperative group decision-making structure, and utilization of new uncertainty sets in MULTIMOORA model are the main challenges. From the practical viewpoint, industrial and socio-economic fields are appealing to be studied intensively.

1. Introduction

Multi-Criteria Decision-Making (MCDM) approaches tackle the problem of finding the best solution from a set of candidate alternatives in respect of multiple criteria. Often, there is no alternative which dominates the others on all criteria; thus, decision-makers usually look for the satisfactory solution [1]. The MCDM approaches can be categorized into three groups: (1) Value Measurement Methods, like SAW (Simple Additive Weighting) [2] and WASPAS (Weighted Aggregated Sum Product Assessment) [3]; (2) Goal or Reference Level Models, such as TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) [4] and VIKOR (VIse Kriterijumska Optimizacija kompromisno Resenje, in Serbian, Multiple Criteria Optimization Compromise Solution) [5]; and (3) Outranking Techniques, like PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations) [6], ELECTRE (ELimination Et Choix Traduisant la REalité, in French, ELimination and Choice Expressing the Reality) [7], ORESTE (Organísation, Rangement Et SynThèse de donnéEs relarionnelles, in French, Organization, Arrangement and Synthesis of Relational Data) [8], and GLDS (Gained and Lost Dominance Score) method [9].

In 2006, Brauers and Zavadskas [10] introduced MOORA (Multi-Objective Optimization on the basis of a Ratio Analysis) combining Ratio System and Reference Point Approach. In 2010, Brauers and Zavadskas [11] improved MOORA to MULTIMOORA (Multi-Objective Optimization on the basis of a Ratio Analysis plus the full MULTIplicative form) by adding Full Multiplicative Form and employing Dominance Theory to obtain a final integrative ranking based on the results of these triple subordinate methods. Ratio System and Full Multiplicative Form belong to the first group of MCDM approaches (i.e., Value Measurement Methods) while Reference Point Approach falls in the second group of MCDM approaches (i.e., Goal or Reference Level Models).

As Ratio system employs arithmetic weighted aggregation operator, it is useful in applications like student selection in which "independent" criteria exist in the problem. Suppose, we compare two students based on their exam marks. As the exams are independent on each other, arithmetic operator works fine for the case. That is, it is not important that

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https://doi.org/10.1016/j.inffus.2018.12.002
Received 26 November 2018; Accepted 6 December 2018
Available online 7 December 2018

in which exams the student has better performance. Thus, the overall performance in all exams (which are independent) is significant. However, Ratio system has defects in the cases where "dependent" criteria appear in a MCDM problem. Suppose, we compare two investment companies based on their portfolios in different years. The performance of an investment company in each year is "dependent" on the other years, that is, investment in a particular year influences the status of the following years. For example, if the portfolio return in one year were very poor, in reality, this issue should affect the overall performance dramatically. Geometric operator could consider the dependency of performances of each year while arithmetic operator neglects the issue. In the cases where "dependent" criteria exist in MCDM problems, Full Multiplicative Form can be helpful as it applies geometric weighted aggregation operator. Reference Point Approach which utilizes Min-Max Metric is a "conservative" method useful for the cases where the optimal choice for decision-makers is the alternative that does not have a very bad performance on none of the criteria.

To integrate the outcomes of the three subordinate parts, a variety of ranking aggregation techniques can be deployed. In this regard, the most common ranking aggregation tool in the literature of MULTIMOORA is Dominance Theory which is also the concept adopted in the original MULTIMOORA suggested by Brauers and Zavadskas [11]. Other ranking aggregation tools such as Dominance-Directed Graph, Rank Position Method, Technique of Precise Order Preference, Borda Rule, Improved Borda Rule, ORESTE Method, and Optimization Model have also been applied to generate the final ranking of the MULTIMOORA approach.

Only one survey study was previously conducted on MULTIMOORA, by Baležentis and Baležentis [1] in 2014. The work is limited to a few models regarding Group Decision-Making, Fuzzy Set Theory, and practical applications. In the current overview, we discuss MULTIMOORA models not only based on Group Decision-Making, Fuzzy Set Theory and applications, but also evaluate multiple theoretical features, various uncertainty theories, and applications in different fields besides provide bibliometric analysis, and identify significant theoretical and practical challenges. In this regard, the contributions of this paper can be presented as the following itemized list:

(1) We highlight the theoretical features of MULTIMOORA by discussing the ternary subordinate utilities and several tools for ranking aggregation to produce the final rankings and clarifying the robustness of the MCDM method. Besides, we analyze weighting methods, group decision-making structures, and the models used for combination.
(2) We present the developments of MULTIMOORA based on uncertainty theories including Interval Number, Fuzzy Set, Linguistic Term, Neutrosophic Set, Rough Set, Z-number, and Cloud Model Theories as well as their combinations. The formulations of the significant uncertain extensions are also provided and all developments are evaluated statistically.
(3) We present the applications of MULTIMOORA in the sectors of industries, economics, civil services and environmental policymaking, healthcare management, and information and communications technologies. Also, all applications are evaluated statistically.
(4) We discuss the challenges on several theoretical aspects including subordinate ranking methods, ranking aggregation tools, weighting methods, group decision-making, combination models, and uncertain developments as well as practical applications.

This overview is organized as six sections. Section 2 focuses on the bibliometric analysis, the theory, and the robustness of MULTIMOORA. Section 3 introduces the uncertain developments. In this section, we categorize and analyze the mathematical features of uncertain MULTIMOORA models. Then, the formulations of several important uncertain developments are discussed. Section 4 goes through the real-world applications. We present challenges for future studies on MULTIMOORA in Section 5. Concluding remarks including the advantages and summary of the overview are given in Section 6.

2. MULTIMOORA theory and robustness

In the following sections, the theoretical features of MULTIMOORA besides its robustness and a brief bibliometric analysis are discussed. Section 2.1 presents the bibliometric analysis of the studies on MULTIMOORA by discussing the distributions of journals and publication years. Section 2.2 introduces the triple subordinate ranking methods of MULTIMOORA. Section 2.3 presents ranking aggregation tools for integration of the results of the subordinate rankings. The ranking aggregation tools utilized in MULTIMOORA models include Dominance Theory, Arithmetic/Geometric Mean, Borda Rule, Dominance-Directed Graph, Improved Borda Rule, Optimization Model, ORESTE Method, Rank Position Method, and Technique of Precise Order Preference. Section 2.4 describes the weighting methods employed in MULTIMOORA models, including Entropy-Based Method, AHP (Analytic Hierarchical Process), SWARA (Stepwise Weight Assessment Ratio Analysis), BWM (Best-Worst Method), DEMATEL (DEcision MAking Trial and Evaluation Laboratory), Statistical Variance, CRITIC (CRiteria Importance Through Intercriteria Correlation), Maximizing Deviation Method, Choquet Integral, Logarithmic Least Square Method, MACBETH (Measuring Attractiveness by a Categorical Based Evaluation TecHnique), Numeric Logic, Optimization Model, and TOPSIS-Inspired Method. Section 2.5 explains the group decision-making structures. Section 2.6 focuses on the methods combined with MULTIMOORA, including Failure Mode and Effects Analysis, Quality Function Deployment, Data Envelopment Analysis, Goal Programming, Cluster Analysis, Fine-Kinney Method, Finite Element Simulation, Geographic Information System, Prospect Theory, and Regret Theory. Section 2.7 justifies the robustness of MULTIMOORA by describing the advantages of the approach and analyzing its performance comparing with other MCDM methods. Finally, Section 2.8 provides a graphical summary of all theoretical features of MULTIMOORA.

2.1. Bibliometric analysis of studies on MULTIMOORA

To have a glance about the publication distribution related to MULTIMOORA research, in this section, we go through the bibliometric analysis of the main researches conducted on the method. First, journals are listed with their frequencies to analyze publication sources. Second, distribution of the year of publications is presented graphically.

Table 1 gives a list of journals sorted based on the number of published works on MULTIMOORA. The first and second position are held by journals in the field of Economics while the majority of journals with publication frequencies equal to 2 and 3, fall within the scope of Decision-Making, Soft Computing, and Applied Mathematics.

An exploration into the publication years is provided in Fig. 1. Based on the figure, about a half of works on MULTIMOORA are published from 2016 onward. In 2011, 2012, 2015, and 2016, an identical percentage of publication (i.e., 9%) exist. The lowest positions related to publication years are occupied by 2010 and 2014.

2.2. Subordinate ranking methods of MULTIMOORA

MULTIMOORA exploits the vector normalization technique for generating comparable ratings and three subordinate ranking methods entitled Ratio System, Reference Point Approach, and Full Multiplicative Form. Each of the three ranking methods has some privileges but suffers from shortcomings; thus, MULTIMOORA uses more than one approach. In this section, we make a description about these three subordinate ranking method to facilitate the understanding of the MULTIMOORA method.

The first step in an MCDM problem is constructing a decision matrix and weight vector. Thus, for MULTIMOORA, decision matrix composed

Table 1
Distribution of journals (items with frequency ≥ 2).

Journal	Frequency	Percentage frequency	References
Economic Computation and Economic Cybernetics Studies and Research	7	6.6	[12–18]
Technological and Economic Development of Economy	6	5.7	[11,19–23]
Renewable and Sustainable Energy Reviews	4	3.8	[24–27]
E a M: Ekonomie a Management	3	2.8	[28–30]
Engineering Applications of Artificial Intelligence	3	2.8	[31–33]
Informatica	3	2.8	[34–36]
Journal of Industrial Engineering International	3	2.8	[37–39]
Soft Computing	3	2.8	[40–42]
Transformations in Business and Economics	3	2.8	[43–45]
Applied Mathematical Modelling	2	1.9	[46,47]
Computers and Industrial Engineering	2	1.9	[48,49]
Engineering Economics	2	1.9	[50,51]
Entrepreneurial Business and Economics Review	2	1.9	[52,53]
Expert Systems with Applications	2	1.9	[54,55]
IEEE Transactions on Fuzzy Systems	2	1.9	[56,57]
Information Fusion	2	1.9	[58,59]
International Journal of Strategic Property Management	2	1.9	[60,61]
International Transactions in Operational Research	2	1.9	[62,63]
Journal of Business Economics and Management	2	1.9	[64,65]
Journal of Civil Engineering and Management	2	1.9	[66,67]
Journal of Cleaner Production	2	1.9	[68,69]
Mathematical Problems in Engineering	2	1.9	[70,71]
Neural Computing and Applications	2	1.9	[72,73]
Sustainability	2	1.9	[74,75]

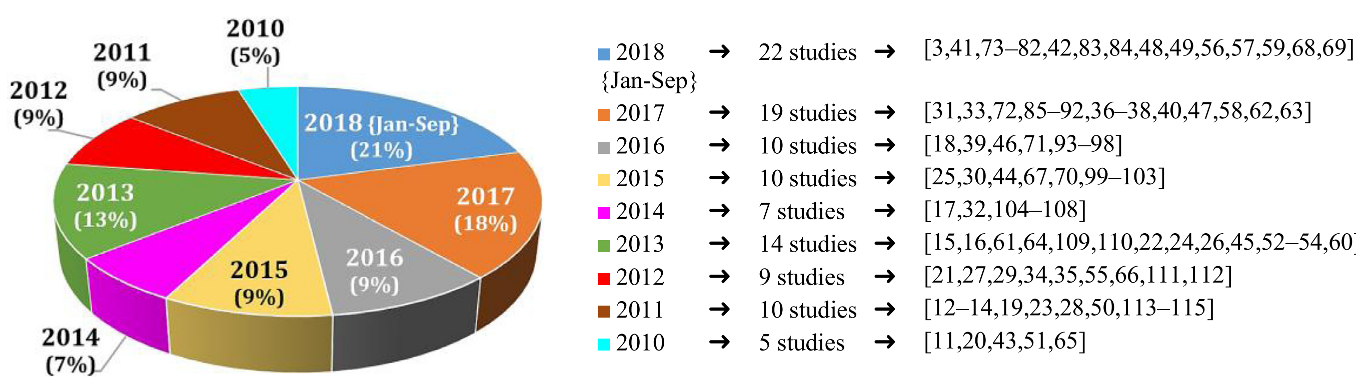

Fig. 1. Distribution of publication years.

of the ratings x_{ij} of m candidate alternatives of the problem with respect to n criteria is first constructed, as follows [38]:

$$\begin{array}{cc} & \begin{array}{ccccc} c_1 & \cdots & c_j & \cdots & c_n \end{array} \\ \mathbf{X} = & \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \vdots & & \vdots & & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & & \vdots & & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \begin{array}{c} A_1 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{array} \\ \mathbf{W} = & \begin{bmatrix} w_1 & \cdots & w_j & \cdots & w_n \end{bmatrix} \end{array} \quad (1)$$

Because the ratings of alternatives on the multiple criteria of the problem may have different dimensions, the ratings should be normalized before utilization in a MCDM model. Different normalization schemes have been employed in MCDM methods [10,116]. Liao et al. [117] made a comparison over different normalization schemes. Brauers et al. [118] claimed that Van Delft and Nijkamp (i.e., Vector) Normalization is the most robust choice for application in MULTIMOORA. Vector Normalization is represented as follows [10]:

$$x_{ij}^{*} = x_{ij} \Big/ \sqrt{\sum_{i=1}^{m} (x_{ij})^2}. \quad (2)$$

Ratio System, as a fully compensatory model, is useful when "independent" criteria exist in the problem. For cases with the existence of "dependent" criteria, Full Multiplicative Form, as an incompletely-compensatory model, is a beneficial tool. Reference Point Approach, as a non-compensatory model, is a "conservative" method comparing Ratio System and Full Multiplicative Form. Ratio System and Full Multiplicative Form both provide the opportunity to compensate the poor performance of an alternative on one criterion by the performances on other criteria (the degree of compensation related to the two techniques is not equal); however, Reference Point Approach does not allow such an opportunity. As "dependent" and "independent" criteria may exist simultaneously in the problem and for the sake of having a "conservative" result, MULTIMOORA integrates the triple methods to exploit the advantages of each of them and reach a final outcome that is more robust than the individual results [35]. We discuss the derivation of the triple subordinate ranking methods besides the connection of the methods with other MCDM approaches, as follows:

- Ratio System

Ratio System which uses the arithmetic weighted aggregation operator is a fully compensatory model. It means that small normalized values of an alternative could be completely compensated by the same degree of large values. In other words, an alternative with poor performance in respect to some criteria and fine performance in respect to the remained criteria can be substituted by an alternative with moderate performance in respect to all criteria [59]. To compute the utility of Ratio System, the weighted normalized ratings are added for beneficial criteria and deducted for non-beneficial criteria as follows [39]:

$$y_i = \sum_{j=1}^{g} w_j x_{ij}^* - \sum_{j=g+1}^{n} w_j x_{ij}^*, \tag{3}$$

where g is the number of beneficial criteria and $(n - g)$ is the number of non-beneficial criteria. The best alternative based on Ratio System has the maximum utility y_i and the ranking of this method is obtained in descending order as:

$$\mathbf{R}_{\mathrm{RS}} = \left\{ A_{i|\max_i y_i} \succ \quad \cdots \quad \succ A_{i|\min_i y_i} \right\}. \tag{4}$$

Ratio System, is inspired by SAW. In SAW, same as Ratio System, the utility is obtained by aggregation of the weighted normalized alternatives ratings; however, there is only one term for sum (i.e., no term exists for subtraction) because SAW's normalization is based on a linear ratio. For beneficial criteria, each alternative rating is divided by the maximum value of ratings per criterion and for non-beneficial criteria, minimum value of ratings per criterion is divided by each alternative rating. The concept of Ratio System can be also found in other MCDM methods like WASPAS and MOOSRA (Multi-Objective Optimization by Simple Ratio Analysis). The first term of WASPAS utility is inspired by Ratio System. In MOOSRA, the beneficial sum is divided by the non-beneficial sum while in Ratio System, the non-beneficial sum is subtracted from the beneficial sum.

- Reference Point Approach

In Reference Point Approach, the best alternative is the one that its worst value in respect of all criteria is not very bad [59]. This approach, as a non-compensatory model, first finds the alternatives ratings with the worst performance with respect to each criterion and finally selects the overall best value (i.e., the minimum value) from these worst ratings. Reference Point Approach is based on Tchebycheff Min–Max Metric [10]. Tchebycheff Min–Max Metric is originated from the general theory of Murkowski Metric which is the source of several decision analysis approaches in literature such as Goal Programming. To obtain the utility, first, Maximal Objective Reference Point (MORP) Vector is defined as [10]:

$$r_j = \left\{ \max_i \ x_{ij}^*, \quad j \le g; \quad \min_i \ x_{ij}^*, \quad j > g \right\}. \tag{5}$$

The distance between the weighted value of each member of MORP Vector and the weighted alternative rating is obtained as [100]:

$$d_{ij} = \left| w_j r_j - w_j x_{ij}^* \right|. \tag{6}$$

The utility of Reference Point Approach is obtained by maximizing the distance introduced in Eq. (6) as follows [100]:

$$z_i = \max_j \ d_{ij}. \tag{7}$$

The best alternative based on Reference Point Approach has the minimum utility z_i and the ranking of the approach is produced in ascending order as:

$$\mathbf{R}_{\mathrm{RPA}} = \left\{ A_{i|\min_i z_i} \succ \cdots \succ A_{i|\max_i z_i} \right\}. \tag{8}$$

In Reference Point Approach, the distance of each alternative rating from MORP Vector is obtained. There are other forms of Reference Point Vectors in the literature, including:

- Utopian Objective Reference Point (UORP) Vector: In this vector, higher values are targeted not the maximum values, necessarily;
- Aspiration Objective Reference Point (AORP) Vector: This vector tries to moderate aspirations as finding the maximum distance from the target values; that is, finding the alternatives with the worst performance.

TOPSIS and VIKOR also fall into the group of "Goal or Reference Level Models." Both of them are based on L_P-*Metric*. TOPSIS is supported on L_2 while VIKOR is formulated on the basis of L_1 and L_∞. In TOPSIS, there exist two Reference Points, including the Positive-Ideal Solution (PIS) inspired by MORP and the Negative-Ideal Solution (NIS) inspired by AORP. In Classical Reference Point Approach, only MORP Vector is considered without paying attention to AORP Vector, but in Extended Reference Point Approach suggested by Eghbali-Zarch et al. [79], AORP Vector is also taken into account. Reference Point Approach sometimes cannot differ on two or more alternatives; that is, the approach leads to same rankings [89]. Thus, Reference Point Approach is often integrated with other decision-making tools to remedy the defect.

- Full Multiplicative Form

Full Multiplicative Form, which uses the geometric weighted aggregation operator, is an incompletely-compensatory model. In this technique, small normalized values of an alternative could not be completely compensated by the same degree of large values. Thus, the issue leads to the perception that an alternative with moderate performance may be superior to an alternative which has both good and bad performances with respect to different criteria [59]. To obtain the utility of Full Multiplicative Form, the product of weighted normalized alternatives ratings on beneficial criteria are divided by the product of weighted normalized alternatives ratings on non-beneficial criteria [39]:

$$u_i = \prod_{j=1}^{g} \left(x_{ij}^* \right)^{w_j} / \prod_{j=g+1}^{n} \left(x_{ij}^* \right)^{w_j}. \tag{9}$$

In utility formula of Full Multiplicative Form, multiplying normalized ratings with weights leads to the same result as the situation in which no weights are considered. Thus, weights should be considered as exponent in utility equation of Full Multiplicative Form. The best alternative based on Full Multiplicative Form has the maximum utility $u_i$and the ranking of this technique is generated in descending order as:

$$\mathbf{R}_{\mathrm{FMF}} = \left\{ A_{i|\max_i u_i} \succ \cdots \succ A_{i|\min_i u_i} \right\}. \tag{10}$$

The concept of Full Multiplicative Form can be observed in other MCDM techniques like WASPAS. That is, the second term of WASPAS utility index is similar to Full Multiplicative Form. However, WASPAS uses a linear ratio for normalization considering the maximum and minimum values of alternatives ratings.

2.3. Ranking aggregation tools

After obtaining the subordinate rankings, we need to fuse these rankings to obtain the final ranking of alternatives. As discussed by Brauers and Zavadskas [35], by aggregating multiple subordinate rankings, we could obtain an integrative ranking list that is more robust than each individual ranking. This section mainly reviews these ranking aggregation tools.

The existing aggregation tools to combine subordinate rankings of MULTIMOORA are listed in Table 2. As we can see, four types of ranking aggregation tools have been used in MULTIMOORA developments, including Dominance-based concepts (original Dominance Theory and Dominance-Directed Graph), Mathematical operators (Arithmetic/Geometric Mean, Borda Rule, Improved Borda Rule, and Rank Position Method), MCDM approaches (ORESTE Method and Technique of Precise Order Preference), and Programming approaches (such as the Nonlinear Optimization Model). It is clear that Dominance Theory has the most frequencies; however, in the recent years, other tools which have more advantages have been used in place of the theory. From the tools introduced in Table 2, the Improved Borda Rule has a different concept as it also uses the subordinate utilities besides subordinate rankings to produce final ranking list.

We continue this section with explaining the theory of the ranking aggregation tools used in MULTIMOORA models, as follows:

Table 2
Distribution of ranking aggregation tools.

Ranking aggregation tool	Frequency	Percentage frequency	Reference(s)
Dominance theory	100	94	[3,11,20–29,12,30–39,13,40,42–50,14,51–55,57,58,60–62,15,63–72, 16,73–77,79–83,17,84–88,90–94,18,95–101,103–105,19,106–115]
Arithmetic/geometric mean	2	1.9	[89,102]
Borda rule	1	0.9	[67]
Dominance-directed graph	1	0.9	[67]
Improved Borda rule	1	0.9	[56]
Optimization model	1	0.9	[41]
ORESTE method	1	0.9	[59]
Rank position method	1	0.9	[67]
Technique of precise order preference	1	0.9	[78]

- Dominance Theory and Dominance-Directed Graph

Dominance Theory was used in the original MULTIMOORA method. This theory is supported on some principles including Dominance (Absolute Dominance and Partial Dominance), Equality (Absolute Equality, Partial Equality, and Equality according to Circular Reasoning), and Transitiveness [35]. There are some drawbacks to utilizing Dominance Theory: (1) obtaining ranks of alternatives is hard as the theory is not yet automated [85]; (2) the theory only uses ordinal values by neglecting the relative importance of alternatives; and (3) circular reasoning happens in some cases which leads to identical ranks which is not satisfactory [59].

Dominance-Directed Graph, also called Tournaments, considers each of three subordinate rankings of MULTIMOORA as a tournament [67]. Besides, each alternative could be also considered as a team. In this theory, team a can dominate team b or vice versa, but not both. Vertex matrix $\mathbf{M}$ is produced which shows the relation of dominance among alternatives for each tournament. In matrix $\mathbf{M} = [m_{PQ}]$ of each tournament, if team a dominates team b, m_{PQ} equals to 1, otherwise 0. Afterwards, $\mathbf{M}^2$ is computed and then $\mathbf{A} = \mathbf{M}+\mathbf{M}^2$. The row summation of $\mathbf{A}$ represents relative preference. The highest value of row sums shows the best alternative and the lowest value indicates the worst alternative.

- Rank Position Method

This ranking aggregation approach, also entitled Reciprocal Rank Method, takes into consideration the position of each alternative according to each subordinate ranking technique [67]. Rank Position Method is based on score $RPM(A_i)$ for each alternative employed to generate final ranking. The score is as follows [67]:

$$RPM(A_i) = 1/\left(1/r(y_i) + 1/r(z_i) + 1/r(u_i)\right), \tag{11}$$

where $r(y_i)$, $r(z_i)$, and $r(u_i)$ are the rankings of Ratio System, Reference Point approach, and Full Multiplicative Form, respectively. The best alternative based on Rank Position Method has the minimum value of $RPM(A_i)$.

- Technique of Precise Order Preference

Technique of Precise Order Preference uses the concept of MCDM to obtain a compromise solution. First, it constructs a decision matrix from the results of the ranking methods [119]. In case of MULTIMOORA, a decision matrix is composed of the utility values of candidate alternatives in response to Ratio System, Reference Point approach, and Full Multiplicative Form. If the utility values are not linguistic, normalization is also needed. Then, relative weights of each method can be computed subjectively based on comments of experts [78] or objectively using a weighting technique like Entropy [119]. Technique of Precise Order Preference consolidates the normalized subordinate utilities and their computed weights to reach Precise Selection Index. The best alternative based on this ranking aggregation tool is identified by minimizing Precise Selection Index. Details of the process of Technique of Precise Order Preference can be found in Refs. [78,119].

- Borda and Improved Borda Rules

Borda Rule, also named Borda Count, is an easy but effective technique from the group of single-winner election methods in which the number of votes equals to the number of alternatives [67]. In this method, if there are t alternatives, the first-ranked alternative gets $t$votes and the second-ranked gets one vote less, and so on. The final score of Borda Rule is computed by the summation of the scores of the subordinate methods. The highest value of Borda Rule score shows the best alternative.

Improved Borda Rule is based on Borda Count [56]; however, it integrates both cardinal and ordinal values (i.e., utilities and rankings, respectively) of each subordinate methods of MULTIMOORA. In this sense, the Improved Borda Rule is superior to Dominance Theory. To employ the Improved Borda Rule, first, the subordinate utilities are normalized based on Vector Normalization to produce y_i^*, z_i^*, and u_i^*. The assessment value of Improved Borda Rule, i.e., $IMB(A_i)$, is obtained using the following equation [56]:

$$IMB(A_i) = y_i^* \frac{m - r(y_i) + 1}{m(m+1)/2} - z_i^* \frac{r(z_i)}{m(m+1)/2} + u_i^* \frac{m - r(u_i) + 1}{m(m+1)/2}, \tag{12}$$

where $r(y_i)$, $r(z_i)$, and $r(u_i)$ are the rankings of Ratio System, Reference Point approach, and Full Multiplicative Form, respectively. The best alternative based on Improved Borda Rule has the maximum value of $IMB(A_i)$.

Remark. Dominance Theory is complicated due to pairwise comparisons and probable occurrence of circular reasoning. The case would be more confusing for decision-makers when the number of alternatives and criteria are large because Dominance Theory is based on manual comparison. Nevertheless, Improved Borda Rule neither needs any manual comparison, nor has special conditions.

- ORESTE Method

ORESTE Method belongs to the third group of MCDM approaches (i.e., Outranking Techniques). ORESTE has a multi-level procedure to produce decision results. First, weak rankings are generated and then they are improved to global rankings. The outcomes are not a single ranking but in the form of preference, indifference, and incomparability correlations of alternatives [120]. For integration of subordinate rankings of MULTIMOORA using ORESTE, a decision matrix of the rankings is first constructed [59]. Second, the weak Besson's mean ranks are generated. Third, the global preference score is computed for each alternative. Fourth, the global Besson's mean ranks are calculated for each subordinate parts of MULTIMOORA. Eventually, the final ranking is obtained by summation of the ternary global Besson's mean ranks.

- Optimization Model

The final ranking of MULTIMOORA can also be obtained using an Optimization Model. The concept of the model is based on the expectation that the final result has the minimum overall deviation comparing the three subordinate rankings. An Optimization Model is considered

Table 3
Distribution of weighting methods.

Weighting method	Frequency	Percentage frequency	Reference(s)
Entropy	9	8.5	[15,39,40,74,77,82,88,94,100]
AHP	8	7.5	[3,37,56,68,76,80,92,102]
SWARA	7	6.6	[31,73,75,79,89,101,110]
BWM	3	2.8	[69,74,81]
DEMATEL	3	2.8	[25,83,92]
Statistical variance	3	2.8	[84,100,107]
CRITIC	2	1.9	[56,100]
Maximizing deviation method	2	1.9	[62,69]
Choquet integral	1	0.9	[48]
Logarithmic least square method	1	0.9	[59]
MACBETH	1	0.9	[95]
Numeric logic	1	0.9	[47]
Optimization model	1	0.9	[57]
TOPSIS-inspired method	1	0.9	[72]

to minimize the sum of deviation between the final rankings and three ranking results as follows [41]:

$$\begin{aligned} \min \quad & \left(\sum_{i=1}^{m} |R_i - r(y_i)| + \sum_{i=1}^{m} |R_i - r(z_i)| + \sum_{i=1}^{m} |R_i - r(u_i)| \right), \\ \text{s.t.} \quad & R_i = R_k, \quad i,k = 1,2,\ \ldots, m, \quad i \neq k, \\ & R_i > R_k \text{ if } r(y_i) > r(y_k),\ r(z_i) > r(z_k), \text{ and } r(u_i) > r(u_k), \\ & R_i \leq R_k \text{ if } r(y_i) \leq r(y_k),\ r(z_i) \leq r(z_k), \text{ and } r(u_i) \leq r(u_k), \\ & 1 \leq R_i \leq m, \quad i = 1,2,\ \ldots, m, \end{aligned} \tag{13}$$

where $r(y_i), r(z_i)$, and $r(u_i)$ are the rankings of Ratio System, Reference Point approach, and Full Multiplicative Form, respectively. Eq. (13) is a nonlinear programming model for which some mathematical computations are needed. The related details can be found in Ref. [41].

2.4. Weighting methods for criteria

In an MCDM problem, there are multiple different criteria that their significance are not necessarily identical; thus, criteria weights play a key role in evaluating the overall utility values of the alternatives for the problem [121]. The weights are importance parameters employed to differentiate the effect of each criterion on the final result [122]. The criterion weights could be subjective, i.e., based on the comments made by the experts, or objective, i.e., those which evaluate the structure of the data of decision matrix. The procedure of weighting criteria can be one expert or multiple decision-makers [123]. In the category of subjective weighting methods, AHP, supported on the concept of pairwise comparison, is the most common method. BWM is another important subjective weighting method which is based on comparison according to the best and worst criteria. In the category of objective weighting methods, there are different techniques like Entropy and CRITIC. For MULTIMOORA models, a variety of weighting methods have been used to provide contrast between criteria. Table 3 provides the list of these weighting methods. Entropy and AHP have the most frequent application as weighting methods for MULTIMOORA.

The classification of the utilized weighting methods with MULTIMOORA according to subjective or objective type is as follows:

- *Subjective Weighting Methods*: AHP, SWARA, BWM, DEMATEL, MACBETH, Numeric Logic, and Optimization Model.
- *Objective Weighting Methods*: Entropy, Statistical Variance, CRITIC, Maximizing Deviation Method, Choquet Integral, Logarithmic Least Square Method, and TOPSIS-Inspired Method.

The number of subjective weighting methods is equal to that of objective weighting approaches (i.e., both 7 items); however, utilization frequency of subjective weighting methods is near two-fold comparing objective weighting approaches (i.e., 27 to 16, respectively). Weighting methods can also be categorized into three groups based on their scientific origins:

- *Operations Research and Decision-Making*: AHP, BWM, SWARA, DEMATEL, TOPSIS-Inspired Method, Optimization Model, MACBETH, and Numeric Logic.
- *Statistical Analysis*: Statistical Variance, CRITIC, Maximizing Deviation Method, Choquet Integral, and Logarithmic Least Square Method.
- Engineering: Entropy.

The methods in the group of Operations Research and Decision-Making can also be employed to compute relative utilities of alternatives; thus, they can act as MCDM approaches, in practice. Entropy originates form Thermodynamics theory which is an important concept in Engineering.

2.5. Group decision-making

In real life, many significant decisions are made through a group of elites and experts rather than considering an individual decision-maker. In industries and factories, technical expert panel takes the crucial decisions on identifying plans and strategies, selecting staff, and exploiting available resources. In practical problems like legal systems, healthcare management, and social services, the significant decisions are usually made based on collective opinions of multiple advisors and experts. Sometimes, experts may have different fields and levels of expertise; therefore, in such cases, collective decisions are analyzed to handle the conflicts among various opinions [124].

Group decision-making can be done in cooperative or non-cooperative styles. Cooperative group decisions are significant in engineering, medical, and scientific fields while non-cooperative group decisions are common in economic and political areas. Even by considering cooperative group decisions, reaching a complete consensus among all members of the group on the eventual solution is nearly infeasible because decision-makers, who are supposed to have identical goals, may have some opinion conflicts, in practice [125].

Near a half of total studies on MULTIMOORA has a group decision-making structure, which shows the importance of group decision-making in MCDM. In Appendix, Table A.5 shows the related references on group decision-making. In some studies on MULTIMOORA, group decision-making structure is employed to generate criteria weights and alternatives ratings on the criteria; however, in the others, multiple decision-makers only participate in criteria weighting procedure.

2.6. Combination with other models

MCDM techniques could be combined with other models from different scientific scopes to handle complex and interdisciplinary

Table 4
Distribution of models combined with MULTIMOORA.

Models combined with MULTIMOORA	Frequency	Percentage frequency	Reference(s)
Failure mode and effects analysis	3	2.8	[32,40,80]
Quality function deployment	3	2.8	[62,69,74]
Data envelopment analysis	2	1.9	[22,113]
Goal programming	2	1.9	[63,93]
Cluster analysis	1	0.9	[49]
Fine-Kinney method	1	0.9	[48]
Finite element simulation	1	0.9	[47]
Geographic information system	1	0.9	[68]
Prospect theory	1	0.9	[42]
Regret theory	1	0.9	[77]

Table 5
Performance of MOORA regarding other MCDM methods [35].

MCDM method	Computational time	Simplicity	Mathematical calculations	Stability	Information type
MOORA	*Very less*	*Very simple*	*Minimum*	*Good*	*Quantitative*
AHP	Very less	Very critical	Maximum	Poor	Mixed
TOPSIS	Moderate	Moderately critical	Moderate	Medium	Quantitative
VIKOR	Less	Simple	Moderate	Medium	Quantitative
ELECTRE	High	Moderately critical	Moderate	Medium	Mixed
PROMETHEE	High	Moderately critical	Moderate	Medium	Mixed

problems. For instance, there are some hybrid TOPSIS extensions based on the following approaches: Artificial Neural Network (ANN), Genetic Algorithm, Regression Model, Fractional Programming, K-Means Clustering, Taguchi Method, And Particle Swarm Optimization [126]. Another MCDM method that has been often combined to produce hybrid models is ELECTRE. This approach has been integrated with concepts including Regression Approach, Heuristic Algorithm, and Axiomatic Design Principles [127]. When it comes to the case of MULTIMOORA, a variety of models are used to generate hybrid models as collected in Table 4. Failure Mode and Effects Analysis and Quality Function Deployment have the most application for integrative models.

The methods used for hybrid MULTIMOORA models have six different scientific origins, as follows:

- *Risk Management*: Failure Mode and Effects Analysis and Fine-Kinney Method.
- *Engineering*: Quality Function Deployment, Finite Element Simulation.
- *Operations Research and Decision-Making*: Data Envelopment Analysis, Goal Programming, and Regret Theory.
- *Data Mining*: Cluster Analysis.
- *Geography*: Geographic Information System.
- *Cognitive Psychology*: Prospect Theory.

2.7. Robustness of MULTIMOORA

In Table 5, the performance of MOORA which is a part of MULTIMOORA is compared with other MCDM methods. As we can find from Table 5, MOORA is simple and reliable. Original MULTIMOORA combines MOORA with the full multiplicative form using the dominance theory. Brauers and Zavadskas [35] claimed that “use of two different methods of multi-objective optimization is more robust than the use of a single method; the use of three methods is more robust than the use of two, and so on;” thus, “MULTIMOORA is more robust than MOORA.”

Generally, the advantages of MULTIMOORA include: (1) simple mathematics, (2) low computational time, (3) straightforwardness for decision-makers, (4) using three different methods for determining subordinate rankings, and (5) employing ranking aggregation tools for integrating the subordinate rankings. To clarify item (5), it is worthwhile to mention that many MCDM methods have only one utility function; however, MULTIMOORA produces an integrative outcome by combining three utility values employing a ranking aggregation tool.

The three subordinate parts of MULTIMOORA are based on the fully compensatory, non-compensatory, and incompletely-compensatory models. As discussed in Sections 2.2, each of the approaches may have some shortcomings, in practice. Therefore, integration of their outcomes would lead to a more robust final result comparing to the individual outcomes by curing the existing defects.

2.8. Graphical summary of MULTIMOORA theory

The concepts used in Sections 2.2 and 2.3 to derive the model of MULTIMOORA can be summarized into five phases as illustrated in Fig. 2. Decision matrix and weight vector are constructed in Phase 1. The decision matrix is normalized in Phase 2. The utilities of subordinate parts of MULTIMOORA, i.e., Ratio System, Reference Point Approach, and Full Multiplicative Form, are computed in Phase 3. Rankings of subordinate methods are produced in Phase 4. Eventually, the subordinate rankings are combined into final outcomes of MULTIMOORA in Phase 5.

Fig. 3 graphically shows the theoretical features of the main studies on MULTIMOORA, except uncertainty theories which are separately described in Section 3. In the group of weighting models, there exist a number of different approaches; however, the frequencies of objective weighting method is lower. Generally, weighting models has frequency 43 with Entropy and AHP as the more significant methods with frequencies 9 and 8, respectively. Totally, in 16 studies, integrative models have been employed from which Failure Mode and Effects Analysis and Quality Function Deployment have the most application with frequency 3. When it comes to ranking aggregation tools, Dominance Theory has been mostly used by researchers on MULTIMOORA for fusion of rankings with frequency 100. Group decision-making is a significant concept in MULTIMOORA models as it has frequency 48.

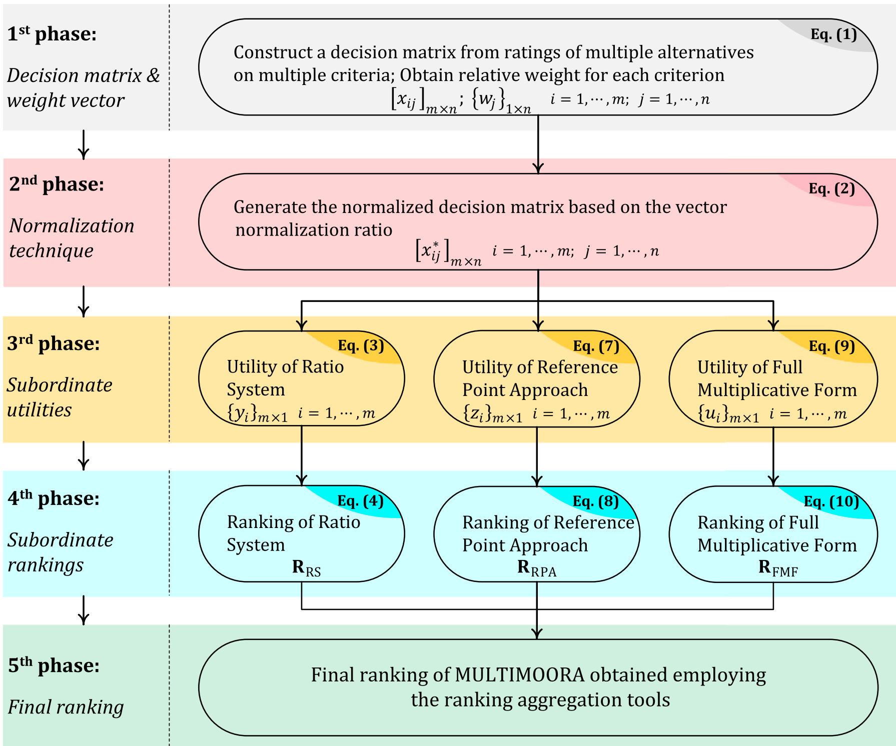

Fig. 2. Flowchart of MULTIMOORA phases.

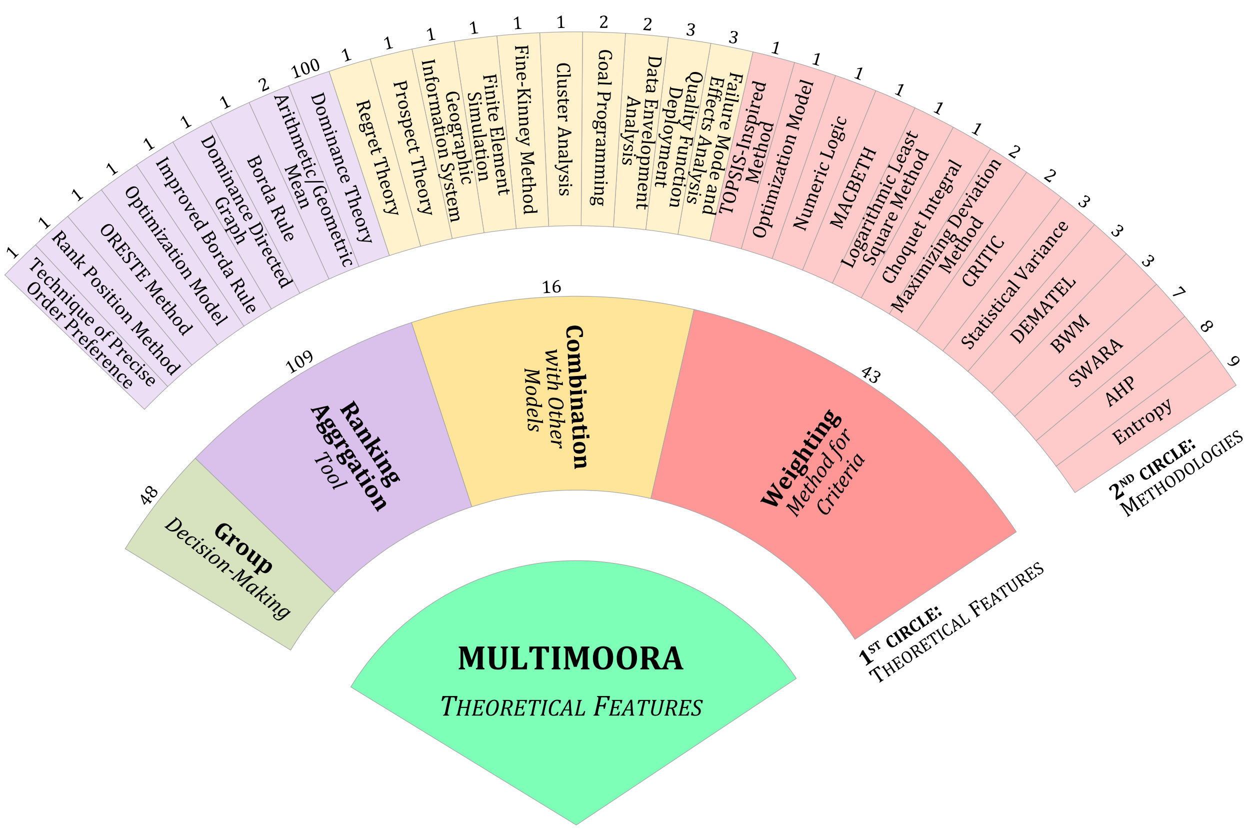

Fig. 3. Infographics of MULTIMOORA theoretical features (numerals represent the frequencies).

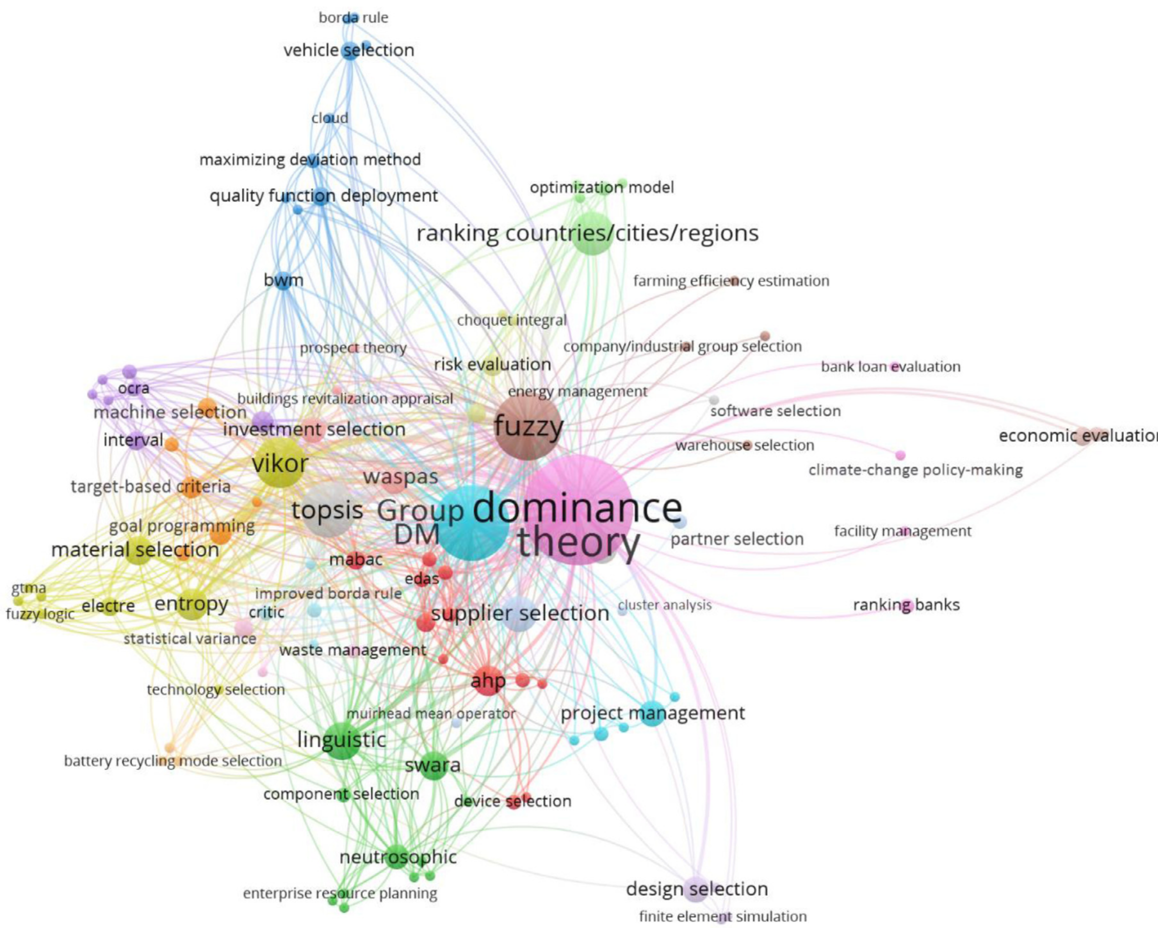

Fig. 4. Co-occurrence network for MULTIMOORA theoretical features.

The co-occurrence network of MULTIMOORA theoretical features (i.e., related to the categories: ranking aggregation tools, weighting methods, group decision-making, combination with other models, and verification techniques) are illustrated in Fig. 4 (with number of occurrences of a keyword ≥ 3). The list of verification techniques for MULTIMOORA are collected in Table A.6 in Appendix. Fig. 4 emphasizes the importance of Dominance Theory, Group Decision-Making, Fuzzy Set Theory, Linguistic Term Theory, TOPSIS, and VIKOR in the studies on MULTIMOORA. The most applied scope in the real-world applications is the case of Ranking Countries/Cities/Regions.

In Appendix, Tables A.1–A.4 give the details of the main studies on MULTIMOORA including theoretical and practical features and the bibliographical information. These tables are presented based on time periods, i.e., Tables A.1–A.4 are related to the studies conducted in the periods: 2018 (Jan-Sep), 2016–17, 2013–15, and 2010–12, respectively. The tables shows that from 2010 to 2018, the theoretical aspects of the developments are getting more complicated.

3. Analysis of the developments of MULTIMOORA based on uncertainty theories

In the present section, we discuss the extensions of MULTIMOORA supported by the theories of uncertainty. Section 3.1 is allocated to the developments based on Interval Number Theory. In this section, first, the advantages of Interval Numbers are depicted and then the related studies are explained. Fuzzy Set Theory is discussed in Section 3.2. In the section, first, the theories are introduced followed by explaining the mathematics of several related extensions and the formulas of the important models. Section 3.3 goes through Linguistic Term Theory. Section 3.4 describes the significance of Neutrosophic Fuzzy Set Theory and studies the related significant studies besides introducing a fundamental model in the field. In Sections 3.1–3.3, for simplicity and briefness, we avoid to separately present the mathematical preliminaries of uncertainty theories; instead, the related mathematical relations are inserted within the formulas of the subordinate utility values. Section 3.5 presents a discussion on the models based on Rough Set, *Z*-number, and Cloud Model Theories. Section 3.6 evaluates MULTIMOORA uncertain developments by presenting the distribution based on uncertainty theories and uncertainty sets as well as illustrating the timeline of uncertain works. Finally, Section 3.7 summarizes this section through demonstrating an infographics of MULTIMOORA uncertain developments. In Appendix, Table A.8 lists all acronyms used in this paper.

3.1. Developments based on interval number theory

Interval Number Theory is a simple but applicable concept of considering vagueness in decision-making problems. Interval Numbers (INs) can be defined as: (1) an extension of a real number; (2) a degenerate flat fuzzy number without membership function; and (3) an α-cut of a fuzzy number. INs are important in MCDM problems, because: (1) INs require the minimum amount of data; (2) decision-makers could easily present the range of available data as interval numbers; and (3) INs are very practical as many data in real problems are essentially reported in the form of ranges.

There are four MULTIMOORA extensions based on Interval Theory. Kracka and Zavadskas [60] proposed Interval MULTIMOORA utilizing arithmetic of INs (MOORE Rule), the crisp distance of INs, and comparison based on arithmetic average. Hafezalkotob et al. [46] suggested a new model of Interval MULTIMOORA by using Preference matrix without degeneration of INs. Hafezalkotob and Hafezalkotob [33] presented Interval Target-Based MULTIMOORA employing MOORE Rule, Interval distance of INs, and the preference matrix. Hafezalkotob and Hafezalkotob [38] developed Interval Target-Based MULTIMOORA by adding preference-based rankings of INs. Interval Target-Based MULTIMOORA [38], which is an important model in the context of Interval Number Theory, is formulated as follows.

In Interval Target-Based MULTIMOORA, alternatives ratings are in the form of INs $\bar{x}_{ij} = [x_{ij}^L, x_{ij}^U]$ and the preference matrix is used to obtain the maximum, minimum, and ranking of INs. Interval distance of INs is employed in this method. Normalization ratio $\bar{x}_{ij}^*$ in this method is defined as follows:

$$\bar{x}_{ij}^* = \left[x_{ij}^{*,L}, x_{ij}^{*,U}\right] = \exp\left(-\frac{\bar{d}^*(\bar{x}_{ij},\bar{t}_j)}{\max_i d^*(\bar{x}_{ij},\bar{t}_j)}\right)$$
$$= \exp\left(-\frac{\begin{cases}\left[\min\left\{\left|x_{ij}^L - t_j^U\right|, \left|x_{ij}^U - t_j^L\right|\right\}, \left|\left(\left(x_{ij}^L + x_{ij}^U\right)/2\right) - \left(\left(t_j^L + t_j^U\right)/2\right)\right|\right], & \text{if } \bar{x}_{ij}\cap\bar{t}_j = \emptyset \\ \left[0, \left|\left(\left(x_{ij}^L + x_{ij}^U\right)/2\right) - \left(\left(t_j^L + t_j^U\right)/2\right)\right|\right], & \text{if } \bar{x}_{ij}\cap\bar{t}_j \neq \emptyset\end{cases}}{\max_i \begin{cases}\left(\min\left\{\left|x_{ij}^L - t_j^U\right|, \left|x_{ij}^U - t_j^L\right|\right\} + \left|\left(\left(x_{ij}^L + x_{ij}^U\right)/2\right) - \left(\left(t_j^L + t_j^U\right)/2\right)\right|\right)/2, & \text{if } \bar{x}_{ij}\cap\bar{t}_j = \emptyset \\ \left|\left(\left(x_{ij}^L + x_{ij}^U\right)/2\right) - \left(\left(t_j^L + t_j^U\right)/2\right)\right|/2, & \text{if } \bar{x}_{ij}\cap\bar{t}_j \neq \emptyset\end{cases}}\right), \tag{14}$$

where $\bar{t}_j$ is interval target value of each criterion and is calculated as $\bar{t}_j = [t_j^L,\ t_j^U] = \{\max_i \bar{x}_{ij},\ \text{if } j \in I;\ \min_i \bar{x}_{ij},\ \text{if } j \in J;\ \bar{g}_j,\ \text{if } j \in K\}$ where I, J, and K is the sets of beneficial, non-beneficial, and target-based criteria, respectively. Besides, $\bar{g}_j$ is the interval goal value of each target-based criterion. The utility values of interval target-based models of Ratio system, Reference Point Approach, and Full Multiplicative Form, i.e., $\bar{y}_i^T$, $\bar{z}_i^T$, and $\bar{u}_i^T$, respectively, are obtained as follows:

$$\bar{y}_i^T = \left[y_i^{T,L}, y_i^{T,U}\right] = \sum_{j=1}^{g} w_j \bar{x}_{ij}^* = \left[\sum_{j=1}^{g} w_j x_{ij}^{*,L},\ \sum_{j=1}^{g} w_j x_{ij}^{*,U}\right], \tag{15}$$

$$\bar{z}_i^T = \left[z_i^{T,L}, z_i^{T,U}\right] = \max_j \bar{d}^*\left(w_j[1,1], w_j\bar{x}_{ij}^*\right) = \max_j\left(w_j \cdot \left\{\left[\min\left\{\left|1 - x_{ij}^U\right|, \left|1 - x_{ij}^L\right|\right\}, \left|1 - \left(\left(x_{ij}^L + x_{ij}^U\right)/2\right)\right|\right],\right.\right.$$
$$\left.\left.\text{if}\,[1,1]\cap\bar{x}_{ij}^* = \emptyset;\ \left[0,\ \left|1 - \left(\left(x_{ij}^L + x_{ij}^U\right)/2\right)\right|\right],\quad \text{if}\,[1,1]\cap\bar{x}_{ij}^* \neq \emptyset\right\}\right), \tag{16}$$

$$\bar{u}_i^T = \left[u_i^{T,L}, u_i^{T,U}\right] = \prod_{j=1}^{g}\left(\bar{x}_{ij}^*\right)^{w_j} = \left[\prod_{j=1}^{g}\left(x_{ij}^{*,L}\right)^{w_j}, \prod_{j=1}^{g}\left(x_{ij}^{*,U}\right)^{w_j}\right]. \tag{17}$$

3.2. Developments based on fuzzy set theory

Fuzzy Set Theory, introduced by Zadeh [128] in 1965, is an important theory of uncertainty which models the vagueness or imprecision of the human cognitive process. A Fuzzy Set (FS) is generally introduced by a membership function that maps elements to degrees of membership in a certain interval [69]. The theory is very applicable in various fields such as decision making, artificial intelligence, expert systems, control theory, and neural networks. There are different types of Fuzzy Sets like Interval-Valued Fuzzy Number (IVFN), Intuitionistic Fuzzy Number (IFN), and Interval Type-2 Fuzzy Set (IT2FS) [129].

As Fuzzy Theory is one of most important concepts of uncertainty, there are many extensions of MULTIMOORA based on this theory. Triangular Fuzzy Number (TFN) is the simplest form of representing the fuzziness of data. TFN with mathematical features such as Vertex method for crisp distance and centroid-based method for defuzzification has combined with MULTIMOORA in several studies [19,25,26,34,55,63,79,80,85,87,91,93,98,114]. However, Tian et al. [69] employed graded mean integration as defuzzification technique to generate Triangular Fuzzy MULTIMOORA. Trapezoidal Fuzzy Number (TrFN) with concepts of Vertex method for crisp distance and centroid-based method for defuzzification is used for three developments [32,88,94]. Liu et al. [74] applied the integral of area for defuzzification to derive Trapezoidal Fuzzy MULTIMOORA. Stanujkic et al. [44] suggested Interval-Valued Fuzzy MULTIMOORA based on the weighted averaging operator and the geometric averaging operator of IVFNs. Dorfesh et al. [78] suggested Interval Type-2 Fuzzy MULTIMOORA. Generalized Interval-Valued Fuzzy Number (GIVFN) is a basis for four developments [54,97,103,108]. In these studies, centroid-based method is used for crisp distance of GIVFNs and defuzzification is also based on the crisp distance. Baležentis and Baležentis [18] introduced Intuitionistic Fuzzy MULTIMOORA based on the power ordered weighted average operator and the power ordered weighted geometric operator as well as Euclidean distance and expected values of IFNs. Baležentis et al. [17] presented another version of Intuitionistic Fuzzy MULTIMOORA using negation operator, the power ordered weighted average operator, the power ordered weighted geometric operator, comparison rule, and crisp distance of IFNs. Interval-Valued Intuitionistic Fuzzy MULTIMOORA has been developed considering the weighted average operator, the weighted geometric operator, and score function of IVIFNs [40,70]. Hesitant Fuzzy Set (HFS) was exploited in three studies [16,106,130] for new developments.

This section continues with the presentation of the formulations of the subordinate utility values of two developments of MULTIMOORA. The extensions that are discussed below are based on GIVFN and IVIFN.

- Generalized Interval-Valued Fuzzy MULTIMOORA

In this technique, alternatives ratings are in the form of GIVFNs shown as $\tilde{\tilde{x}}_{ij} = [\tilde{x}_{ij}^L, \tilde{x}_{ij}^U] = [(x_{ij,1}^L, x_{ij,2}^L, x_{ij,3}^L, x_{ij,4}^L; w_{\tilde{x}_{ij}^L}), (x_{ij,1}^U, x_{ij,2}^U, x_{ij,3}^U, x_{ij,4}^U; w_{\tilde{x}_{ij}^U})]$. Normalization ratio $\tilde{\tilde{x}}^*{}_{ij}$ and the utility values of generalized interval-valued fuzzy models of Ratio system, Reference Point Approach, and Full Multiplicative Form, i.e., $\tilde{y}_i^{GIV}$, z_i^{GIV}, and $\tilde{u}_i^{GIV}$, respectively, are obtained as follows:

$$\tilde{\tilde{x}}_{ij}^* = \left[\tilde{x}_{ij}^{*,L}, \tilde{x}_{ij}^{*,U}\right] = \left[\left(x_{ij,1}^{*,L}, x_{ij,2}^{*,L}, x_{ij,3}^{*,L}, x_{ij,4}^{*,L}; w_{\tilde{x}_{ij}^{*,L}}\right), \left(x_{ij,1}^{*,U}, x_{ij,2}^{*,U}, x_{ij,3}^{*,U}, x_{ij,4}^{*,U}; w_{\tilde{x}_{ij}^{*,U}}\right)\right]$$
$$= \left[\left(k_j x_{ij,1}^L, k_j x_{ij,2}^L, k_j x_{ij,3}^L, k_j x_{ij,4}^L; w_{\tilde{x}_{ij}^L}\right), \left(k_j x_{ij,1}^U, k_j x_{ij,2}^U, k_j x_{ij,3}^U, k_j x_{ij,4}^U; w_{\tilde{x}_{ij}^U}\right)\right], \tag{18}$$

where $k_j = (\sum_{i=1}^m \sum_{p=1}^4 (x_{ij,p}^L)^2 + \sum_{i=1}^m \sum_{q=1}^4 (x_{ij,q}^U)^2)^{-1/2}$,

$$\tilde{\tilde{y}}_i^{GIV} = \left[\tilde{y}_i^{GIV,L}, \tilde{y}_i^{GIV,U}\right] = \left[\left(y_{i,1}^{GIV,L}, y_{i,2}^{GIV,L}, y_{i,3}^{GIV,L}, y_{i,4}^{GIV,L}; w_{\tilde{y}_i^{GIV,L}}\right), \left(y_{i,1}^{GIV,U}, y_{i,2}^{GIV,U}, y_{i,3}^{GIV,U}, y_{i,4}^{GIV,U}; w_{\tilde{y}_i^{GIV,U}}\right)\right]$$
$$= \left[\left(\left\{\sum_{j=1}^g w_j x_{ij,1}^{*,L} - \sum_{j=g+1}^n w_j x_{ij,4}^{*,L}\right\}, \left\{\sum_{j=1}^g w_j x_{ij,2}^{*,L} - \sum_{j=g+1}^n w_j x_{ij,3}^{*,L}\right\}, \left\{\sum_{j=1}^g w_j x_{ij,3}^{*,L} - \sum_{j=g+1}^n w_j x_{ij,2}^{*,L}\right\},\right.\right.$$
$$\left\{\sum_{j=1}^g w_j x_{ij,4}^{*,L} - \sum_{j=g+1}^n w_j x_{ij,1}^{*,L}\right\}; \min_{1\le j\le n}\left\{w_{\tilde{x}_{ij}^{*,L}}\right\}\right), \left(\left\{\sum_{j=1}^g w_j x_{ij,1}^{*,U} - \sum_{j=g+1}^n w_j x_{ij,4}^{*,U}\right\},\right.$$
$$\left.\left.\left\{\sum_{j=1}^g w_j x_{ij,2}^{*,U} - \sum_{j=g+1}^n w_j x_{ij,3}^{*,U}\right\}, \left\{\sum_{j=1}^g w_j x_{ij,3}^{*,U} - \sum_{j=g+1}^n w_j x_{ij,2}^{*,U}\right\}, \left\{\sum_{j=1}^g w_j x_{ij,4}^{*,U} - \sum_{j=g+1}^n w_j x_{ij,1}^{*,U}\right\}; \min_{1\le j\le n}\left\{w_{\tilde{x}_{ij}^{*,U}}\right\}\right)\right], \tag{19}$$

$$z_i^{GIV} = \max_j d\left(w_j \tilde{\tilde{r}}_j, w_j \tilde{\tilde{x}}_{ij}^*\right) = \max_j\left[w_j \cdot \sqrt{\frac{1}{4}\left(\left(e_{\tilde{r}_j^L} - e_{\tilde{x}_{ij}^{*,L}}\right)^2 + \left(f_{\tilde{r}_j^L} - f_{\tilde{x}_{ij}^{*,L}}\right)^2 + \left(e_{\tilde{r}_j^U} - e_{\tilde{x}_{ij}^{*,U}}\right)^2 + \left(f_{\tilde{r}_j^U} - f_{\tilde{x}_{ij}^{*,U}}\right)^2\right)}\right], \tag{20}$$

where $\tilde{\tilde{r}}_j = [\tilde{r}_j^L, \tilde{r}_j^U] = [(r_{j,1}^L, r_{j,2}^L, r_{j,2}^L, r_{j,4}^L; w_{\tilde{r}_j^L}), (r_{j,1}^U, r_{j,2}^U, r_{j,2}^U, r_{j,4}^U; w_{\tilde{r}_j^U})] = \{(1,1,1,1;\ 1),\ j \le g;\ (0,0,0,0;\ 1),\ j > g\}$, $e_{\tilde{r}_j^L} = [f_{\tilde{r}_j^L}(r_{j,2}^L + r_{j,3}^L) + (r_{j,1}^L + r_{j,4}^L)(1 - f_{\tilde{r}_j^L})]/2$, $f_{\tilde{r}_j^L} = \{(r_{j,3}^L - r_{j,2}^L)/(r_{j,4}^L - r_{j,1}^L) + 2,\ r_{j,1}^L \ne r_{j,4}^L;\ 1/2\ r_{j,1}^L = r_{j,4}^L\}$, $e_{\tilde{r}_j^U} = [f_{\tilde{r}_j^L}(r_{j,2}^U + r_{j,3}^U) + (r_{j,1}^U + r_{j,4}^U)(1 - f_{\tilde{r}_j^U})]/2$, and $f_{\tilde{r}_j^U} = \{(r_{j,3}^U - r_{j,2}^U)/(r_{j,4}^U - r_{j,1}^U) + 2,\ r_{j,1}^U \ne r_{j,4}^U;\ 1/2\ r_{j,1}^U = r_{j,4}^U\}$,

$$\tilde{\tilde{u}}_i^{GIV} = \left[\tilde{u}_i^{GIV,L}, \tilde{u}_i^{GIV,U}\right] = \left[\left(u_{i,1}^{GIV,L}, u_{i,2}^{GIV,L}, u_{i,3}^{GIV,L}, u_{i,4}^{GIV,L}; w_{\tilde{u}_i^{GIV,L}}\right), \left(u_{i,1}^{GIV,U}, u_{i,2}^{GIV,U}, u_{i,3}^{GIV,U}, u_{i,4}^{GIV,U}; w_{\tilde{u}_i^{GIV,U}}\right)\right]$$
$$= \left[\left(\min s^L, \min\left(s^L \backslash p^L\right), \max\left(s^L \backslash q^L\right), \max s^L; \min_{1\le j\le n}\left\{w_{\tilde{x}_{ij}^{*,L}}\right\}\right),\right. \tag{21}$$
$$\left.\left(\min s^U, \min\left(s^U \backslash p^U\right), \max\left(s^U \backslash q^U\right), \max s^U; \min_{1\le j\le n}\left\{w_{\tilde{x}_{ij}^{*,U}}\right\}\right)\right],$$

where $s^L = \{\{\prod_{j=1}^g (x_{ij,1}^{*,L})^{w_j} / \prod_{j=g+1}^n (x_{ij,4}^{*,L})^{w_j}\}, \{\prod_{j=1}^g (x_{ij,2}^{*,L})^{w_j} / \prod_{j=g+1}^n (x_{ij,3}^{*,L})^{w_j}\}, \{\prod_{j=1}^g (x_{ij,3}^{*,L})^{w_j} / \prod_{j=g+1}^n (x_{ij,2}^{*,L})^{w_j}\}, \{\prod_{j=1}^g (x_{ij,4}^{*,L})^{w_j} / \prod_{j=g+1}^n (x_{ij,1}^{*,L})^{w_j}\}\}$, $s^U = \{\{\prod_{j=1}^g (x_{ij,1}^{*,U})^{w_j} / \prod_{j=g+1}^n (x_{ij,4}^{*,U})^{w_j}\}, \{\prod_{j=1}^g (x_{ij,2}^{*,U})^{w_j} / \prod_{j=g+1}^n (x_{ij,3}^{*,U})^{w_j}\}, \{\prod_{j=1}^g (x_{ij,3}^{*,U})^{w_j} / \prod_{j=g+1}^n (x_{ij,2}^{*,U})^{w_j}\}, \{\prod_{j=1}^g (x_{ij,4}^{*,U})^{w_j} / \prod_{j=g+1}^n (x_{ij,1}^{*,U})^{w_j}\}\}$, $p^L = \min s^L$, $p^U = \min s^U$, $q^L = \max s^L$, $q^U = \max s^U$, and the operator "\" shows the exclusion of the right hand term from the left hand set.

- Interval-Valued Intuitionistic Fuzzy MULTIMOORA

In this approach, alternatives ratings are in the form of IVIFNs shown as $\tilde{x}_{ij} = ([x_{ij,\mu}^L, x_{ij,\mu}^U], [x_{ij,\nu}^L, x_{ij,\nu}^U])$ where $[x_{ij,\mu}^L, x_{ij,\mu}^U]$ and $[x_{ij,\nu}^L, x_{ij,\nu}^U]$ are related to ranges of membership and non-membership functions, respectively. Normalization ratio $\tilde{x}_{ij}^*$ and the utility values of interval-valued intuitionistic fuzzy models of Ratio system, Reference Point Approach, and Full Multiplicative Form, i.e., $\tilde{y}_i^{IVI}$, z_i^{IVI}, and $\tilde{u}_i^{IVI}$, respectively, are obtained as follows:

$$\tilde{x}_{ij}^* = \left(\left[x_{ij,\mu}^{*,L}, x_{ij,\mu}^{*,L}\right], \left[x_{ij,\nu}^{*,L}, x_{ij,\nu}^{*,L}\right]\right) = \left(\left[k_j x_{ij,\mu}^L, k_j x_{ij,\mu}^U\right], \left[k_j x_{ij,\nu}^L, k_j x_{ij,\nu}^U\right]\right), \tag{22}$$

where $k_j = 4(\sum_{i=1}^m ((x_{ij,\mu}^L)^2 + (x_{ij,\mu}^U)^2 + (x_{ij,\nu}^L)^2 + (x_{ij,\nu}^U)^2))^{-\frac{1}{2}}$,

$$\tilde{y}_i^{IVI} = \left(\left[y_{i,\mu}^{IVI,L}, y_{i,\mu}^{IVI,U}\right], \left[y_{i,\nu}^{IVI,L}, y_{i,\nu}^{IVI,U}\right]\right) = \left(\left[\min\left\{\left(1 - \prod_{j=1}^g \left(1 - x_{ij,\mu}^{*,L}\right)^{w_j}\right), \left(1 - \prod_{j=g+1}^n \left(1 - x_{ij,\mu}^{*,L}\right)^{w_j}\right)\right\},\right.\right.$$
$$\left.\min\left\{\left(1 - \prod_{j=1}^g \left(1 - x_{ij,\mu}^{*,U}\right)^{w_j}\right), \left(1 - \prod_{j=g+1}^n \left(1 - x_{ij,\mu}^{*,U}\right)^{w_j}\right)\right\}\right], \left[\max\left\{\prod_{j=1}^g \left(x_{ij,\nu}^{*,L}\right)^{w_j}, \prod_{j=g+1}^n \left(x_{ij,\nu}^{*,L}\right)^{w_j}\right\},\right.$$
$$\left.\left.\max\left\{\prod_{j=1}^g \left(x_{ij,\nu}^{*,U}\right)^{w_j}, \prod_{j=g+1}^n \left(x_{ij,\nu}^{*,U}\right)^{w_j}\right\}\right]\right), \tag{23}$$

$$z_i^{IVI} = \max_j \left|\left\{\max_i \left(1 - \left(1 - x_{ij,\mu}^{*,L}\right)^{w_j}\right),\quad j \le g; \min_i\left(1 - \left(1 - x_{ij,\mu}^{*,L}\right)^{w_j}\right),\quad j > g\right\} - \left\{\min_i\left(x_{ij,\nu}^{*,L}\right)^{w_j},\quad j \le g;\right.\right.$$
$$\left.\max_i \left(x_{ij,\nu}^{*,L}\right)^{w_j},\quad j > g\right\} + \left\{\max_i \left(1 - \left(1 - x_{ij,\mu}^{*,U}\right)^{w_j}\right),\quad j \le g;\ \min_i \left(1 - \left(1 - x_{ij,\mu}^{*,U}\right)^{w_j}\right),\quad j > g\right\} \tag{24}$$
$$\left.- \left\{\min_i\left(x_{ij,\nu}^{*,U}\right)^{w_j},\quad j \le g;\ \max_i \left(x_{ij,\nu}^{*,U}\right)^{w_j},\quad j > g\right\} - \left(1 - \left(1 - x_{ij,\mu}^{*,L}\right)^{w_j}\right) + \left(x_{ij,\nu}^{*,L}\right)^{w_j} - \left(1 - \left(1 - x_{ij,\mu}^{*,U}\right)^{w_j}\right) + \left(x_{ij,\nu}^{*,U}\right)^{w_j}\right|,$$

$$\tilde{u}_i^{IVI} = \left(\left[u_{i,\mu}^{IVI,L}, u_{i,\mu}^{IVI,U}\right], \left[u_{i,\nu}^{IVI,L}, u_{i,\nu}^{IVI,U}\right]\right) = \left(\left[\min\left\{\left(g - \prod_{j=1}^{g}\left(1 - x_{ij,\mu}^{*,L}\right)^{w_j}\right), \left((n-g) - \prod_{j=g+1}^{n}\left(1 - x_{ij,\mu}^{*,L}\right)^{w_j}\right)\right\},\right.\right.$$
$$\min\left\{\left(g - \prod_{j=1}^{g}\left(1 - x_{ij,\mu}^{*,U}\right)^{w_j}\right), \left((n-g) - \prod_{j=g+1}^{n}\left(1 - x_{ij,\mu}^{*,U}\right)^{w_j}\right)\right\}\Bigg], \Bigg[\max\left\{\left(\left(\sum_{j=1}^{g}\left(x_{ij,\nu}^{*,L}\right)^{w_j}\right.\right.\right.$$
$$- \sum_{\substack{j_1<j_2 \\ j_1,j_2\in\{1,2,\dots,g\}}}\left(\left(x_{ij_1,\nu}^{*,L}\right)^{w_{j_1}}\cdot\left(x_{ij_2,\nu}^{*,L}\right)^{w_{j_2}}\right) + \cdots + (-1)^{k+1}\sum_{\substack{j_1<j_2<\cdots<j_k \\ j_1,j_2,\dots,j_k\in\{1,2,\dots,g\}}}\left(\left(x_{ij_1,\nu}^{*,L}\right)^{w_{j_1}}\cdot\left(x_{ij_2,\nu}^{*,L}\right)^{w_{j_2}}\cdot\cdots\cdot\left(x_{ij_k,\nu}^{*,L}\right)^{w_{j_k}}\right)$$
$$+\cdots+(-1)^{g+1}\left(\left(x_{i1,\nu}^{*,L}\right)^{w_{j_1}}\cdot\left(x_{i2,\nu}^{*,L}\right)^{w_{j_2}}\cdot\cdots\cdot\left(x_{ig,\nu}^{*,L}\right)^{w_g}\right)\Bigg), \left(\sum_{j=g+1}^{n}\left(x_{ij,\nu}^{*,L}\right)^{w_j} - \sum_{\substack{j_1<j_2 \\ j_1,j_2\in\{(g+1),(g+1),\dots,n\}}}\left(\left(x_{ij_1,\nu}^{*,L}\right)^{w_{j_1}}\cdot\left(x_{ij_2,\nu}^{*,L}\right)^{w_{j_2}}\right)\right.$$
$$+\cdots+(-1)^{k+1}\sum_{\substack{j_1<j_2<\cdots<j_k \\ j_1,j_2,\dots,j_k\in\{(g+1),(g+1),\dots,n\}}}\left(\left(x_{ij_1,\nu}^{*,L}\right)^{w_{j_1}}\cdot\left(x_{ij_2,\nu}^{*,L}\right)^{w_{j_2}}\cdot\cdots\cdot\left(x_{ij_k,\nu}^{*,L}\right)^{w_{j_k}}\right)$$
$$+\cdots+(-1)^{n+1}\left(\left(x_{i(g+1),\nu}^{*,L}\right)^{w_{(g+1)}}\cdot\left(x_{i(g+2),\nu}^{*,L}\right)^{w_{(g+2)}}\cdot\cdots\cdot\left(x_{in,\nu}^{*,L}\right)^{w_n}\right)\Bigg)\Bigg\}, \max\left\{\left(\left(\sum_{j=1}^{g}\left(x_{ij,\nu}^{*,U}\right)^{w_j}\right.\right.\right.$$
$$- \sum_{\substack{j_1<j_2 \\ j_1,j_2\in\{1,2,\dots,g\}}}\left(\left(x_{ij_1,\nu}^{*,U}\right)^{w_{j_1}}\cdot\left(x_{ij_2,\nu}^{*,U}\right)^{w_{j_2}}\right) + \cdots + (-1)^{k+1}\sum_{\substack{j_1<j_2<\cdots<j_k \\ j_1,j_2,\dots,j_k\in\{1,2,\dots,g\}}}\left(\left(x_{ij_1,\nu}^{*,U}\right)^{w_{j_1}}\cdot\left(x_{ij_2,\nu}^{*,U}\right)^{w_{j_2}}\cdot\cdots\cdot\left(x_{ij_k,\nu}^{*,U}\right)^{w_{j_k}}\right)$$
$$+\cdots+(-1)^{g+1}\left(\left(x_{i1,\nu}^{*,U}\right)^{w_{j_1}}\cdot\left(x_{i2,\nu}^{*,U}\right)^{w_{j_2}}\cdot\cdots\cdot\left(x_{ig,\nu}^{*,U}\right)^{w_g}\right)\Bigg), \left(\sum_{j=g+1}^{n}\left(x_{ij,\nu}^{*,U}\right)^{w_j} - \sum_{\substack{j_1<j_2 \\ j_1,j_2\in\{(g+1),(g+1),\dots,n\}}}\left(\left(x_{ij_1,\nu}^{*,U}\right)^{w_{j_1}}\cdot\left(x_{ij_2,\nu}^{*,U}\right)^{w_{j_2}}\right)\right.$$
$$+\cdots+(-1)^{k+1}\sum_{\substack{j_1<j_2<\cdots<j_k \\ j_1,j_2,\dots,j_k\in\{(g+1),(g+1),\dots,n\}}}\left(\left(x_{ij_1,\nu}^{*,U}\right)^{w_{j_1}}\cdot\left(x_{ij_2,\nu}^{*,U}\right)^{w_{j_2}}\cdot\cdots\cdot\left(x_{ij_k,\nu}^{*,U}\right)^{w_{j_k}}\right)$$
$$+\cdots+(-1)^{n+1}\left(\left(x_{i(g+1),\nu}^{*,U}\right)^{w_{(g+1)}}\cdot\left(x_{i(g+2),\nu}^{*,U}\right)^{w_{(g+2)}}\cdot\cdots\cdot\left(x_{in,\nu}^{*,U}\right)^{w_n}\right)\Bigg)\Bigg\}\Bigg]\Bigg). \tag{25}$$

3.3. Developments based on linguistic term theory

In many decision-making problems, a realistic approach is to employ linguistic evaluation instead of numerical values. The significance of linguistic decision-making can be underscored as: (1) the information may be unquantifiable and essentially by linguistic terms; (2) the precise quantitative information may not be provided due to its unavailability or the translation cost of the data may be very high [131]. Linguistic variables are not numbers but words or sentences in a natural or artificial language. Linguistic decision-making has a broad range of real-world applications in different areas such as supply chain management, personnel evaluation, medical diagnostics, and online auctions [132]. There are a variety of linguistic term sets like Interval 2-Tuple Linguistic Term set (ITLTS), Uncertain Linguistic Variable (ULV), and Two-Dimension Uncertain Linguistic Variable (TDULV). The concept of fuzzy sets and linguistic variables have been employed in a number of hybrid models of uncertain data such as Hesitant Fuzzy Linguistic Term Set (HFLTS), Unbalanced Hesitant Fuzzy Linguistic Term Set (UHFLTS), and Double Hierarchy Hesitant Fuzzy Linguistic Term Set (DHHFLTS).

2-Tuple Linguistic Term set (TLTS) was utilized in three developments [12,14,96]. In the researches, the mathematical concepts like negation operator, arithmetic average, linguistic distance, geometric average, and comparison rule of TLTSs are applied. Liu et al. [84] put forward Hesitant Fuzzy Linguistic MULTIMOORA considering transformation of HFLTSs to TLTSs, linguistic distance, and comparison rule of TLTSs. Gou et al. [58] suggested Double Hierarchy Hesitant Fuzzy Linguistic MULTIMOORA by using crisp distance and expectation function of DHHFLTSs. Unbalanced Hesitant Fuzzy Linguistic Term Set (UHFLTS) was a basis for another development considering a novel Score function based on Hesitant Degrees and Linguistic Scale Functions (Score-HeDLiSF) [59]. Liu et al. [107] introduced Interval 2-Tuple Linguistic MULTIMOORA by exploiting linguistic distance and comparison rule of ITLTSs. Probabilistic Linguistic Term Set (PLTS) was a motivation for a new model [56] in which crisp distance and expectation function of PLTSs were the governing concepts. Liu et al. [83] generated Uncertain Linguistic MULTIMOORA supported on negation operator, crisp distance, and preference degree of Uncertain Linguistic Variables (ULVs). Two-Dimension Uncertain Linguistic Variable (TDULV) was used in another extension considering negation operator, perceived-value-based expectation value of TDULVs, and regret theory [77].

We provide the derivations of the subordinate utility values of three linguistic developments of MULTIMOORA based on ITLTS, DHHFLTS, and PLTS, as follows:

- Interval 2-Tuple Linguistic MULTIMOORA

In this method, alternatives ratings are in the form of ITLTSs represented as $\tilde{x}_{ij}$=[(s_{ij}, α_{ij}), $(t_{ij}, \varepsilon_{ij})$]. The performance of one alternative on a criterion is between the 2-tuples (s_{ij}, α_{ij}) and (t_{ij}, ε_{ij}). Weighted normalization ratio $\tilde{x}_{ij}^*$ in Interval 2-Tuple Linguistic MULTIMOORA is defined as:

$$\tilde{x}_{ij}^*=\left[\left(s_{ij}^*, \alpha_{ij}^*\right), \left(t_{ij}^*, \varepsilon_{ij}^*\right)\right]=\Delta\left[w_j k_j\,\Delta^{-1}\left(s_{ij}, \alpha_{ij}\right), \; w_j k_j\,\Delta^{-1}\left(t_{ij}, \varepsilon_{ij}\right)\right], \tag{26}$$

where $k_j = (\sum_{i=1}^{m}(\Delta^{-1}(s_{ij}, \alpha_{ij}))^2 + \sum_{i=1}^{m}(\Delta^{-1}(t_{ij}, \varepsilon_{ij}))^2)^{-1/2}$ and Δ and Δ^{-1} are the translation functions as follows (let $P = \{p_1, p_2, \dots, p_h\}$ be a linguistic term set and $\beta \in [0, 1]$ a value showing the result of a symbolic aggregation operation):

$$\Delta(\beta) = \left(p_l, \delta\right), \quad \text{with } \left\{p_l,\, l = round\,(\beta\cdot h);\; \delta = \beta - l/h,\; \delta \in \left[-1/(2h), 1/(2h)\right]\right\}, \tag{27}$$

$$\Delta^{-1}\left(p_l,\ \delta\right) = (l/h+\delta) = \beta, \tag{28}$$

The utility values of interval 2-tuple linguistic models of Ratio system, Reference Point Approach, and Full Multiplicative Form, i.e., $\tilde{y}_i^{ITL}$, z_i^{ITL}, and $\tilde{u}_i^{ITL}$, respectively, are obtained as follows:

$$\tilde{y}_i^{ITL} = \left[\left(s_{ij}^y, \alpha_{ij}^y\right),\ \left(t_{ij}^y, \varepsilon_{ij}^y\right)\right] = \Delta\left[\left(\sum_{j=1}^{g}\Delta^{-1}\left(s_{ij}^*, \alpha_{ij}^*\right) - \sum_{j=g+1}^{n}\Delta^{-1}\left(t_{ij}^*, \varepsilon_{ij}^*\right)\right),\ \left(\sum_{j=1}^{g}\Delta^{-1}\left(t_{ij}^*, \varepsilon_{ij}^*\right) - \sum_{j=g+1}^{n}\Delta^{-1}\left(s_{ij}^*, \alpha_{ij}^*\right)\right)\right], \tag{29}$$

$$z_i^{ITL} = \max_j\ d\left(\tilde{r}_j,\ \tilde{x}_{ij}^*\right) = \Delta\left[\max\left(\left|\Delta^{-1}\left(s_{ij}^*, \alpha_{ij}^*\right) - \Delta^{-1}\left(r_j,\ \gamma_j\right)\right|,\ \left|\Delta^{-1}\left(t_{ij}^*, \varepsilon_{ij}^*\right) - \Delta^{-1}\left(r_j,\ \gamma_j\right)\right|\right)\right], \tag{30}$$

where $\tilde{r}_j = [(r_j,\ \gamma_j)] = \{\max_i\{(t_{ij}^*, \varepsilon_{ij}^*)\},\ j \le g;\ \ \min_i\{(s_{ij}^*, \alpha_{ij}^*)\},\ j > g\}$,

$$\tilde{u}_i^{ITL} = \left[\left(s_{ij}^u, \alpha_{ij}^u\right),\ \left(t_{ij}^u, \varepsilon_{ij}^u\right)\right] = \Delta\left[\left(\prod\nolimits_{j=1}^{g}\Delta^{-1}\left(s_{ij}^*, \alpha_{ij}^*\right)/\prod\nolimits_{j=g+1}^{n}\Delta^{-1}\left(t_{ij}^*, \varepsilon_{ij}^*\right)\right),\ \left(\prod\nolimits_{j=1}^{g}\Delta^{-1}\left(t_{ij}^*, \varepsilon_{ij}^*\right)/\prod\nolimits_{j=g+1}^{n}\Delta^{-1}\left(s_{ij}^*, \alpha_{ij}^*\right)\right)\right]. \tag{31}$$

- Double Hierarchy Hesitant Fuzzy Linguistic MULTIMOORA

In this technique, alternatives ratings are in the form of DHHFLTSs represented as $h_{S_O}^{ij} = \{(S_{\phi_l < O_{\varphi_l}>})_{ij} \mid S_{\phi_l < O_{\varphi_l}>} \in S_O;\ l = 1,\ 2,\ \dots,\ L\}$where L is the number of double hierarchy linguistic terms in $h_{S_O}^{ij}$ and $(S_{\phi_l < O_{\varphi_l}>})_{ij}$ in each $h_{S_{O_{ij}}}$ are continuous linguistic terms in S_O, i.e., double hierarchy linguistic term set. Normalization ratio $h_{S_O}^{*,ij}$ in Double Hierarchy Hesitant Fuzzy Linguistic MULTIMOORA is presented as:

$$h_{S_O}^{*,ij} = E\left(h_{S_O}^{ij}\right)/\sum_{i=1}^{m}E\left(h_{S_O}^{ij}\right), \tag{32}$$

where $E(h_{S_O}^{ij})$ is the expected value of $h_{S_O}^{ij}$and defined as $E(h_{S_{O_{ij}}}) = \frac{1}{L}\sum_{l=1}^{L}F((S_{\phi_l < O_{\varphi_l}>})_{ij})$ with transformation function F from double hierarchy hesitant fuzzy linguistic to hesitant fuzzy alternative ratings. The utility values of double hierarchy hesitant fuzzy linguistic models of Ratio system, Reference Point Approach, and Full Multiplicative Form, i.e., y_i^{DHHFL}, z_i^{DHHFL}, and u_i^{DHHFL}, respectively, are obtained as follows:

$$y_i^{DHHFL} = \sum_{j=1}^{g}h_{S_O}^{*,ij} - \sum_{j=g+1}^{n}h_{S_O}^{*,ij}, \tag{33}$$

$$z_i^{DHHFL} = \max_j\ d\left(h_{S_O}^{j+},\ h_{S_O}^{*,ij}\right) = \max_j\ \sqrt{\frac{1}{L}\sum_{l=1}^{L}\left(\eta_1^l - \eta_2^l\right)^2};\ \ \eta_1 \in F\left(h_{S_O}^{j+}\right),\ \ \eta_2 \in F\left(h_{S_O}^{*,ij}\right), \tag{34}$$

where $h_{S_O}^{j+} = \{\max_i\ h_{S_O}^{*,ij},\ j \le g;\ \ \min_i\ h_{S_O}^{*,ij},\ j > g\}$,

$$u_i^{DHHFL} = \prod_{j=1}^{g}h_{S_O}^{*,ij}/\prod_{j=g+1}^{n}h_{S_O}^{*,ij}. \tag{35}$$

- Probabilistic Linguistic MULTIMOORA

In this method, alternatives ratings are in the form of PLTSs represented as $h_S^{ij}(p) = \{s^{ij(l)}(p^{(l)}) \mid s^{ij(l)} \in S,\ p^{(l)} \ge 0;\ l = 1,\ 2,\ \dots,\ L,\ \sum_{l=1}^{L}p^{(l)} \le 1\}$ where $s^{ij(l)}(p^{(l)})$ is the lth linguistic term $s^{ij(l)}$ with the probability $p^{(l)}$, L is the number of linguistic terms in $h_S^{ij}(p)$. Normalization ratio $h_S^{*,ij}(p)$ in Probabilistic Linguistic MULTIMOORA is introduced as:

$$h_S^{*,ij}(p) = E\left(h_S^{ij}(p)\right)/\sqrt{\sum_{i=1}^{m}\left[E\left(h_S^{ij}(p)\right)\right]^2}, \tag{36}$$

where $E(h_S^{ij}(p))$ is the expected value of $h_S^{ij}(p)$. For $h_S(p)$, we have $E(h_S(p)) = \sum_{l=1}^{L}(\frac{\alpha^{(l)}+\tau}{2\tau}p^{(l)})/\sum_{l=1}^{L}p^{(l)}$ with $\alpha^{(l)}$ being the subscript of the linguistic term $s_\alpha^{(l)}$, $\alpha = -\tau,\ \dots,\ -1,\ 0,\ 1,\ \dots,\ \tau$. The utility values of probabilistic linguistic models of Ratio system, Reference Point Approach, and Full Multiplicative Form, i.e., y_i^{PL}, z_i^{PL}, and u_i^{PL}, respectively, are obtained as follows:

$$y_i^{PL} = \sum_{j=1}^{g}w_j h_{S_O}^{*,ij} - \sum_{j=g+1}^{n}w_j h_{S_O}^{*,ij}, \tag{37}$$

$$z_i^{PL} = \max_j\ \left\{w_j\left[d\left(h_S^{j+}(p),\ h_S^{ij}(p)\right)/d\left(h_S^{j-}(p),\ h_S^{j+}(p)\right)\right]\right\}, \tag{38}$$

where $h_S^{j+}(p) = \{\max_i\ \{h_S^{ij}(p)\},\ j \le g;\ \ \min_i\ \{h_S^{ij}(p)\},\ j > g\}$, $h_S^{j-}(p) = \{\min_i\ \{h_S^{ij}(p)\},\ j \le g;\ \ \max_i\ \{h_S^{ij}(p)\},\ j > g\}$ and d is distance function of probabilistic linguistic terms and can be defined based on different concepts.

$$u_i^{PL} = \sqrt[g]{\prod_{j=1}^{g}\left(1 - \left(1 - h_S^{*,ij}(p)\right)^{w_j}\right)}/\sqrt[n-g]{\prod_{j=g+1}^{n}\left(1 - \left(1 - h_S^{*,ij}(p)\right)^{w_j}\right)}. \tag{39}$$

3.4. Development based on neutrosophic set theory

Neutrosophic Sets (NSs), suggested by Smarandache [133] in 1998, are the extensions of Intuitionistic Fuzzy Sets (IFSs). The word "neutrosophy" means "the knowledge of neutral thought" which is the main distinction between fuzzy and intuitionistic fuzzy. NSs are defined based on membership (i.e., truth-membership), indeterminacy membership, and non-membership (i.e., falsity-membership) functions. Indeterminacy is independent of truth and falsity values. No constraints exist between the degree of truth, indeterminacy, and falsity [134]. Some applications of NSs include conflict resolution, decision-making, education, medical diagnosis, image processing, social problem, and robotics [135]. Various types of NS extensions exist, such as Single-Valued Neutrosophic Set (SVNS), Interval-Valued Neutrosophic set (IVNS), and Neutrosophic Soft Set (NSS) [136]. There are some combined sets based on Linguistic and Neutrosophic Theories like Linguistic Neutrosophic Number (LNN) and Simplified Neutrosophic Linguistic Set (SNLS).

Five studies have utilized the theory of NSs to produce extensions of MULTIMOORA. Liang et al. [73] developed an MULTIMOORA extension based on LNN employing the improved generalized weighted Heronian mean operator, the generalized distance, score function of LNNs, and the improved generalized geometric weighted Heronian mean operator. Tian et al. [72] suggested Simplified Neutrosophic Linguistic MULTIMOORA based on the normalized weighted Bonferroni mean, the normalized geometric weighted Bonferroni mean, besides crisp distance and score function of SNLSs. Zavadskas et al. [31] introduced Single-Valued Neutrosophic MULTIMOORA supported on the concepts of crisp distance of SVNSs and score function of SVNSs. The model is further developed by considering the weighted average operator, the weighted geometric operator, and crisp maximum distance of SVNSs [36,76]. As SVNS has been used more than the other types of NSs in the literature, we present the formulation of its combination with MULTIMOORA model as follows.

In Single-Valued Neutrosophic MULTIMOORA, alternatives ratings are in the form of SVNSs shown as $\tilde{x}_{ij} = (x_{ij,T},\ x_{ij,I},\ x_{ij,F})$ where $x_{ij,T}$, $x_{ij,I}$, and $x_{ij,F}$ are terms based on truth-membership, indeterminacy-membership, and falsity-membership functions, respectively. $\tilde{x}_{ij}$ is supposed to be comparable with values between 0 and 1; thus, normalization is not needed. The utility values of neutrosophic models of Ratio system, Reference Point Approach, and Full Multiplicative Form, i.e., y_i^N, z_i^N, and u_i^N, respectively, are obtained as follows:

$$\begin{aligned} y_i^N = &\left(2 - \prod_{j=1}^{g}\left(1 - x_{ij,T}\right)^{w_j} - 2\prod_{j=1}^{g}\left(x_{ij,I}\right)^{w_j} - \prod_{j=1}^{g}\left(x_{ij,F}\right)^{w_j}\right)/2 \\ &-\left(2 - \prod_{j=g+1}^{n}\left(1 - x_{ij,T}\right)^{w_j} - 2\prod_{j=g+1}^{n}\left(x_{ij,I}\right)^{w_j} - \prod_{j=g+1}^{n}\left(x_{ij,F}\right)^{w_j}\right)/2, \end{aligned} \tag{40}$$

$$z_i^N = \max_j\ d_{\max}\left(w_j\tilde{r}_j,\ w_j\tilde{x}_{ij}\right) = \max_j\left(w_j.\left\{\left|r_{j,T} - x_{ij,T}\right|,\quad j \le g;\quad \left|r_{j,F} - x_{ij,F}\right|,\quad j \le g\right\}\right), \tag{41}$$

where $\tilde{r}_j = (r_{j,T},\ r_{j,I},\ r_{j,F}) = \{(\max_i x_{ij,T},\ \max_i x_{ij,I},\ \max_i x_{ij,F}),\ j \le g;\ \ (\min_i x_{ij,T},\ \min_i x_{ij,I},\ \min_i x_{ij,F}),\ j > g\}$,

$$\begin{aligned} u_i^N = &\left\{\left(-2 + \prod_{j=1}^{g}\left(x_{ij,T}\right)^{w_j} + 2\prod_{j=1}^{g}\left(1 - x_{ij,I}\right)^{w_j} + \prod_{j=1}^{g}\left(1 - x_{ij,F}\right)^{w_j}\right)/2\right\} \\ &/\left\{\left(-2 + \prod_{j=g+1}^{n}\left(x_{ij,T}\right)^{w_j} + 2\prod_{j=g+1}^{n}\left(1 - x_{ij,I}\right)^{w_j} + \prod_{j=g+1}^{n}\left(1 - x_{ij,F}\right)^{w_j}\right)/2\right\}. \end{aligned} \tag{42}$$

3.5. Development based on rough Set, Z-number, and cloud theories

Rough Set Theory was introduced by Pawlak [137] (in 1982) to interpret uncertainty in different way comparing the previous theories such as Fuzzy Set Theory. Rough Set Theory is not focused on obtaining membership of an uncertain value. In fact, the theory presents a new idea in the context of uncertainty concepts which is "indiscernibility." It related to our perception about elements of the universe. In real life, two various elements can be "seen" as the same although they are essentially different. That is, the elements are "indiscernible" according to the information that can be perceived from them [138]. Rough Set Theory is helpful for many practical problems such as knowledge acquisition, expert systems, machine learning, pattern recognition, and medical diagnostics applications [139]. Two studies have developed Rough MULTIMOORA models [3,92].

Z-number (ZN) was proposed by Zadeh [140] (in 1998) to provide the "reliability" of information which is one of the limits of traditional fuzzy numbers. Typically, a ZN has two components, i.e., $Z = (A,\ B)$, in which A is a constraint on the values of a real-valued uncertain variable and B is an indicator for the degree of reliability of A. Normally, A and B are expressed using natural language. ZNs are beneficial for application in many areas including risk evaluation, decision-making, economics, and prediction [57]. ZNs can be transformed to classical fuzzy numbers [141]. Peng and Wang [57] introduced Z-MULTIMOORA. For the model, first, it is needed that ZNs are translated into normal Z^+-values. The following key features of Z^+-values were used in the development: generalized normal power weighted average operator, crisp distance rule, normal power weighted geometric operator, and closeness coefficient inspired by TOPSIS.

Cloud Model, suggested by Li et al. [142] in 2009, considers the "randomness" of data besides its fuzziness. By considering probability theory and fuzzy sets, Cloud Model provides a new way of cognition of uncertainty [62]. Randomness and fuzziness are significant uncertainties inherent in human cognition necessary to be tackled in artificial intelligence research. By using a generalized normal distribution with weak constraints, Cloud Model is adaptive for description of uncertainty embodied in linguistic concepts. The model avoids quantifying the membership degree of an element as an accurate value as it is usual in Fuzzy Set Theory [142]. Clouds has been employed in various applications like tunneling excavation technology, wind farm site selection, healthcare waste treatment, and efficiency of energy consumption. Wu el al. [62] formulated Cloud MULTIMOORA using negation operator, crisp distance, and comparison rule of clouds.

3.6. Statistical evaluation of MULTIMOORA uncertain developments

Table 6 scrutinizes the frequencies of uncertainty theories employed for extensions of MULTIMOORA. With no surprise, Fuzzy Set Theory has been used more than the other uncertainty theories. Interval Number and Linguistic Set Theories have the subsequent ranks of the table with near the same utilization frequencies. Also, they have often been employed in a combined mode together with other uncertainty theories as aforementioned in previous sections.

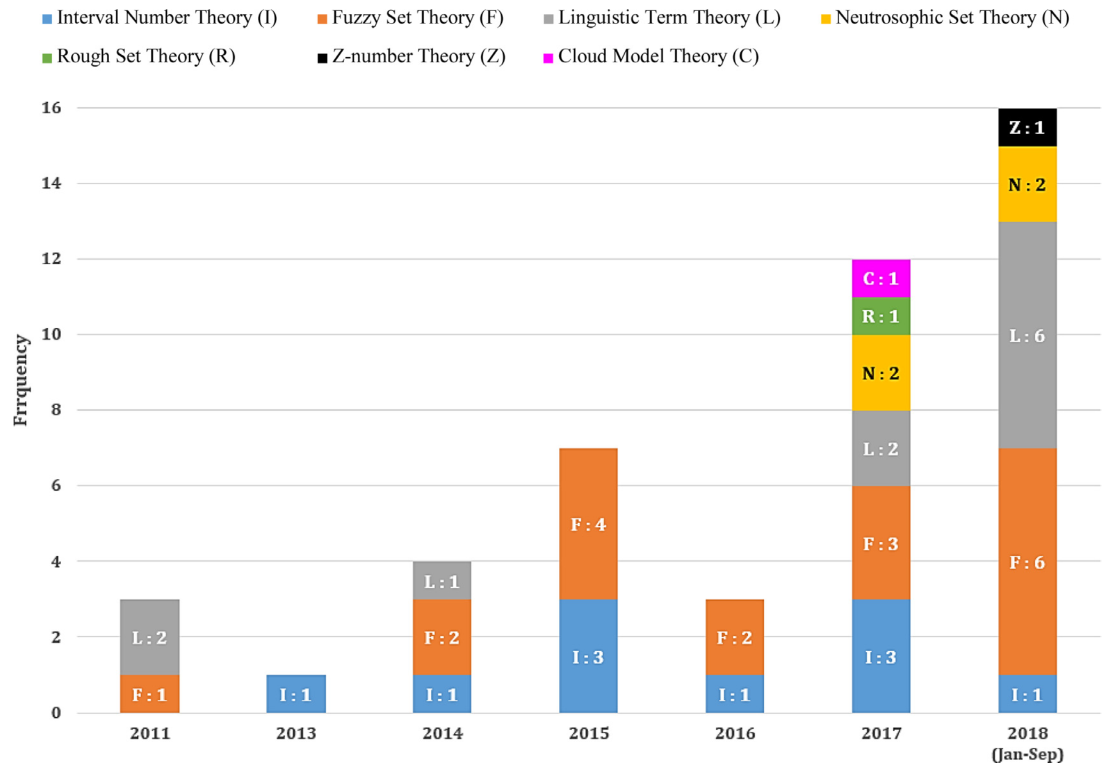

Fig. 5. Timeline of uncertainty theories.

Table 6
Distribution of uncertainty theories.

Uncertainty theory	Frequency	Percentage frequency	Reference(s)
Fuzzy set theory	39	36.8	[14,16,41,42,44,48,54,55,58,59,63,69,17,70,71,74,78-80,84,85,87,88,18,91,93,94,97,98,103,106,108,114,19,25,26,32,34,40]
Interval number theory	13	12.2	[33,38,103,107,108,40,44,46,54,60,70,78,97]
Linguistic term theory	12	11.3	[12,14,96,107,56,58,59,72,73,77,83,84]
Neutrosophic set theory	5	4.7	[31,36,72,73,76]
Rough set theory	2	1.9	[3,92]
Cloud model theory	1	0.9	[62]
Z-number theory	1	0.9	[57]

Table 7
Distribution of uncertainty sets (items with frequency ≥ 3).

Uncertainty set	Frequency	Percentage frequency	Reference(s)
Triangular Fuzzy Number (TFN)	20	18.9	[14,19,69,71,79,80,85,87,91,93,98,114,25,26,34,41,42,48,55,63]
Interval Number (IN)	4	3.8	[33,38,60,108]
Generalized Interval-Valued Fuzzy Number (GIVFN)	4	3.8	[54,97,103,108]
Trapezoidal Fuzzy Number (TrFN)	4	3.8	[32,74,88,94]
2-Tuple Linguistic Term set (TLTS)	3	2.9	[12,14,96]
Single-Valued Neutrosophic Set (SVNS)	3	2.9	[31,36,76]

Fig. 5 displays an overall upward trend in the employment of uncertainty theories with passing of time; however, there is a modest fall in 2016. In 2017, it was the beginning of utilization of Cloud Model, Rough Set, and Neutrosophic Term Theories in modeling uncertain MULTIMOORA followed by an extensive investigation into uncertainty theories, in 2018, besides unveiling Z-MULTIMOORA. Interval Number and Fuzzy Set Theories are nearly employed in all the years; however, there is a rugged trend in exploitation of Linguistic Term Theory.

The frequencies of studies on uncertainty sets are collected in Table 7. TFN which is the simplest type of fuzzy numbers has the most application in the uncertain developments of MULTIMOORA. The table shows that simpler uncertainty sets have been exploited more frequently by researchers.

3.7. Graphical summary of MULTIMOORA uncertain developments

As Fig. 6 shows, there are various uncertainty theories used to develop extensions of MULTIMOORA. The first circle illustrates seven uncertainty theories (i.e., Interval Number, Fuzzy Set, Linguistic Term, Neutrosophic Set, Z-number, Rough Set, and Cloud Model Theories)

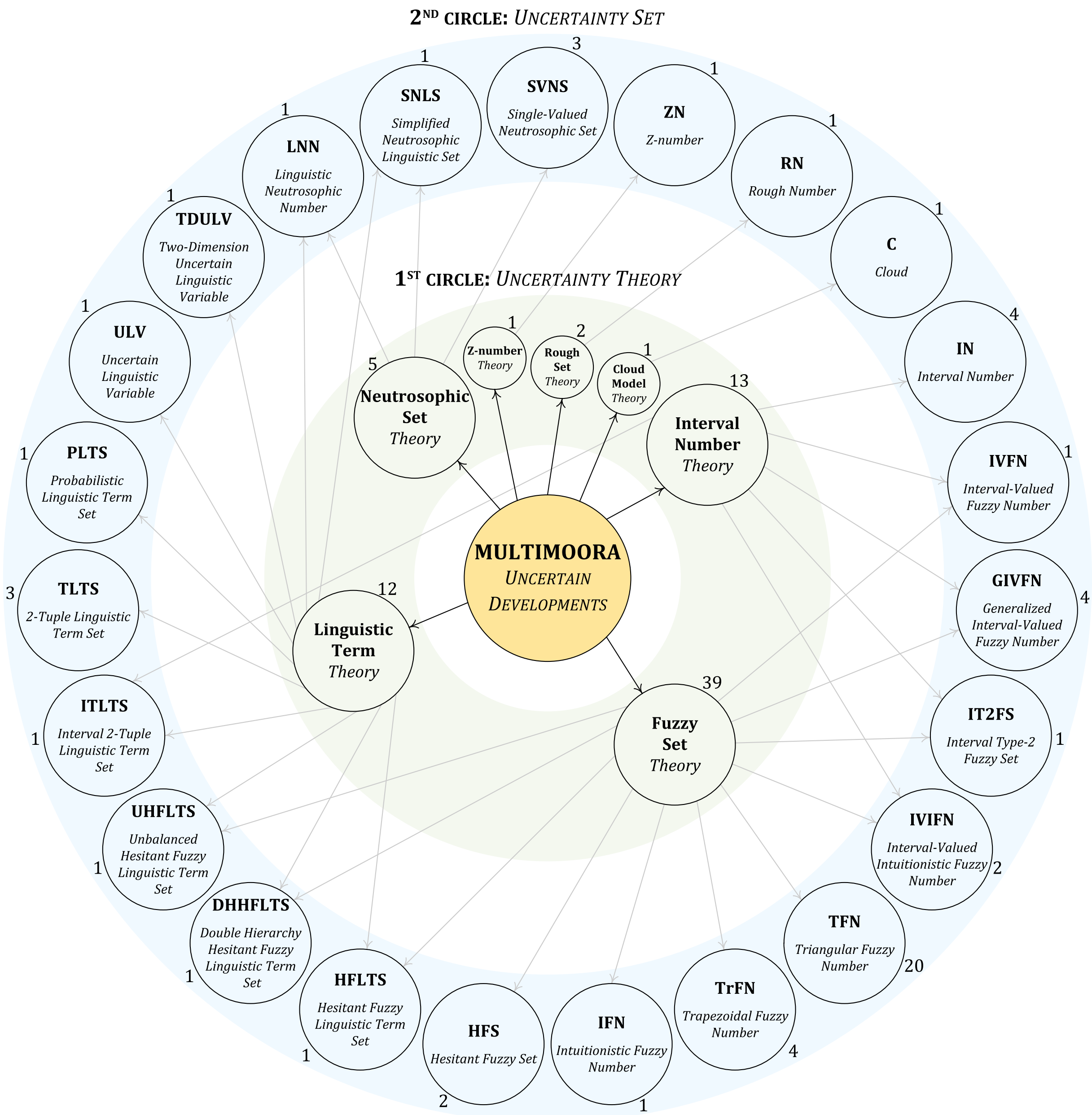

Fig. 6. Infographics of MULTIMOORA uncertain developments. (numerals represent the frequencies).

which are the sources of uncertainty sets of the second circles. Some sets originate from more than one theory. Furthermore, this figure provides the frequencies of utilization of the uncertainty theories and sets.

In the first circle, Fuzzy Set Theory has the most frequency 39 and Z-number and Cloud Model Theories have the minimum frequency 1. Interval Number and Linguistic Term Theories are also important in MULTIMORA uncertain developments which have frequencies 13 and 12, respectively. In the second circle, TFN is the mostly used uncertainty set with frequency 20. The important unmixed sets which are only based on one uncertainty theory include: IN (with frequency 4), TrFN (with frequency 4), TLTS (with frequency 3), and SVNS (with frequency 3). From the category of hybrid sets which are based on two uncertainty theories GIVFN has the most exploitation in MULTIMORA uncertain models with frequency 4. There are some sets that have high-degree of uncertainty, including: HFLTS, DHHFLTS, UHFLTS, and TDULV.

4. Analysis of the applications of MULTIMOORA

In this section, the applications of MULTIMOORA are discussed. Section 4.1 presents the applications of MULTIMOORA in the field of Industries which is the most frequent applications of the MCDM technique. Section 4.2 goes through the problems in the area of Economics. The applications related to Civil Services and Environmental Policy-Making are described in Section 4.3. Medical/Healthcare Management and Information and Communications Technologies (ICT) applications are depicted in Section 4.4. In Section 4.5, all practical problems of MULTIMOORA are evaluated statistically by discussing the distribution based on application sectors and subsectors as well as case studies besides illustrating the timeline of application types. Eventually, Section 4.6 encapsulates this section by presenting an infographics of MULTIMOORA applications. In Appendix, Table A.7 lists some MULTIMOORA applications in miscellaneous areas.

4.1. Applications in the sector of industries

The applications of MULTIMOORA in the sector of Industries are divided into the following subsectors: Construction, Automotive, Agricultural, Mining, Entertainment, Logistics, Steel, Aviation, Beverage, Carpentry, Energy, Ship-Building, and Textile Industries, besides Manufacturing System. In Construction Industry subsector, there are several case studies related to Buildings Revitalization Appraisal [70], Project Management [78,102], and Ranking Countries/Cities/Regions [61] besides the selection of Investment [70], Component [31,66], Design [15,51,60], Material [31], Supplier [92], and Technology [110]. In Automotive Industry subsector, there are multiple case studies related to Battery Recycling Mode Selection [77] and Location Planning [83] as well as the selection of Material [39,94], Robot [84], Supplier [89], and Vehicle [62,67,95]. In Agricultural Industry subsector, the case studies include Farming Efficiency Estimation [114] and the selection of Crop [26], Machine [81], and Supplier [74]. In Mining Industry subsector, there exist four case studies related to Design Selection [36,44], Mining Technique Selection [73], and Personnel Management [101]. In Entertainment Industry subsector, two case studies exist concerning Company/Industrial Group Selection [56] and Device Selection [76]. In Logistics Industry subsector, two case studies have considered the problems regarding Partner Selection [85] and Transportation Efficiency Evaluation [113]. In Manufacturing System subsector, the practical cases are Enterprise Resource Planning [72] and the selection of Design [47], Machine [33,97], and Material [39,46]. In Steel Industry subsector, two researches exist in respect to Risk Evaluation [40,80].

For other subsectors of Industries sector, there is only one case study. Dorfeshan et al. [78] evaluated a project management problem in the area aircraft component development planning. Çebi and Otay [93] tackled a supplier selection problem in a company operating in beverage industry. Stojić et al. [3] assessed selection process of supplier for a PVC carpentry manufacturing company. Hafezalkotob and Hafezalkotob [88] handled material selection process for the blades of industrial gas turbine. Qin and Liu [96] chose a suitable supplier for purchasing components of ship equipment. Brauers and Zavadskas [29] undertook a project management problem for Tunisian textile industry.

4.2. Applications in the sector of economics

The applications of MULTIMOORA in the sector of Economics are divided into the following subsectors: Sustainable Development, Economic Growth, Banking System, and Stock Exchange. In Sustainable Development subsector, there are several case studies related to Ranking Countries/Cities/Regions, Facility Management, and Energy Management. Five studies measured the performance of the European Union countries with respect to the goals of the Lisbon Strategy 2000–2008 [19,20,28,50,112]. Two researches evaluated the level of preparation of European Union countries for Europe 2020 targets [21,109]. Lazauskas et al. [30] ranked several cities for the development of sustainable construction. Stankevičienė and Rosov [52] evaluated the public debt risks of European Union member states in 2005–2010 considering structural indicators. Baležentis et al. [115] assessed European Union member states according to well-being level. Stankevičienė et al. [53] analyzed the country risk besides economic sustainability and security in European Union Baltic Sea region countries. Brauers et al. [86] examined the preference of alternatives of the facilities sector in Lithuania. Streimikiene et al. [27] tackled a problem about sustainable electricity production technologies.

In Economic Growth subsector, there exist four case studies related to Ranking Countries/Cities/Regions and Economic Evaluation. Brauers and Zavadskas [45] compared 27 European Union countries according to economic growth. Baležentis et al. [22] appraised economic sectors in Lithuania with respect to indicators of efficiency and productivity. Brauers and Zavadskas [43] dealt with economic scenarios for an optimal Input-output structure in Tanzania. Brauers and Ginevičius [65] scrutinized economic scenarios in Belgian regions. In Banking System subsector, four case studies have tackled the problems concerning Ranking Countries/Cities/Regions, Ranking Banks, and Bank Loan Evaluation. Önay [90] assessed Turkey' Regions according to the performance of banks. There are two researches into ranking banks in Lithuania [104,105]. Brauers and Zavadskas [143] handled a problem regarding bank loans from different banks to purchase property in Lithuania. In Stock Exchange subsector, two case studies have dealt with the decision-making about investment in Belgian shares based on BEL20® index (i.e., the benchmark stock market index of Euronext Brussels) [64,99].

4.3. Applications in the sector of civil services and environmental policy-making

For this sector, there are two subsectors: Environmental Policy-Making and Bike-Sharing Program. In Environmental Policy-Making subsector, there are several case studies related to Climate Change Policy-Making, Ranking Countries/Cities/Regions, Ranking Countries/Cities/Regions, Supplier Selection, Warehouse Selection, and Warehouse Selection. Streimikiene and Baležentis [24] analyzed climate change mitigation measures in Lithuania. Gou et al. [58] assessed China cities with respect to air pollution control measures for treating haze. Peng and Wang [57] tackled the practical problem of air pollution potential evaluation in Chengdu, China. Sen et al. [91] dealt with the problem of suppliers' appraisement according to environmental issues. Sezer [98] evaluated the alternatives of warehouse for hazardous materials. Chen et al. [41] appraised the candidates of wastewater treatment. In Bike-Sharing Program subsector, there exist three case studies related to Investment Selection, Location Planning, and Service Selection. Tian et al. [69] conducted a study on the performance of bike-sharing services in Changsha, China. Kabak et al. [68] examined the priorities of bike-share stations in Izmir, Turkey. Liao et al. [59] assessed an investment problem in shared-bikes service in China.

4.4. Applications in the sectors of medical/healthcare management and ICT

The applications of MULTIMOORA in the sector of Medical/Healthcare Management are divided into the following subsectors: Medical Service, Biomedical Service, and Health-Care Management. In Medical Service subsector, there is one case study related to pharmacological selection of type 2 diabetes [79]. In Biomedical Service subsector, two studies has conducted on the selection process of biomaterials for hip and knee surgical prostheses [38,100]. In Health-Care Management subsector, three case studies have handled Risk Evaluation and Waste Management. Liu et al. [32] used the concept of failure mode and effects analysis to prevent infant abduction from hospitals. Two researched analyzed the treatment technologies regarding health-care waste management in Shanghai, China [25,107].

The applications of MULTIMOORA in the sector of ICT are divided into two subsectors: Information System and Telecommunication System. Li [106] tackled a software selection problem concerning a computer center at a university. Aytaç Adalı and Tuş Işık [37] addressed a problem about suitable laptops for administrative affairs. Three studies have been undertaken on choosing a manager for research and development department of a telecommunication company [16,18,54].

4.5. Statistical evaluation of MULTIMOORA applications

Fig. 7 exhibits the percentages of application sectors of MULTIMOORA as a pie-chart besides providing the related frequencies and references in its legend. MULTIMOORA has mostly been utilized for Industrial and Economic application sectors with frequency percentages 41 and 22, respectively. Medical/Healthcare Management as well as Information and Communications Technologies application sectors have the minimum frequency percentages 6 and 5, respectively.

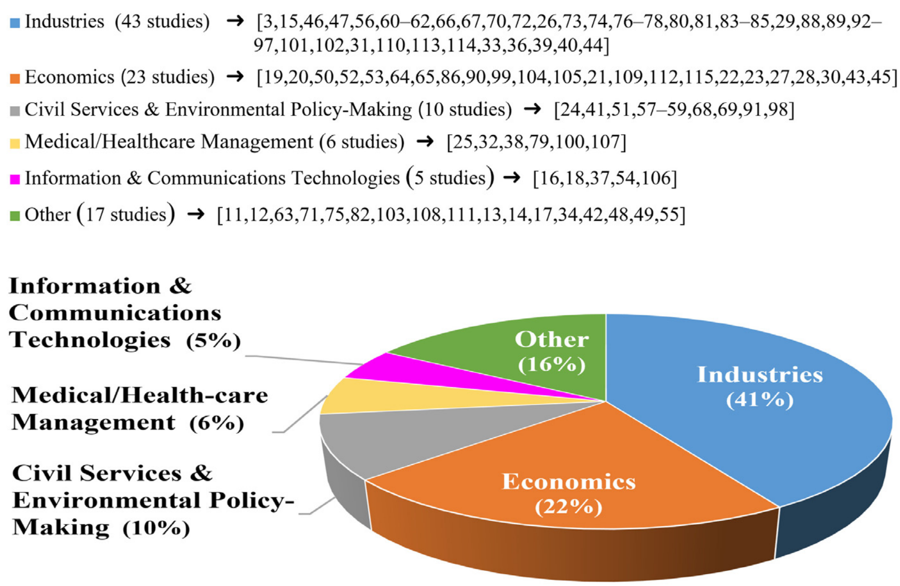

Fig. 7. Distribution of application sectors.

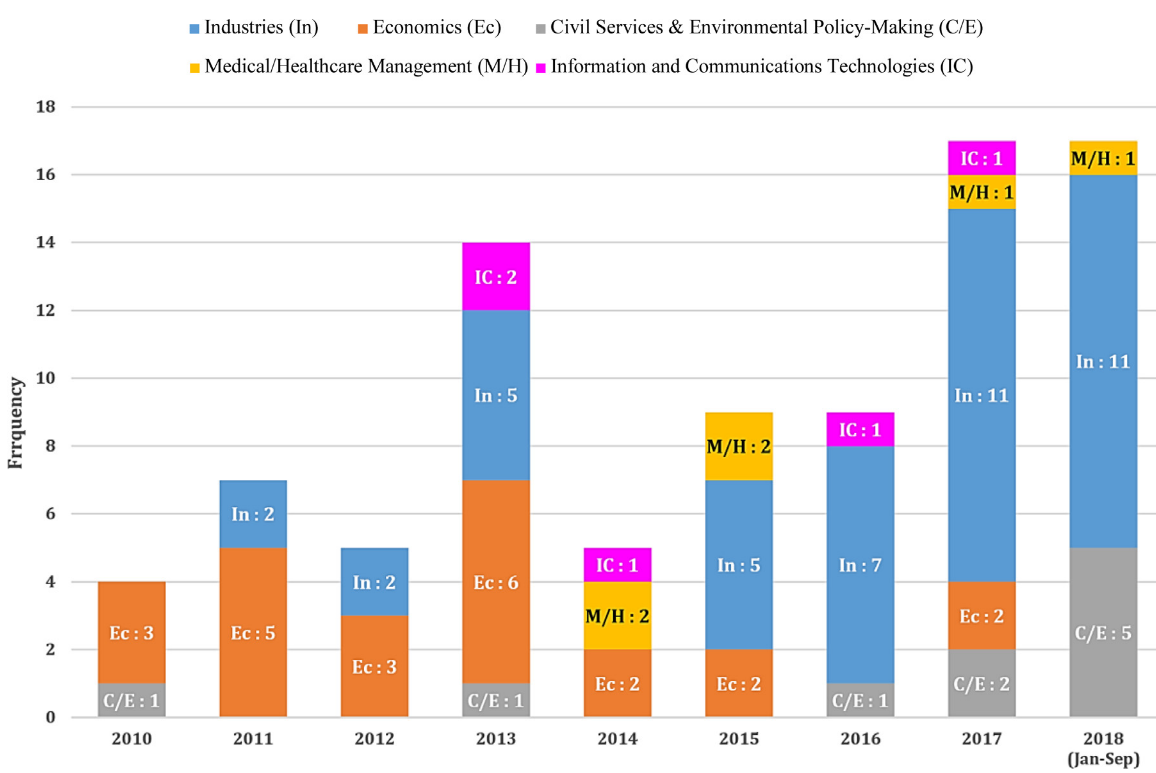

Fig. 8. Timeline of application sectors.

Fig. 8 illustrates the timeline of application sectors of MULTIMOORA. From the figure, it can be perceived that there is a upward trend in the frequencies of applications with passing time except the case of year 2013 to 2014. The other point is the gradual decrease in the amount of works in the field of Economics; instead, the area of Industries grabs more attention from researchers in the recent years. The application sector regarding Civil Services & Environmental Policy-Making is rarely employed in period 2010–17; however, it has been considered markedly in 2018 with frequency 5. From 2013 onward, Medical/Healthcare Management as well as Information and Communications Technologies application sectors have been used with a low frequency rate.

The frequency of works in different application subsectors are sorted in Table 8. Sustainable Development, Construction Industry, and Automotive Industry (with frequencies 13, 11, and 9, respectively) totally have more than a one-third share of all items of application subsectors.

The frequency of studies in various case studies are shown in Table 9. Ranking Countries/Cities/Regions, Supplier Selection, and Personnel management (with frequencies 16, 11, and 8, respectively) together have a one-third share of all items of case studies.

Table 8
Distribution of application subsectors.

Application subsector	Frequency	Percentage frequency	Reference(s)
Sustainable development	13	12.3	[19,20,109,112,115,21,27,28,30,50,52,53,86]
Construction industry	11	10.4	[15,31,110,60,61,66,70,78,89,92,102]
Automotive industry	9	8.5	[39,51,62,67,77,83,84,94,95]
Environmental policy-making	6	5.7	[24,41,57,58,91,98]
Manufacturing system	6	5.7	[33,39,46,47,72,97]
Agricultural industry	4	3.8	[26,74,81,114]
Banking system	4	3.8	[23,90,104,105]
Economic growth	4	3.8	[22,43,45,65]
Mining industry	4	3.8	[36,44,73,101]
Bike-sharing program	3	2.8	[59,68,69]
Healthcare management	3	2.8	[25,32,107]
Telecommunication sector	3	2.8	[16,18,54]
Biomedical service	2	1.9	[38,100]
Entertainment industry	2	1.9	[56,76]
Information system	2	1.9	[37,106]
Logistics industry	2	1.9	[85,113]
Steel industry	2	1.9	[40,80]
Stock exchange	2	1.9	[64,99]
Aviation industry	1	0.9	[78]
Beverage industry	1	0.9	[93]
Carpentry industry	1	0.9	[3]
Energy industry	1	0.9	[88]
Medical service	1	0.9	[79]
Ship-building industry	1	0.9	[96]
Textile industry	1	0.9	[29]

Table 9
Distribution of case studies.

Case study	Frequency	Percentage frequency	Reference(s)
Ranking countries/cities/regions	16	15.1	[19,20,58,61,90,109,112,115,21,28,30,45,50,52,53,57]
Supplier selection	11	10.4	[3,12,103,14,49,74,89,91-93,96]
Personnel management	8	7.5	[16–18,34,54,55,82,101]
Material selection	7	6.6	[31,38,39,46,88,94,100]
Design selection	6	5.7	[15,36,44,47,51,60]
Investment selection	6	5.7	[42,59,64,70,71,99]
Project management	6	5.7	[11,13,29,78,102,111]
Risk evaluation	4	3.8	[32,40,48,80]
Economic evaluation	3	2.8	[22,43,65]
Machine selection	3	2.8	[33,81,97]
Vehicle selection	3	2.8	[62,67,95]
Company industrial group selection	2	1.9	[56,108]
Component selection	2	1.9	[31,66]
Device selection	2	1.9	[37,76]
Location planning	2	1.9	[68,83]
Partner selection	2	1.9	[85,103]
Ranking banks	2	1.9	[104,105]
Waste management	2	1.9	[25,107]
Bank loan evaluation	1	0.9	[23]
Battery recycling-mode selection	1	0.9	[77]
Buildings revitalization appraisal	1	0.9	[70]
Climate change policy-making	1	0.9	[24]
Crop selection	1	0.9	[66]
Energy management	1	0.9	[26]
Enterprise resource planning	1	0.9	[27]
Facility management	1	0.9	[72]
Farming efficiency estimation	1	0.9	[86]
Fuel selection	1	0.9	[114]
Mining technique selection	1	0.9	[75]
Robot selection	1	0.9	[31]
Service selection	1	0.9	[73]
Software selection	1	0.9	[85]
Student selection	1	0.9	[84]
Technology selection	1	0.9	[69]
Therapy selection	1	0.9	[106]
Transportation efficiency evaluation	1	0.9	[63]
Warehouse selection	1	0.9	[103]
Wastewater treatment	1	0.9	[110]

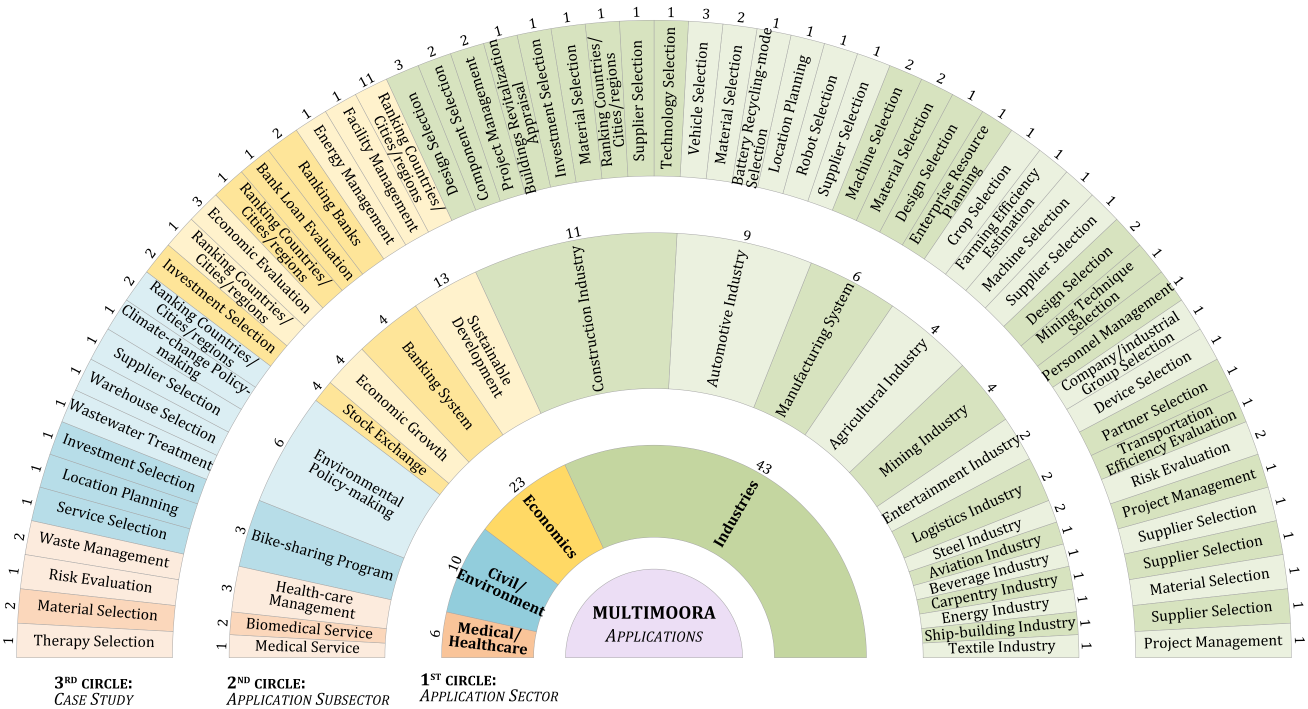

Fig. 9. Infographics of MULTIMOORA applications (numerals represent the frequencies; items with frequency of application sectors ≥ 6).

4.6. Graphical summary of MULTIMOORA applications

Fig. 9 demonstrates a multi-level categorization of MULTIMOORA applications. The first circle includes the application sectors: Industries, Economics, Civil Services & Environmental Policy-Making, and Medical/Healthcare Management (the application sector regarding Information and Communications Technologies is omitted from Fig. 9 due to its low frequencies). Each application sector is then expanded in the second and third circles of categorization to include application subsectors and the related case studies, respectively. The frequencies of items in the circles are also mentioned in the figure.

Industries Sector (with frequency 43) has 14 application subsectors including: Construction, Automotive, Agricultural, Mining, Entertainment, Logistics, Steel, Aviation, Beverage, Carpentry, Energy, Ship-Building, and Textile Industries as well as Manufacturing System. The mostly utilized application subsectors from the category of Industries, are Construction Industry and Automotive Industry with frequencies 11 and 9, respectively. Economics Sector (with frequency 23) has 4 application subsectors including: Sustainable Development, Banking System, Economic Growth, and Stock Exchange. The mostly employed application subsector from the category of Economics, is Sustainable Development with frequency 13. Civil Services & Environmental Policy-Making Sector (with frequency 10) has 2 application subsectors including: Environmental Policy-Making and Bike-Sharing Program with frequencies 6 and 3, respectively. Medical/Healthcare Management Sector (with frequency 6) has 3 application subsectors including: Healthcare Management, Biomedical Service, and Medical Service with frequencies 3, 2, and 1, respectively.

5. Challenges to future studies on MULTIMOORA

In this section, we present challenges for future researches into theory, developments, and applications of MULTIMOORA. The challenges are presented in the following seven sections regarding subordinate ranking methods, ranking aggregation tools, weighting methods for criteria, group decision-making, combination with other models, uncertain developments, and practical applications, respectively.

5.1. Challenges for subordinate ranking methods

For MCDM approaches, there exist a number of normalization ratios like Weitendorf, Peldschus, Jüttler, Stopp, Jüttler and Körth, Logarithmic, Voogd (i.e., Linear), and Pattern Normalizations as well as Standardization, Maximum Standardization, and Peldschus Nonlinear Normalization. In this regard, a research can be conducted on comparative analysis of the normalization ratios to determine the effect of changing normalization ratio on final result of MULTIMOORA model.

Based on the concept of TOPSIS, Eghbali-Zarch et al. [79] extended the Reference Point Approach by considering negative ideal point. For future developments, Reference Point Approach could be extended based on UORP Vector to consider near-ideal point. Extensions of Ratio System and Full Multiplicative Form are also interesting. For example, a coefficient can be considered for the terms related the beneficial and non-beneficial criteria to consider the unidentical importance for the terms. In contrast to Ratio System, MOOSRA employs operator "division" instead of "subtraction." According to this issue, the effect of changing the mathematical operator "division" to "subtraction" can be assessed in the utility function of Full Multiplicative Form. Generally, a study can be conducted on comparatively analyzing the effect of different mathematical operators in the triple subordinate utility functions of MULTIMOORA.

5.2. Challenges for ranking aggregation tools

As potential researches into the field of ranking aggregation of rankings of MULTIMOORA, the application of Copeland, Nanson, Dodgson, Kemeny-Young methods could be interesting. In Copeland method, alternatives are ordered based on the number of pairwise victories and pairwise defeats. Each alternative is compared against other candidates in a series of imaginary one-on-one contests. The alternative that defeats the largest number of others is the Copeland winner, i.e., the best alternative [144].

Nanson method is on the basis of Borda scores of alternatives. It has a multistage system in which alternatives with the lowest Borda score are eliminated at each stage, then new scores are calculated for the remaining alternatives. The elimination procedure continues to reach only one alternative which is identified as the best candidate [144]. Dodgson method is another ranking aggregation which works supported on the concept of pairwise comparison and swap of alternatives. Based on this technique, the best alternative is the candidate that needs the minimum number of pairwise swaps [145].

Kemeny-Young method considers a score for each imaginary sequence in which each sequence determines which alternative may be the most suitable, which alternative may be the second-most suitable, which alternative may be the third-most suitable, and so on down to which alternative may be the least-popular. The sequence with the highest score is the winner sequence in which its first alternative is identified as the best candidate [146]. A comparative research on applications of different ranking aggregation tools in the model of MULTIMOORA and analysis of the advantages and drawbacks of each tool could also be an appealing prospective study.

5.3. Challenges for weighting methods for criteria

Some important weighting approaches are missed to be utilized in the model of MULTIMOORA, such as: Analytical Network Process (ANP), Simos method, and Simple Multi-Attribute Rating Technique (SMART). ANP is the general extension of AHP. In the model of AHP, target, criteria, and alternatives are considered in the decision-making problem based on a hierarchical structure; however, ANP tackles the problem as a network. Both techniques use a pairwise comparisons structure to obtain the weights of criteria [147]. ANP could decrease the error related to judgmental forecast based on the concept of "reliability of information processing." In AHP, each criterion is supposed to be independent according to other criteria, but in practical cases, there may exist "interdependence" among criteria. ANP does not need "independence" among criteria; thus, the results of a potential ANP-MULTIMOORA methodology would be more reliable [148].

Simos method is on the basis of "card playing" procedure where various criteria are categorized into varied levels by the decision-maker followed by ranking and weighting of the assigned levels [149]. SMART, as a compensatory MCDM technique, is designed to present a way to implement the initial steps of Multi-Attribute Utility Theory (MAUT). SMART employs the concept of SAW for the weighting procedure [150]. Besides, low works have been employed using the integrated weights, i.e., via combining objective and subjective weights. Analysis of the effects of various weighting methods for application in the algorithm of MULTIMOORA can be also an issue for potential studies.

5.4. Challenges for group decision-making

Future studies can focus on multi-level group decision-making structure in which there is a senior decision-maker who manages an expert panel. This structure is practically common, for example in public organizations (e.g., parliaments or commissions) and private institutes (e.g., industrial factories or social service companies). In a hierarchical structure, more power can be considered for the senior decision-maker and in an extreme case, this leader can make the decision on his/her own regardless of or with low attention to the opinions of the expert panel.

As another hint for complementary works on group decision-making, prospective researchers may focus on cooperative and non-cooperative multi-expert MULTIMOORA models. The comparative analysis of the cooperative and non-cooperative group decision-making models can also be interesting. A further step in the field could be a consensus-based MULTIMOORA model. In consensus-based decision-making, the expert panel negotiates to reach an acceptable group solution which may not necessarily be the favorite opinion of each decision-maker [125].

In the previous studies on MULTIMOORA, it is supposed that decision-makers have the same expertise level; thus, the weights of their comments were usually considered to be identical. However, in real-world problems, the expertise level are not necessarily equal. In this regard, the evaluation of differentiating the level of influence of each expert in MULTIMOORA group decision model could be a valuable research. Another significant issue for potential studies is assessing the consistency of the structure of decision analysis of the expert panel. Consistency is important both for individual and collective decisions [125]. The occurrence of inconsistencies may lead to erroneous judgments and incoherent outcomes.

5.5. Challenges for combination with other models

For the integrative MULTIMOORA-based approaches, useful ideas like Enterprise Resource Planning (ERP) and ANN can be employed. ERP which is a key tool concerning the management of business processes can be considered as a solution for inefficient business processes. It standardizes the processes of a firm and stores data besides recalls the information when it is needed in real time environment [151].

ANN could also be beneficial in MULTIMOORA model. It can be used to narrow down the decision analysis from a pool of alternatives to reach a set of candidates as a decision matrix which will be then tackled in the MULTIMOORA approach to reach the optimal alternative. In contrast with the conventional programming, ANNs present an approach to computing which does not require a thorough algorithmic specification. A genetic algorithm-based ANNs can decrease the time of computing and increase the precision of the results. This approach has been previously employed in TOPSIS model [152].

Risk Management and Data Mining approaches are also less worked in the studies on MULTIMOORA. Measuring multifarious risks and specifying the acceptability degree of each risk and analysis of costs and advantages of considering risks are the challenges at the heart of real-world MCDM problems. As discussed in Section 2.6, only one study has combined a data mining technique with MULTIMOORA. Thus, in this area, novel works could be implemented by integrating MULTIMOORA with data mining methods. For instance, clustering and classification of data is essential before constructing a decision-matrix in MCDM approaches. Many methods in the area of data mining can implement the task of clustering and classification.

5.6. Challenges for uncertain developments

As shown in Fig. 5, the uncertainty sets previously used in MULTIMOORA uncertain developments are limited to 23 items. Thus, interesting and applicable researches could be conducted on MULTIMOORA by exploiting new uncertainty sets such as Hesitant Linguistic Neutrosophic Number (HLNN), Hesitant Uncertain Linguistic Z-number (HULZN), Interval-Valued Neutrosophic Soft Set (IVNSS), Generalized Interval Neutrosophic Rough Set (GINRS), and Hesitant Fuzzy Rough Set (HFRS).

Cui and Ye [153] introduced HLNNs for MCDM process based on similarity measures and the least common multiple cardinality. Peng and Wang [154] suggested HULZNs and assessed its application in MCDM with multiple experts using the power aggregation operators and VIKOR model. Mukherjee [155] developed IVNS, IVNSS, and discussed different types of IVNSS relations. Yang et al. [156] proposed GINRS supported on interval neutrosophic relations and evaluate the hybrid methodology using constructive technique and axiomatic approach. Yang et al. [157] studied HFRS based on constructive and axiomatic approaches.

Recently, some hybrid uncertain sets have been developed using Cloud model. In this regard, Wang et al. [158] presented an interval-valued intuitionistic linguistic group decision-making procedure using

Trapezium Cloud Model. Kumar and Sanjay [159] introduced Interval-Valued Intuitionistic Hesitant Fuzzy Set (IVIHFS) based on Trapezium Cloud Model. Thus, for further studies, Cloud model could be integrated with other uncertain sets to be applied in the MULTIMOORA algorithm. Also, the hybrid MULTIMOORA models based on stochastic data or proposing integrative hypotheses supported on probability theory such as probabilistic neutrosophic set are worthwhile to be scrutinized.

5.7. Challenges for practical applications

Additionally, despite a number of various real-world decision-making problems have been tackled to date exploiting MULTIMOORA and its developments, researchers can prospectively work on examining fundamental problems in Industrial and Socio-Economic Fields. For instance, the following applications can be regarded: Industrial Field → Technology Selection, Food Industry, and Power Plants Management; Socio-Economic Field → E-Commerce Application and Analysis of Online Social Networks.

Moreover, low works have been implemented in the sector of Information and Communications Technologies. Besides, applications of MULTIMOORA in the medical/biomedical sector are very limited as discussed in Section 4.4. In this field, target-based decision-making is very useful. In spite of the benefits and applicability of target-based criteria, the field is somewhat ignored in decision-making algorithm of MULTIMOORA (i.e., target-based MULTIMOORA models are limited to four studies [33,38,81,100]). In target-based MULTIMOORA, unlike traditional MCDM models, the objective of criteria is not only maximization or minimization but also assessing the distance to the goal point. Significance of target-based criteria can be impressively grasped in real-life problems such as biomedical applications concerning finding suitable biomaterial for surgical prostheses. The suitable biomaterial for a prosthesis should have the closest properties to the properties of its nearby body tissue (which are supposed as the target values) to minimize iterations and harmful side effects [100].

6. Conclusions

Among a variety of MCDM methods, MULTIMOORA is a significant MCDM technique that combines three subordinate rankings obtained by the fully compensatory, non-compensatory and incompletely-compensatory models entitled Ratio System, Reference Point Approach, and Full Multiplicative Form. The results of the three ranking methods are then fused to a final ranking list for which different ranking aggregation tools such as Dominance Theory, Arithmetic/Geometric Mean, Borda Rule, Dominance-Directed Graph, Improved Borda Rule, Optimization Model, ORESTE Method, Rank Position Method, and Technique of Precise Order Preference can be utilized. In this paper, we presented an exhaustive overview on MULTIMOORA by surveying 106 important researches. First, we highlighted the theory of MULTIMOORA through scrutinizing its robustness and several features including deriving the utilities of subordinate rankings methods, ranking aggregation tools, approaches of criteria weighting, multi-experts structure in the decision-making process, and integrative models besides a short bibliometric exploration regarding analysis of journals and publication years. The bibliometric co-occurrence graph was produced by employing VOSViewer software. Second, we prepared a detailed review on uncertain developments of MULTIMOORA supported on the concepts of Interval Number, Fuzzy Set, Linguistic Term, Neutrosophic Set, Z-number, Rough Set, and Cloud Model Theories besides presenting the equations of some important models. Third, the practical problems were discussed by categorizing into application sectors, application subsectors, and case studies. Fourth, we presented detailed directions for potential works on MULTIMOORA.

The following items are the benefits of this overview study:

- Only one review study exists on the context of MULTIMOORA which implemented by Baležentis and Baležentis [1] in 2014. The mentioned work only discussed a few extensions besides shortly examining its applications. Apart from addressing the need of surveying the studies from 2014 onward, the present paper has attempted to provide a thorough investigation into MULTIMOORA by considering multiple issues: theory, importance, uncertain extensions, case studies, bibliometric analyses, and directions for further studies.
- The major focus of this overview is on presentation and analysis of the models and applications with giving a minor priority to bibliometric-based survey.
- Separate detailed reviews on developments and applications were provided. Also, the equations of subordinate utilities of several significant MULTIMOORA extensions were discussed.
- A set of challenges were depicted regarding theoretical features and practical applications of MULTIMOORA.

The following theoretical and practical points can be concluded from the discussions presented in this overview:

- Seven uncertainty theories are employed for producing the extensions of MULTIMOORA. Among them, there are some models which mix two concepts to produce high-degree uncertain sets such as DHHFLTSs, TDULVs, and PLTSs. Among the seven discussed uncertainty theories, Interval Number and Fuzzy SetTheories are more used for combination with the other methods. Some uncertain developments need more mathematical concepts for generating the models; however, there are several developments which do not require uncertain arithmetic because they simply use score functions which only need crisp arithmetic, such as: the extensions based on PLTSs, ZNs, UHFLTSs, HFLTSs, and DHHFLTSs. Fuzzy Theory far outweighs the other uncertainty theories. The reason is Fuzzy Theory as a fundamental concept of uncertainty is the source of many fuzzy operators and score functions. From 2017 onward, there is a considerable rise in utilization of uncertainties in addition to inserting new concepts like Cloud Model, Rough Set, and Z-number theories into MULTIMOORA. Among uncertain sets, TFN, as a simple fuzzy number, is mostly applied to develop extensions.
- Regarding the real-world problems of MULTIMOORA, the most frequent application sector, application subsector, and case study are Industries, Sustainable Development, and Ranking Countries/Cities/Regions, respectively. In the recent years, there is a marked tendency for more works in the sector of Industries which is in contrast with the sector of Economics. Medical/Healthcare Management as well as Information and Communications Technologies are the new application sectors of MULTIMOORA.

Acknowledgments

The work was supported in part by the National Natural Science Foundation of China (Nos. 71771156 and 71501135), the 2019 Sichuan Planning Project of Social Science (No. SC18A007), the 2018 Key Project of the Key Research Institute of Humanities and Social Sciences in Sichuan Province (No. Xq18A01, No. LYC18-02), and the Spark Project of Innovation at Sichuan University (No. 2018hhs-43).

Appendix

Table A.1
Details of the main studies on MULTIMOORA in 2018 (Jan–Sep).

Year	Author(s) [Ref.]	Source title	Ranking aggregation tool									Uncertainty theory	Weighting method	GDM*	Target–based criteria	Combination with other models	Case study	Verification technique
			Dominance Theory	Dominance–Directed Graph	Rank Position Method	TPOP* Method	Borda Rule	Improved Borda Rule	ORESTE Method	Optimization Model	Arithmetic/ Geometric Mean							
2018	Aydın [76]	Journal of Enterprise Information Management	√									Neutrosophic	AHP	–	–	–	Device selection	TOPSIS
2018	Chen et al. [41]	Soft Computing								√		Fuzzy	–	√	–	–	Wastewater treatment	–
2018	Dai et al. [42]	Soft Computing	√									Fuzzy	–	√	–	Prospect theory	Investment selection	TOPSIS, VIKOR
2018	Ding and Zhong [77]	Scientific Programming	√									Linguistic	Entropy	√	–	Regret theory	Battery recycling mode selection	VIKOR, TODIM
2018	Dorfeshan et al. [78]	Computers and Industrial Engineering				√						Interval, Fuzzy	–	√	–	–	Project management	–
2018	Eghbali-Zarch et al. [79]	Artificial Intelligence in Medicine	√									Fuzzy	SWARA	–	–	–	Therapy selection	SAW, TOPSIS, VIKOR
2018	Erdogan and Sayin [75]	Sustainability	√									–	SWARA	√	–	–	Fuel selection	–
2018	Fattahi et al. [80]	Safety Science	√									Fuzzy	AHP	√	–	Failure mode and effects analysis	Risk evaluation	–
2018	Hafezalkotob et al. [81]	Computers and Electronics in Agriculture	√									–	BWM	–	√	–	Machine selection	WASPAS
2018	Ijadi Maghsoodi et al. [82]	Computers and Industrial Engineering	√									–	–	–	–	Cluster analysis	Supplier selection	–
2018	Ijadi Maghsoodi et al. [49]	Frontiers of Business Research in China	√									–	Entropy	–	–	–	Personnel management	TOPSIS
2018	Kabak et al. [68]	Journal of Cleaner Production	√									–	AHP	√	–	Geographic Information System	Location planning	–
2018	Liang et al. [73]	Neural Computing and Applications	√									Linguistic, Neutrosophic	SWARA	√	–	–	Mining technique selection	TOPSIS, LNWAA operator, LNWGA operator
2018	Liao et al. [59]	Information Fusion							√			Fuzzy, Linguistic	Logarithmic least square method	√	–	–	Investment selection	TOPSIS, VIKOR
2018	Liu et al. [74]	Journal of Testing and Evaluation	√									Fuzzy, Linguistic	Statistical variance	√	–	–	Robot selection	TOPSIS, VIKOR
2018	Liu et al. [83]	IEEE Transactions on Intelligent Transportation Systems	√									Linguistic	DEMATEL	√	–	–	Location planning	–
2018	Liu et al. [84]	Sustainability	√									Fuzzy	Entropy, BWM	√	–	Quality function deployment	Supplier selection	TOPSIS, VIKOR, COPRAS
2018	Peng and Wang [57]	IEEE Transactions on Fuzzy Systems	√									Z	Optimization model	√	–	–	Ranking coun-tries/cities/regions	TOPSIS, VIKOR, Cloud score function
2018	Stojić et al. [3]	Information	√									Rough	AHP	√	–	–	Supplier selection	SAW, VIKOR, WASPAS, EDAS, MABAC, MAIRCA
2018	Tian et al. [69]	Journal of Cleaner Production	√									Fuzzy	BWM, Maximizing deviation method	√	–	Quality function deployment	Service selection	TOPSIS, VIKOR, Weighted average aggregation operator
2018	Wang et al. [48]	Computers & Industrial Engineering	√									Fuzzy	Choquet integral	√	–	Fine-Kinney method	Risk evaluation	VIKOR
2018	Wu et al. [56]	IEEE Transactions on Fuzzy Systems						√				Linguistic	AHP, CRITIC	√	–	–	Company selection	–

* **TPOP**: Technique Of Precise Order Preference; **GDM**: Group Decision-Making.

Table A.2
Details of the main studies on MULTIMOORA in 2016–17.

Year	Author(s) [Ref.]	Source title	Ranking aggregation tool									Uncertainty theory	Weighting method	GDM	Target–based criteria	Combination with other models	Case study	Verification technique
			Dominance Theory	Dominance–Directed Graph	Rank Position Method	TPOP Method	Borda Rule	Improved Borda Rule	ORESTE Method	Optimization Model	Arithmetic/ Geometric Mean							
2017	Awasthi and Baležentis [85]	International Journal of Logistics Systems and Management	√									Fuzzy	–	√	–	–	Partner selection	–
2017	Aytaç Adalı and Tuş Işık [37]	Journal of Industrial Engineering International	√									–	AHP	–	–	–	Device selection	MOOSRA
2017	Brauers et al. [86]	Romanian Journal of Economic Forecasting	√									–	–	–	–	–	Facility management	–
2017	Ceballos et al. [87]	International Journal of Intelligent Systems	√									Fuzzy	–	–	–	–	–	TOPSIS, VIKOR, WASPAS
2017	Deliktas and Ustun [63]	International Transactions in Operational Research	√									Fuzzy	–	√	–	Goal programming	Student selection	–
2017	Gou et al. [58]	Information Fusion	√									Fuzzy, Linguistic	–	√	–	–	Ranking countries/cities/regions	TOPSIS
2017	Hafezalkotob and Hafezalkotob [38]	Engineering Applications of Artificial Intelligence	√									Interval	–	–	√	–	Machine selection	VIKOR, FAD
2017	Hafezalkotob and Hafezalkotob [33]	Applied Soft Computing	√									Fuzzy	Entropy	–	–	–	Material selection	FAD
2017	Hafezalkotob and Hafezalkotob [88]	Journal of Industrial Engineering International	√									Interval	–	–	√	–	Material selection	TOPSIS, VIKOR, ELECTRE, Limits on properties method, Goal programming, MABAC
2017	Karaca and Ulutaş [89]	Economics, Management, & Econometrics									√	–	SWARA	√	–	–	Supplier selection	–
2017	Önay [90]	Applying Predictive Analytics Within the Service Sector	√									–	–	–	–	–	Ranking countries/cities/regions	–
2017	Sen et al. [91]	International Journal of Services and Operations Management	√									Fuzzy	–	√	–	–	Supplier selection	TOPSIS
2017	Souzangarzadeh et al. [47]	Applied Mathematical Modelling	√									–	Numeric logic	–	–	Finite element simulation	Design selection	–
2017	Stanujkic et al. [36]	Informatica	√									Neutrosophic	–	–	–	–	Design selection	–
2017	Stević et al. [92]	Symmetry	√									Rough	AHP, DEMATEL	√	–	–	Supplier selection	COPRAS, EDAS, MABAC, MAIRCA
2017	Tian et al. [72]	Neural Computing and Applications	√									Linguistic, Neutrosophic	TOPSIS-inspired method	–	–	–	Enterprise resource planning	TOPSIS, Simplified Neutrosophic Linguistic Normalized Weighted Bonferroni (SNLNWB) mean operator
2017	Wu et al. [62]	International Transactions in Operational Research	√									Cloud	Maximizing deviation method	√	–	Quality function deployment	Vehicle selection	TOPSIS, VIKOR
2017	Zavadskas et al. [31]	Engineering Applications of Artificial Intelligence	√									Neutrosophic	SWARA	√	–	–	Material & component selection	–
2017	Zhao et al. [40]	Soft Computing	√									Interval, Fuzzy	Entropy	√	–	Failure mode and effects analysis	Risk evaluation	TOPSIS, WASPAS
2016	Baležentis and Baležentis [18]	Economic Computation and Economic Cybernetics Studies and Research	√									Fuzzy	–	√	–	–	Personnel management	–

(*continued on next page*)

Table A.2 (*continued*)

Year	Author(s) [Ref.]	Source title	Ranking aggregation tool									Uncertainty theory	Weighting method	GDM	Target–based criteria	Combination with other models	Case study	Verification technique
			Dominance Theory	Dominance–Directed Graph	Rank Position Method	TPOP Method	Borda Rule	Improved Borda Rule	ORESTE Method	Optimization Model	Arithmetic/ Geometric Mean							
2016	Çebi and Otay [93]	Information Sciences	√									Fuzzy	–	√	–	Goal programming	Supplier selection	TOPSIS, VIKOR
2016	Dai et al. [71]	Mathematical Problems in Engineering	√									Fuzzy	–	√	–	–	Investment selection	TOPSIS, VIKOR, PROMETHEE, OCRA
2016	Hafezalkotob and Hafezalkotob [94]	Journal of Intelligent & Fuzzy Systems	√									Fuzzy	Entropy	√	–	–	Material selection	VIKOR
2016	Hafezalkotob and Hafezalkotob [39]	Journal of Industrial Engineering International	√									–	Entropy	–	–	–	Material selection	TOPSIS, VIKOR, ELECTRE, Linear assignment, WPM, GTMA, Fuzzy logic, Z–transformation
2016	Hafezalkotob et al. [46]	Applied Mathematical Modelling	√									Interval	–	–	–	–	Material selection	TOPSIS, VIKOR, PROMETHEE, ORESTE, COPRAS, OCRA, EXPROM2, Projection
2016	Kundakci [95]	Alphanumeric Journal	√									–	MACBETH	–	–	–	Vehicle selection	–
2016	Qin and Liu [96]	Kybernetes	√									Linguistic	–	–	–	–	Supplier selection	Muirhead mean operator
2016	Sahu et al. [97]	International Journal of Computer Aided Engineering and Technology	√									Fuzzy	–	√	–	–	Machine selection	–
2016	Sezer et al. [98]	Journal of Economics Bibliography	√									Interval, Fuzzy	–	√	–	–	Warehouse selection	–

Table A.3
Details of the main studies on MULTIMOORA in 2013–15.

Year	Author(s) [Ref.]	Source title	Ranking aggregation tool									Uncertainty theory	Weighting method	GDM	Target–based criteria	Combination with other models	Case study	Verification technique
			Dominance Theory	Dominance–Directed Graph	Rank Position Method	TPOP Method	Borda Rule	Improved Borda Rule	ORESTE Method	Optimization Model	Arithmetic/ Geometric Mean							
2015	Altuntas et al. [67]	Journal of Civil Engineering and Management	√	√	√		√					–	–	–	–	–	Vehicle selection	–
2015	Brauers et al. [99]	International Journal of Applied Nonlinear Science	√									–	–	–	–	–	Investment selection	–
2015	Hafezalkotob and Hafezalkotob [100]	Acta Montanistica Slovaca	√									–	SWARA	–	–	–	Personnel management	–
2015	Karabasevic et al. [101]	Materials & Design	√									–	Entropy, Statistical variance, CRITIC	–	√	–	Material selection	TOPSIS, VIKOR, Limits on properties method, Goal programming
2015	Lazauskas et al. [102]	Journal of the Croatian Association of Civil Engineers									√	–	AHP	√	–	–	Project management	ARAS
2015	Lazauskas et al. [30]	E a M: Ekonomie a Management	√									–	–	–	–	–	Ranking coun- tries/cities/regions	–
2015	Liu et al. [25]	Renewable and Sustainable Energy Reviews	√									Fuzzy	DEMATEL	√	–	–	Waste management	TOPSIS, VIKOR
2015	Mishra et al. [103]	International Journal of Operational Research	√									Interval, Fuzzy	–	√	–	–	Supplier/partner selection	–
2015	Stanujkic et al. [44]	Transformations in Business and Economics	√									Interval, Fuzzy	–	√	–	–	Design selection	–
2015	Zavadskas et al. [70]	Mathematical Problems in Engineering	√									Interval, Fuzzy	–	√	–	–	Buildings revitalization appraisal, Investment selection	TOPSIS, WASPAS, COPRAS, IFOWA
2014	Baležentis et al. [17]	Economic Computation and Economic Cybernetics Studies and Research	√									Fuzzy	–	√	–	–	Personnel management	–
2014	Brauers et al. [104]	Panoeconomicus	√									–	–	–	–	–	Ranking banks	–
2014	Brauers et al. [105]	Annals of Management Science	√									–	–	–	–	–	Ranking banks	–
2014	Li [106]	Journal of Applied Mathematics	√									Fuzzy	–	√	–	–	Software selection	–
2014	Liu et al. [32]	Engineering Applications of Artificial Intelligence	√									Fuzzy	–	√	–	Failure mode and effects analysis	Risk evaluation	–
2014	Liu et al. [107]	Waste Management	√									Interval, Linguistic	Statistical variance	√	–	–	Waste management	–
2014	Sahu et al. [108]	International Journal of Business Excellence	√									Interval, Fuzzy	–	√	–	–	Company/industrial group selection	–
2013	Balezentiene et al. [26]	Renewable and Sustainable Energy Reviews	√									Fuzzy	–	–	–	–	Crop selection	–
2013	Baležentis and Zeng [54]	Expert Systems with Applications	√									Interval, Fuzzy	–	√	–	–	Personnel management	–
2013	Baležentis et al. [22]	Technological and Economic Development of Economy	√									–	–	–	–	Data envelopment analysis	Economic evaluation	–

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Table A.3 (*continued*)

Year	Author(s) [Ref.]	Source title	Ranking aggregation tool									Uncertainty theory	Weighting method	GDM	Target–based criteria	Combination with other models	Case study	Verification technique
			Dominance Theory	Dominance–Directed Graph	Rank Position Method	TPOP Method	Borda Rule	Improved Borda Rule	ORESTE Method	Optimization Model	Arithmetic/ Geometric Mean							
2013	Brauers and Ginevičius [64]	Journal of Business Economics and Management	√									–	–	–	–	–	Investment selection	–
2013	Brauers and Zavadskas [109]	International Journal of Operations Research	√									–	–	–	–	–	Ranking countries/cities/regions	–
2013	Brauers and Zavadskas [45]	Transformations in Business and Economics	√									–	–	–	–	–	Ranking countries/cities/regions	–
2013	Brauers et al. [61]	International Journal of Strategic Property Management	√									–	–	–	–	–	Ranking countries/cities/regions	–
2013	Kracka and Zavadskas [60]	International Journal of Strategic Property Management	√									Interval	–	–	–	–	Design selection	–
2013	Stankevičienė and Rosov [52]	Entrepreneurial Business and Economics Review	√									–	–	–	–	–	Ranking countries/cities/regions	–
2013	Stankevičienė et al. [53]	Entrepreneurial Business and Economics Review	√									–	–	–	–	–	Ranking countries/cities/regions	–
2013	Streimikiene and Baležentis [24]	Renewable and Sustainable Energy Reviews	√									–	–	–	–	–	Climate change policy-making	–
2013	Zavadskas et al. [110]	Studies in Informatics and Control	√									–	SWARA	√	–	–	Technology selection	TOPSIS, VIKOR, ELECTRE
2013	Zavadskas et al. [15]	Economic Computation and Economic Cybernetics Studies and Research	√									–	Entropy	–	–	–	Design selection	WASPAS
2013	Zeng et al. [16]	Economic Computation and Economic Cybernetics Studies and Research	√									Fuzzy	–	√	–	–	Personnel management	–

Table A.4
Details of the main studies on MULTIMOORA in 2010–12.

Year	Author(s) [Ref.]	Source title	Ranking aggregation tool									Uncertainty theory	Weighting method	GDM	Target–based criteria	Combination with other models	Case study	Verification technique
			Dominance Theory	Dominance-Directed Graph	Rank Position Method	TPOP Method	Borda Rule	Improved Borda Rule	ORESTE Method	Optimization Model	Arithmetic/ Geometric Mean							
	Baležentis et al. [55]	Expert Systems with Applications	√									Fuzzy	–	√	–	–	Personnel management	–
2012	Baležentis et al. [34]	Informatica	√									Fuzzy	–	√	–	–	Personnel management	–
2012	Brauers [111]	Czech Economic Review	√									–	–	–	–	–	Project management	–
2012	Brauers and Zavadskas [35]	Informatica	√									–	–	–	–	–	–	–
2012	Brauers and Zavadskas [29]	E a M: Ekonomie a Management	√									–	–	–	–	–	Project management	–
2012	Brauers et al. [66]	Journal of Civil Engineering and Management	√									–	–	–	–	–	Component selection	–
2012	Brauers et al. [21]	Technological and Economic Development of Economy	√									–	–	–	–	–	Ranking coun-tries/cities/regions	–
2012	Brauers et al. [112]	Actual Problems of Economics	√									–	–	–	–	–	Ranking coun-tries/cities/regions	–
2012	Streimikiene et al. [27]	Renewable and Sustainable Energy Reviews	√									–	–	–	–	–	Energy management	TOPSIS
2011	Baležentis [114]	Management Theory and Studies for Rural Business and Infrastructure Development	√									Fuzzy	–	–	–	–	Farming efficiency estimation	–
2011	Baležentis and Baležentis [113]	Transport	√									–	–	–	–	Data envelopment analysis	Transportation efficiency evaluation	–
2011	Baležentis and Baležentis [50]	Engineering Economics	√									–	–	–	–	–	Ranking coun-tries/cities/regions	–
2011	Baležentis and Baležentis [12]	Economic Computation and Economic Cybernetics Studies and Research	√									Linguistic	–	√	–	–	Supplier selection	–
2011	Baležentis and Baležentis [14]	Economic Computation and Economic Cybernetics Studies and Research	√									Fuzzy, Linguistic	–	–	–	–	Supplier selection	–
2011	Baležentis et al. [115]	Ekonomska Istrazivanja	√									–	–	–	–	–	Ranking coun-tries/cities/regions	–
2011	Baležentis et al. [28]	E a M: Ekonomie a Management	√									–	–	–	–	–	Ranking coun-tries/cities/regions	–
2011	Brauers and Zavadskas [13]	Economic Computation and Economic Cybernetics Studies and Research	√									–	–	–	–	–	Project management	–
2011	Brauers and Zavadskas [23]	Technological and Economic Development of Economy	√									–	–	–	–	–	Bank Loan evaluation	–
2011	Brauers et al. [19]	Technological and Economic Development of Economy	√									Fuzzy	–	–	–	–	Ranking coun-tries/cities/regions	–
2010	Baležentis et al. [20]	Technological and Economic Development of Economy	√									–	–	–	–	–	Ranking coun-tries/cities/regions	–
2010	Brauers and Ginevičius [65]	Journal of Business Economics and Management	√									–	–	–	–	–	Economic evaluation	–
2010	Brauers and Zavadskas [43]	Transformations in Business and Economics	√									–	–	–	–	–	Economic evaluation	–
2010	Brauers and Zavadskas [11]	Technological and Economic Development of Economy	√									–	–	–	–	–	Project management	–
2010	Kracka et al. [51]	Engineering Economics	√									–	–	–	–	–	Design selection	–

Table A.5
Distribution of group decision-making structure.

Item	Frequency	Percentage frequency	Reference(s)
Group Decision-Making Structure	48	45.3	[3,12,41,42,44,48,54-59,16,62,63,68-71,73-75,77,17,78,80,83-85,89,91-94,18,97,98,102,103,106-108,110,25,31,32,34,40]

Table A.6
Distribution of verification techniques.

Verification technique	Frequency	Percentage frequency	Reference(s)
TOPSIS	26	24.5	[25,27,62,69–74,76,79,82,38,84,87,91,93,100,110,39,40,42,46,57-59]
VIKOR	22	20.8	[3,25,62,69,71,74,77,79,84,87,93,94,33,100,110,38,39,42,46,48,57,59]
WASPAS	6	5.7	[3,15,40,70,81,87]
COPRAS	4	3.8	[46,70,74,92]
ELECTRE	3	2.8	[38,39,110]
MABAC	3	2.8	[3,38,92]
EDAS	2	1.9	[3,92]
FAD	2	1.9	[33,88]
Goal programming	2	1.9	[38,100]
Limits on properties method	2	1.9	[38,100]
MAIRCA	2	1.9	[3,92]
OCRA	2	1.9	[46,71]
PROMETHEE	2	1.9	[46,71]
SAW	2	1.9	[3,79]
ARAS	1	0.9	[102]
Cloud score function	1	0.9	[57]
EXPROM2	1	0.9	[46]
Fuzzy logic	1	0.9	[39]
GTMA	1	0.9	[39]
IFOWA operator	1	0.9	[70]
Linear assignment	1	0.9	[39]
LNWAA operator	1	0.9	[73]
LNWGA operator	1	0.9	[73]
MOOSRA	1	0.9	[37]
Muirhead mean operator	1	0.9	[96]
ORESTE	1	0.9	[46]
Projection method	1	0.9	[46]
SNLNWB mean operator	1	0.9	[72]
TODIM	1	0.9	[77]
WAA operator	1	0.9	[77]
WPM	1	0.9	[77]
Z-transformation	1	0.9	[39]

Table A.7
Explanations of MULTIMOORA applications in miscellaneous areas.

Case study	Description of the problem	Reference(s)
Company/industrial group selection	Selection of industrial group according to supply chain performance evaluation index	[108]
Fuel selection	Selection of a suitable fuel from a set of candidate animal fat biodiesels	[75]
Investment selection	Analysis of alternatives for investing by an investment company in China	[42,71]
Personnel management	Personnel selection in an enterprise considering performance criteria and professional experience	[17,34,55]
Personnel management	Ranking employee performance appraisal methods in a multi-national cross-industry company in Iran	[82]
Project management	Enlarged project management in China	[13]
Project management	Evaluating projects for a transition economy	[11]
Project management	Project management of a national economy in search for new projects	[111]
Risk evaluation	Assessment of the risks entailed in a ballast tank maintenance problem	[48]
Student selection	Ranking students based on their performance in English proficiency exam	[160]
Supplier selection	Supplier selection problem regarding a multi-national corporation	[49]
Supplier selection	Supplier selection problem with hybrid data	[14]
Supplier selection	Supplier selection to develop an appropriate procurement policy	[12]
Supplier selection, partner selection	Selection of suitable supplier/partner in an agile supply chain	[103]

Table A.8
List of acronyms and their explanations.

Abbreviation	Explanation
AHP	Analytic Hierarchical Process
ANN	Artificial Neural Network
ANP	Analytical Network Process
AORP	Aspiration Objective Reference Point
ARAS	Additive Ratio ASsessment
BEL20®	The benchmark stock market index of Euronext Brussels
BWM	Best-Worst Method
CODAS	COmbinative Distance-based Assessment

(continued on next page)

Table A.8 (*continued*)

Abbreviation	Explanation
COPRAS	COmplex PRoportional Assessment
CRITIC	CRiteria Importance Through Inter-criteria Correlation
DEMATEL	DEcision MAking Trial and Evaluation Laboratory
DHHFLTS	Double Hierarchy Hesitant Fuzzy Linguistic Term Set
EDAS	Evaluation based on Distance from Average Solution
ELECTRE	ELimination Et Choix Traduisant la REalité, in French (Elimination and Choice Expressing Reality)
ERP	Enterprise Resource Planning
EXPROM2	EXtended PROMethee 2
FAD	Fuzzy Axiomatic Design
FMF	Full Multiplicative Form
FS	Fuzzy Set
GINRS	Generalized Interval Neutrosophic Rough Set
GIVFN	Generalized Interval-Valued Fuzzy Number
GLDS	Gained and Lost Dominance Score
GRA	Gray Relational Analysis
GTMA	Graph Theory and Matrix Approach
HFLTS	Hesitant Fuzzy Linguistic Term Set
HFRS	Hesitant Fuzzy Rough Set
HFS	Hesitant Fuzzy Set
HLNN	Hesitant Linguistic Neutrosophic Number
HULZN	Hesitant Uncertain Linguistic Z-number
ICT	Information and Communications Technologies
IFN	Intuitionistic Fuzzy Number
IFOWA	Intuitionistic Fuzzy Ordered Weighted Averaging
IFS	Intuitionistic Fuzzy Set
IN	Interval Number
IT2FS	Interval Type-2 Fuzzy Set
ITLTS	Interval 2-Tuple Linguistic Term set
IVFN	Interval-Valued Fuzzy Number
IVIFN	Interval-Valued Intuitionistic Fuzzy Number
IVIHFS	Interval-Valued Intuitionistic Hesitant Fuzzy Set
IVNS	Interval-Valued Neutrosophic set
IVNSS	Interval-Valued Neutrosophic Soft Set
LNN	Linguistic Neutrosophic Number
LNWAA	Linguistic Neutrosophic Weighted Arithmetic Averaging
LNWGA	Linguistic Neutrosophic Weighted geometric Averaging
MABAC	Multi-Attributive Border Approximation area Comparison
MABAC	Multi-Attributive Border Approximation area Comparison
MACBETH	Measuring Attractiveness by a Categorical Based Evaluation TecHnique
MAIRCA	Multi-Attributive Ideal-Real Comparative Analysis
MAUT	Multi-Attribute Utility Theory
MCDM	Multiple Criteria Decision-Making
MOORA	Multi-Objective Optimization by Ratio Analysis
MOOSRA	Multi-Objective Optimization by Simple Ratio Analysis
MORP	Maximal Objective Reference Point
MULTIMOORA	Multi-Objective Optimization by Ratio Analysis plus the full MULTIplicative form
NIS	Negative-Ideal Solution
NS	Neutrosophic Set
NSS	Neutrosophic Soft Set
OCRA	Operational Competitiveness Rating Analysis
ORESTE	Organísation, Rangement Et SynThèse de DonnéEs Relarionnelles, in French (Organization, Arrangement and Synthesis of Relational Data)
PIS	Positive-Ideal Solution
PLTS	Probabilistic Linguistic Term Set
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
RN	Rough Number
RPA	Reference Point Approach
RS	Ratio System
SAW	Simple Additive Weighting
SMART	Simple Multi-Attribute Rating Technique
SNLNWB	Simplified Neutrosophic Linguistic Normalized Weighted Bonferroni
SNLS	Simplified Neutrosophic Linguistic Set
SVNS	Single-Valued Neutrosophic Set
SWARA	Stepwise Weight Assessment Ratio Analysis
TDULV	Two-Dimension Uncertain Linguistic Variable
TFN	Triangular Fuzzy Number
TLTS	2-Tuple Linguistic Term set
TODIM	TOmada de Decisao Interativa e Multicritévio, in Portuguese (Interactive and Multiple Criteria Decision-Making)
TOPSIS	Technique for Order Performance by Similarity to Ideal Solution
TPOP	Technique of Precise Order Preference
TrFN	Trapezoidal Fuzzy Number
UHFLTS	Unbalanced Hesitant Fuzzy Linguistic Term Set
ULV	Uncertain Linguistic Variable
UORP	Utopian Objective Reference Point
VIKOR	VIse Kriterijumska Optimizacija kompromisno Resenje, in Serbian (Multiple Criteria Optimization Compromise Solution)
WASPAS	Weighted Aggregated Sum Product Assessment
WPM	Weighted Product Method
ZN	Z-number

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