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Applications of Fuzzy and Neutrosophic Logic in Solving Multi-criteria Decision Making Problems

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Abstract. In daily life, decision makers around the world are seeking for the appropriate decisions while facing many challenges due to conflicting criteria and the presence of many alternatives. In the way of pursuit a powerful decision making process, many researches act in multi-criteria decision making (MCDM) field and many methods were developed. This paper sheds some lights on the applicability of fuzzy set theory and neutrosophic logic in solving multi-criteria decision making problems. Also, it presents the possible applications of each method in MCDM different fields.

Keywords: Fuzzy Set Theory, Neutrosophic logic, Multi-criteria Decision Making.

1 Introduction

The multi-criteria decision making (MCDM) can be defined as the process of ranking a set of alternatives and selecting the most suitable one based on decision criteria [1]. During the second half of the 20th century, MCDM research area has undergone remarkable and fast development, and many MCDM methods have been developed to introduce better solution for multi-criteria decision making problems [1]. MCDM process components are a set of decision criteria (at least two), decision makers, and a set of alternatives which sorted and ranked based on the decision criteria [2]. With a goal of helping decision makers to rank different alternatives and choose the best one that satisfies organization's needs, MCDM has been used to support a wide range of decisions in many areas such as: portfolio optimization, benefit-risk assessment, technology assessment, and software selection [3–4].

This paper analyses two multi-criteria decision making methods and determines their applicability to different situations by evaluating their relative advantages and disadvantages. A comprehensive literature review is conducted to allow a summary of the two methods. A review of the use of these methods and an examination of the evolution of their use is then performed.

This paper is organized as follows: Section 2 introduces a brief background of fuzzy set theory. Fuzzy applications in different MCDM fields are discussed in Section 3. Section 4 introduces a brief background of neutrosophic logic. Section 5 presents the role of neutrosophic logic in solving multi-criteria decision making problems. Finally, conclusions and potential future scope of research are described in Conclusion section.

2 Fuzzy Set Theory

Fuzzy set theory was first introduced in 1965 by Zadeh [5]. It is an extension of classical set theory that helps solving problems with uncertain data and handling information expressed in vague and imprecise terms [6]. Its great strength appears in handling imprecise input and problems with great complexity; however, fuzzy systems are considered difficult and complex to develop, and, in many cases, they may require numerous simulations before being used in the real world [7]. Fuzzy set theory is established and has been used in many applications such as engineering, economics, environmental and social sciences, medicine, and management [7].

Zadeh [5] introduced many definitions of fuzzy sets such as:

Let X be a space of points with a generic element of X denoted by x. Thus X = {x}.

A fuzzy set A in X is characterized by a membership function fA(x) which associates with each point in X a real number in the interval [0,1], with the values of fA(x) at x representing the "grade of membership" of x in A. Thus, the nearer the value of fA(x) to unity, the higher the grade of membership of x in A.

A fuzzy number $\tilde{n}$ is a fuzzy subset in the universe of discourse X whose membership function is both Convex and normal [8]. A fuzzy set is defined by a membership function used to map an item onto an interval [0, 1] that can be associated with linguistic terms [9]. A triangular fuzzy number (TFN) is a special case of a trapezoidal fuzzy number and it is a very popular and common tool in fuzzy applications [10].

Figure 1: shows a fuzzy number [5]

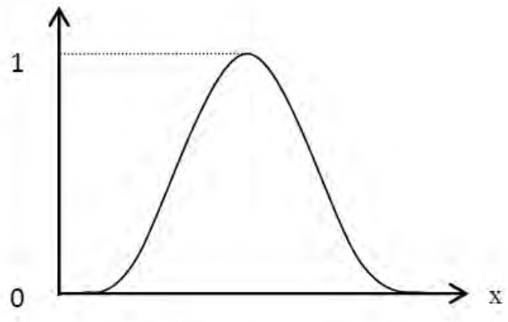

Figure1. A fuzzy number

3 Applications of Fuzzy set in MCDM

3.1 Software Selection Field

Sen et al. [11] proposed a multi criteria decision making approach for Enterprise Resource Planning (ERP) software selection using a heuristic algorithm, a fuzzy multi-criteria, and a multi objective programming model. The proposed approach aimed to evaluate the functional and non-functional ERP software characteristics. To validate the approach, the researchers applied it on an electronic company in Turkey and the results were satisfying for the company's decision makers. The researchers recommended combining their method with expert system for future work.

Lin et al. [12] first developed some aggregation operators for aggregating hesitant fuzzy linguistic information: hesitant fuzzy linguistic weighted average (HFLWA) operator, hesitant fuzzy linguistic ordered weighted average (HFLOWA) operator, and hesitant fuzzy linguistic hybrid average (HFLHA) operator, then the researchers used these operators in fuzzy approaches for solving ERP software selection problem. The proposed method was applied on a real world case study and it ensured its capability in selecting the best ERP software that suited the organization needs.

Ozturkoglu and Esendemir [13] combined the power of grey relational analysis (GRA) with an intuitionistic fuzzy set (IFS) multi-criteria method for developing a hybrid ERP software selection model. After making a survey of all criteria affecting the ERP software selection process and the software packages alternatives, the researchers used the IFS method for obtaining the weight of each criteria, then the GRA method was used for ranking the alternatives and selecting the best one. A service provider firm which offered transportation, warehousing, and packaging services was used as a case study, and the model helped the firm to select the most suitable ERP package.

Vahidi et al. [14] used the fuzzy logic for developing a model for ERP software selection. A triangular fuzzy membership function was used for processing each criterion to measure the efficiency level of each ERP system alternative. For future work, the researchers suggested using a method based on Adaptive-Network-based Fuzzy Inference Systems (ANFIS) as ANFIS method used a learning algorithm that simulate a given training data set.

Lien and Chan [15] developed a Fuzzy-Analytic Hierarchy Process (F-AHP) ERP software selection model. The proposed model was used in two case studies: a company and a college for selecting the best ERP software that mate their needs.

Cebeci [16] presented an approach for selecting the best ERP system in textile industry by using the balanced scorecard and Fuzzy-AHP method. The aims of this research were using balanced scorecard for defining the business objectives and matching them with ERP packages capabilities, and using Fuzzy-AHP model for ranking and selecting the most suitable ERP software package.

Onut and Efendigil [17] introduced a Fuzzy-AHP model for helping organizations in selecting ERP software in the presence of vagueness and with consideration to cost and quality criteria. The researchers combined Fuzzy method to the AHP model to solve the problems of ambiguities and vagueness accompanied by software selection problem. At the end of the research, a real world case study was solved using the proposed model and a comparison between AHP and Fuzzy-AHP solutions was conducted, and the results included that Fuzzy-AHP method showed more accurate results and flexibility in adding new ERP software selection criteria.

Demirtas et al. [18] presented a two stage decision making model for ERP software selection process and applied the model on an urban transportation company. At the first stage, by using Fuzzy-AHP model, the model helped the company to first take the decision whether it would develop a new software package or it would use a vendor software package. If the decision was using a vendor software package, then moving to the second stage, by using Fuzzy-Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) model, the model helped the company to select the most suitable software package fitting its needs and expectation.

Kara and Cheikhrouhou [19] proposed a four steps decision making methodology for selecting business management system to Small and Medium sized Enterprises. First the selection criteria were collected and determined by experts, then criteria weights were calculated using Fuzzy-AHP combined to TOPSIS, finally the best alternative was selected. For ensuring the methodology effectiveness, a sensitivity analysis was conducted and the results demonstrated that uncertainty was reduced.

Kilic et al. [20] used the strength of Fuzzy-AHP and TOPSIS multi-criteria decision making methods for developing a three stage hybrid model for ERP system selection and applied the model for the Airline industry. The first model stage was the determination of all ERP selection process factors and criteria and identifying ERP software packages as alternatives, the second stage was using the Fuzzy-AHP method for obtaining weights for each decision criteria, the final model stage was using the TOPSIS method for ranking the alternatives and selecting the best one. The researchers used the proposed model for helping the Turkish Airlines in selecting ERP software package for its maintenance center and the model proved its effectiveness and efficiency.

Volaric et al. [21] proposed a Fuzzy AHP-TOPSIS model for selecting the best multimedia software for learning and teaching purposes. The Fuzzy AHP method was used for assigning the weight of each criterion and demonstrating the benefit of each criterion to another, finally the TOPSIS method was used for ranking the multimedia software systems and selecting the best one.

Efe [22] developed a hybrid model by integrating Fuzzy-AHP and Fuzzy-TOPSIS for ERP software selection. First the selection criteria were determined, then the weight of each criterion was determined using Fuzzy-AHP, after that Fuzzy-TOPSIS was used for choosing the most appropriate ERP software alternative. For ensuring the model effectiveness, it was applied on an electronic firm and the results demonstrated that the model decreased the uncertainty and the information loss in group decision making. For future work, the researcher recommended using type 2 fuzzy MCDM methods in the ERP selection process.

Karsak and Ozogul [23] developed a multi-criteria decision framework using on quality function deployment (QFD), fuzzy linear regression, and zero–one goal programming for ERP software selection. The QFD method was used for determining and establishing the relationships between user demands and software characteristics, while the fuzzy linear regression method was used for assigning values to the ERP software characteristics, and finally the zero–one goal programming was used for determining the ERP software alternative that achieve the maximum values of company needs. The proposed model was applied on a Turkish automotive parts manufacturer to ensure its effectiveness.

3.2 Risk Assessment and Success Factors Evaluation

Je et al. [24] introduced an integrated fuzzy entropy-weight MCDM method and applied it to evaluate and assess risk of hydropower stations in the Xiangxi River.

Shafiee [25] used Fuzzy Analytic Network Process (F-ANP) approach, based on Chang's extent analysis for selecting the most appropriate risk mitigation strategy for offshore wind farms.

Kong and Liu [26] combined Fuzzy sets with AHP for developing a MCDA model to evaluate success factors in E-commerce projects in order to help the decision makers to determine new opportunities for their organizations.

3.3 Site Selection Field

Rezaeiniya et al. [27] used Fuzzy-ANP for selecting the appropriate location of greenhouses in Mazandaran province, Iran. The application of the model ensured its efficiency in the selection process and ranking of alternatives.

Vahidnia et al. [28] used Fuzzy-AHP in hospital site selection and determining the optimum site for a new hospital in the Tehran urban area.

Chou et al [29] developed a MCDM model by combining Fuzzy set theory and simple additive weighting (SAW) to evaluate facility locations alternatives and selecting the best one.

3.4 Supplier Selection Field

Kahraman et al. [30] proposed a Fuzzy-AHP model for supplier selection, the researchers determined the selection criteria, and then the model was used to select the most suitable supplier that mate the company needs.

Ayhan [31] presented a Fuzzy-AHP model for helping the firms to select the best supplier according to the firm selection criteria, and for ensuring the model effectiveness, it was applies on a gear motor company for assessing its suppliers and selecting the best one.

Junior et al. [32] proposed a comparative analysis of Fuzzy-AHP and Fuzzy-TOPSIS in solving the problem of supplier selection. Both methods were applied on a transmission cables for motorcycles manufacturer which needed to select the suitable supplier among five alternatives and based on five selection criteria, and the results showed that both methods were helpful, however the Fuzzy-TOPSIS method was more effective in the supplier selection problem.

Dargia et al. [33] developed a multi-criteria decision making framework for helping the Iranian automotive industry in supplier selection process. First, the researchers made a huge survey for determining the most critical factor in the supplier selection process by using the Nominated Group Technique (NGT) and the result was seven critical factors, a Fuzzy Analytical Network Process (F-ANP) was then used for determining weights of each selection factor and selecting the most appropriate supplier, the model was applied on an automotive company and it ensured its effectiveness.

Gupta et al. [34] developed an integrated Fuzzy AHP - Fuzzy Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) model for service provider selection under conflicting criteria and uncertainty environment. First, the selection criteria were determined, then Fuzzy AHP method was used for calculating the weight of each criterion, after that Fuzzy PROMETHEE method was used for selecting the best alternative that suited the organization needs, Geometrical Analysis for Interactive Aid (GAIA) software was then used for demonstrating the model results and providing better understanding, a sensitivity analysis was conducted to ensure the model validity and model results ensured high sensitivity to change in criteria weights, finally the proposed model was applied on a real world case study, a cermet company, to select the most appropriate service provider and the model ensured its effectiveness.

Haleh and Hamidi [35] used fuzzy sets to assess and rank the suppliers and selecting the best one.

3.5 Outsourcing Selection Field

Kahraman et al. [36] tried to solve the selection problem of the right ERP outsourcing alternatives under uncertainty conditions using Fuzzy-AHP multi-criteria decision making method, the researchers applied the proposed model on an automotive firm to help it select the best ERP outsourcing alternative and the model proved its effectiveness.

Chen et al [37] integrated the triangular fuzzy method with PROMETHEE method for selecting the most appropriate outsourcing partner for organizations based on seven selection criteria and the proposed model was applied on a real world case study and helped the organization to select the most suitable outsourcing partner among four alternatives.

3.6 Other MCDM Fields

Yilmaz and Dagdeviren [38] integrated Fuzzy-PROMETHEE method with zero-one goal programming to develop a MCDA approach for equipment selection among conflicting criteria.

For handling the uncertainty problem within the quality management consultant selection process, Kabir and Sumi [39] used fuzzy set theory as it is a powerful tool for handling uncertainty, therefore Fuzzy method was integrated with the AHP method for determining the selection criteria weights, then the PROMETHEE method was used for associating a preference function to each criterion and ranking the alternatives.

For extending the power of Data envelopment analysis (DEA) MCDM method, Wen and Li [40] introduced a Fuzzy-DEA method for ranking all the decision-making units (DMUs), for solving the fuzzy model, a hybrid algorithm combined with fuzzy simulation and genetic algorithm was used, finally a numerical example was used for illustrating how the model worked.

Yuen and Ting [41] integrated the triangular fuzzy number and ranking method with PROMETHEE II method for developing a hybrid model used in text book selection and the model was applied on a case study to ensure its validity and effectiveness.

4 Neutrosophic Logic

In realistic decision making situations, information cannot always be described by unique crisp numbers, they may imply indeterminacy, and therefore Neutrosophy was originally introduced by Smarandache [42]. Neutrosophy is a branch of philosophy which studies the origin, nature and scope of neutralities and their interactions with different ideational spectra [42]. Neutrosophy studies the ideas and notions that are neutral, indeterminate, vague, unclear, ambiguous, and incomplete [43]. Neutrosophic sets are capable of dealing with uncertainty, indeterminate and inconsistent information, therefore Smarandache seek to publish the concept of neutrosophic set in all sciences branches, social sciences, and humanities [43]. Smarandache refined the neutrosophic set to n components: $t1$, $t2$, … ; $i1$, $i2$, …,ik ; $f1$, $f2$, …, fl , with j+k+l = n > 3 [43]. The basic concept of neutrosophic set is a generalization of classical set or crisp set [44, 45], fuzzy set [5], intuitionistic fuzzy set [46].

After Smarandache's introducing the concept of neutrosophic set, different sets were quickly proposed in the literature. Wang et al. [47] extended the concept of neutrosophic set to single valued neutrosophic sets (SVNSs) and they also studied the set theoretic operators and various properties of SVNSs; many other sets were introduced, such as neutrosophic soft set [48], weighted neutrosophic soft sets [49], generalized neutrosophic soft set [50], neutrosophic parametrized soft set [51], neutrosophic soft expert sets [52, 53], neutrosophic soft multi-set [54], neutrosophic bipolar set [55], neutrosophic cubic set [56, 57], rough neutrosophic set [58, 59], interval rough neutrosophic set [60], interval-valued neutrosophic soft rough sets [61, 62], etc.

5 Applications of Neutrosophic Logic in MCDM

Yang and Li [63] proposed new aggregation operators under single-valued neutrosophic environment, The researchers used single-valued neutrosophic set (SVNS) which is an extension of traditional fuzzy set, as SVNS can handle incomplete and inconsistent information, then, a MCDM method was introduced according to the proposed operators and cosine similarity measures, finally the proposed method was applied on an illustrative example of helping an investment company to select the best investment option and the results demonstrated that the proposed method was practical and effective. For future work, the researchers recommended studying new aggregation operators under neutrosophic environment.

Jency and Arockiarani [64] proposed a model based on adjustable and mean potentiality approach by means of single valued neutrosophic level soft sets, also the notion of weighted single valued neutrosophic soft set was introduced with an investigation to its applicability in decision making in an imprecise environment.

Biswas et al. [65] proposed a method with the aim of dealing with impreciseness and incompleteness information of decision maker's assessments to achieve better solution to multi-criteria decision making problems. The researcher introduced triangular fuzzy number neutrosophic sets by integrating triangular fuzzy numbers with single valued neutrosophic set. For ensuring the proposed method effectiveness, it was used to help a medical firm in selecting a medical representative.

Chi and Liu [66] introduced a MCDM model by integrating TOPSIS method with interval neutrosophic set for solving multi-criteria decision making problems in uncertainty environment. The proposed method was used in helping an investment company to select the best investment option and the results demonstrated its simplicity and ease of use.

Biswas et al. [67] presented a model for solving MCDM problems with missing or unknown information about criteria weights. They used Grey Relational Analysis (GRA) with single-value neautrosophic for developing the model, finally an illustrative example was used to ensure model practicality and effectiveness.

Dey et al. [68] extended the grey relational analysis (GRA) problems with interval neutrosophic for solving MCDM problems with incomplete or unknown weights of criteria. The researchers first developed two optimization models for recognizing criteria weights, then extended GRA was used for ranking the alternatives, finally a numerical example was used to ensure the applicability of the method.

Broumi et al. [69] proposed an extended TOPSIS model for solving MCDM problems, TOPSIS was integrated with interval neutrosophic for its great ability in handling inconsistent information. The extended TOPSIS model used interval neutrosophic for representing the values of the criteria, then alternatives were ranked using TOPSIS method. Finally an example was solved to illustrate the model effectiveness.

For solving uncertain, imprecise, incomplete, and inconsistent information in MCDM problems, Zhang and Wu [70] developed a two-stage method for single-valued neutrosophic or interval neutrosophic multi-criteria decision making. First a maximizing deviation method was introduced for assigning criteria weights under interval neutrosophic environments, then TOPSIS was used for ranking the alternatives and selecting the optimum choice. Finally the method was applied in a real world case study and proved its effectiveness.

Chen and Ye [71] introduced a projection model of neutrosophic numbers and its application for solving the MCDM problem of clay-bricks selection, an actual case was used for applying the model and the results demonstrated model's applicability and ease of use.

Ye [72] developed a single valued neutrosophic cross-entropy measure and its MCDM method was proposed based on the proposed cross entropy under single valued neutrosophic environment. Finally, an illustrative example was solved to illustrate the application of the proposed method.

Pramanik and Mondal [73] introduced a MCDM method based on interval neutrosophic sets where the rating of altenatives was expressed with interval neutrosophic values characterized by interval truth-membership degree, interval indeterminacy-membership degree, and interval falsity-membership degree. The single valued neutrosophic grey relational analysis method was extended to interval neutrosophic environment and applied MCDM problems. Finally, an illustrative example was solved to illustrate the application of the proposed method.

Mandal and Basu [74] developed a new similarity measures in neutrosophic environment based on hypercompex number system for ranking alternatives and selecting the best one while solving MCDM problems. Finally a numerical example was introduced to ensure the method effectiveness.

Mondal and Pramanik [75] introduced a MCDM method based on Dice and Jaccard similarity measures of interval rough neutrosophic set and interval neutrosophic mean operator and finally they applied the method on a laptop selection case.

Biswas et al. [76] introduced cosine similarity measure between two trapezoidal fuzzy neutrosophic numbers for solving MCDM problems under neutrosophic environment and a numerical example was solved to illustrate the method work.

Ma et al. [77] introduced a time series analysis approach integrated with interval neutrosophic sets for selecting trustworthy cloud service. Three numerical examples were used to illustrate the approach applicability and efficiency in selecting risk-sensitive service.

Mondal and Pramanik [78] developed a neutrosophic MCDM model based on hybrid score-accuracy functions of single valued neutrosophic numbers for teacher selection in recruitment process in higher education, an illustrative example was introduced for demonstrating the model work.

Mondal and Pramanik [79] also proposed a single valued neutrosophic MCDM model for selecting the best school for children. A numerical example was used to prove the model efficiency.

Ye and Smarandache [80] introduced a refined single-valued neutrosophic set (RSVNS) and a similarity measure of RSVNSs, then a MCDM method using RSVNS information was presented based on the similarity measure of RSVNSs. Finally a real case study was used for applying the metod to help a construction firm selecting the best project and the results demonstrated the method effectiveness.

Mondal and Pramanik [81] introduced a rough neutrosophic multi-attribute decision making method based on grey relational analysis by extending the neutrosophic grey relational analysis method to rough neutrosophic grey relational analysis method and applying it to multi-attribute decision making problem. In this method, the rating of all alternatives was expressed with upper and lower approximation operator and the pair of neutrosophic sets which were characterized by truth-membership degree, indeterminacy-membership degree, and falsity-membership degree. Finally a numerical example was used to demonstrate the method applicability.

Mondal and Pramanik [82] also proposed a rough neutrosophic multi-attribute decision making method based on rough accuracy score function. The rating of all alternatives was expressed with upper and lower approximation operator and the pair of neutrosophic sets which were characterized by truth-membership degree, indeterminacy-membership degree, and falsity-membership degree. Finally a numerical example was used to ensure the method effectiveness.

Peng et al. [83] introduced a new outranking approach for solving MCDM problems under neutrosophic environment by integrating simplified neutrosophic sets with ELECTRE method. Two practical examples were provided to ensure the practicality and effectiveness of the proposed approach.

Ye [84] introduced a new MCDM method using the weighted correlation coefficient or the weighted cosine similarity measure of single-valued neutrosophic sets where the alternatives evaluation was made by truth-membership degree, indeterminacy-membership degree, and falsity-membership degree under single-valued neutrosophic environment. Finally, an example was solved for proving the applicability of the proposed method.

Biswas et al. [85] proposed a ranking method for solving MCDM problems using single-valued trapezoidal neutrosophic numbers (SVTrNNs), which was a special case of single-valued neutrosophic numbers. Finally, an example was used for demonstrating the model efficiency.

Conclusion

This study demonstrated the role of fuzzy set theory and neutrosophic logic in the field of multi-criteria decision making; applications and researches of the two methods were presented to illustrate the improvements and developments made in MCDM field using those two methods. It is concluded that there is a weakness point in neutrosophic sets applications in MCDM real world case studies. Although there are many researchers that use numerical examples for applying the neutrosophic model, there is a shortage in real case studies usage. Also, neutrosophic logic should be applied more in MCDM fields like supplier selection, software selection, risk assessment and other fields, where fuzzy set theory made a noticeable development, to investigate its strength and weakness points. Therefore, there are many future works that can be done, such as:

1. Apply Neutrosophic logic on different decision support problems.
2. Apply Neutrosophic logic on software engineering.
3. Propose new adaptive mechanism to update Neutrosophic logic.
4. Solve time series forecasting.
5. Analyze the effect of hybridizing Neutrosophic logic with meta-heuristics algorithms.
6. Apply Neutrosophic logic with neural networks.
7. Design Neutrosophic logic Controller by Particle Swarm Optimization.

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