Recent Developments on Fuzzy AHP and ANP Under Vague and Imprecise Data: Evidence from INFUS Conferences

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ABSTRACT

When a decision maker is not sure about assigning a value for a pairwise comparison, he/she should assign a fuzzy value such as '*between 3 and 4'* or '*around 5*'. These expressions can be represented by fuzzy numbers, which make the use of fuzzy AHP methods possible. Each new fuzzy set extension has caused a new fuzzy AHP method to be developed by researchers. The INFUS conference is a scientific arena where researchers can present their new fuzzy AHP extensions and benefit from the discussions during the sessions. This paper summarizes the latest fuzzy AHP/ANP extensions that have been developed in the recent years at INFUS conferences.

Keywords: fuzzy extensions of AHP; intuitionistic fuzzy AHP; picture fuzzy AHP; neutrosophic AHP; spherical fuzzy AHP; Pythagorean fuzzy AHP; q-rung orthopair fuzzy AHP

1. Introduction

The AHP and ANP are the most popular multi-attribute decision making methods all over the world. Fuzzy set theory has caused almost all multi-attribute methods to be extended under vague and imprecise data where exact and complete data are hard to obtain. Recent extensions of ordinary fuzzy sets such as intuitionistic fuzzy sets, picture fuzzy sets, and neutrosophic sets provided the opportunity for a new extension of each method to be developed. Thus, intuitionistic fuzzy AHP, neutrosophic AHP, spherical fuzzy AHP, picture fuzzy AHP, Pythagorean fuzzy AHP, Fermatean fuzzy AHP, q-rung orthopair fuzzy AHP have appeared in the literature. Sub-extensions of each of these based on the used fuzzy numbers have also been developed such as interval-valued intuitionistic fuzzy AHP, triangular intuitionistic fuzzy AHP, trapezoidal intuitionistic fuzzy AHP and single-valued intuitionistic fuzzy AHP.

INFUS is an acronym for Intelligent and Fuzzy Systems. It is an international research forum with the goal of advancing the foundations and applications of intelligent and fuzzy systems, computational intelligence, and soft computing for applied research in general and for complex engineering and decision support systems. The principal mission of INFUS is bridging the gap between fuzzy and

intelligent systems and real complex systems via joint research between universities and international research institutions, encouraging interdisciplinary research and bringing multidisciplinary researchers together. INFUS is an arena for the newly developed fuzzy extensions of the AHP to be presented and discussed. Many AHP papers have been submitted to INFUS and reviewed by a peer review process each year. These papers have been presented, discussed and then published in Springer proceedings having SCOPUS and WOS indexing. The ANP has rarely been used in fuzzy set approaches since super matrices and limit matrices are not well-defined issues and it is hard to obtain the corresponding equivalent fuzzy operations. Hence, there are almost no papers on fuzzy ANP in the following list of fuzzy AHP/ANP reviews.

The rest of the paper is organized as follows. Section 2 presents AHP/ANP papers from INFUS 2019. Section 3 presents AHP/ANP papers from INFUS 2020. Section 4 summarizes AHP/ANP papers from INFUS 2021. Section 5 summarizes AHP/ANP papers from INFUS 2022. Finally, the paper is concluded in Section 6.

2. INFUS 2019 AHP/ANP papers

At INFUS 2019, a total of 17 papers on fuzzy AHP were presented. These papers developed some new fuzzy extensions of the AHP and applied them to popular problems such as construction company selection, home health care vehicle routing, social suitable development factor evaluation, airline flight carbon election performance assessment, suitability evaluation of blockchain technologies and others. Among these AHP-based papers, many studies combined fuzzy AHP with other multi-criteria decision making methods. One of the most utilized approaches was to combine fuzzy AHP with fuzzy TOPSIS to solve various types of decision making problems. Kabayir et al. (2019) developed a framework for construction company selection by combining the fuzzy AHP and fuzzy TOPSIS methods. Karasan et al. (2019) used a combined AHP and TOPSIS method for evaluating the challenges of sustainable cities. The fuzziness was represented by neutrosophic fuzzy sets. It is not only TOPSIS, but also the COPRAS method that has been widely combined with fuzzy AHP. Seker et al. integrated the fuzzy AHP and fuzzy COPRAS methods for solar power plant location selection. In this study, intuitionistic fuzzy sets were used. Montazer et al. (2019) combined the AHP and COPRAS methods to select a strategic partner for an airline.

At INFUS 2019, many papers used AHP modifications where AHP is modeled with the extensions of fuzzy sets to represent fuzziness. The fuzzy sets where both membership and non-membership can be defined separately, such as intuitionistic fuzzy sets, Pythagorean fuzzy sets and spherical fuzzy sets are the most commonly used extensions of fuzzy sets utilized in AHP modification. Peker et al. (2019) evaluated home health care vehicle routing methods using intuitionistic fuzzy AHP. Ozkan and Aydin (2019) introduced a supplier selection model that combines intuitionistic fuzzy AHP and goal programming. Karasan et al. (2019a) used the Pythagorean fuzzy AHP method for clean energy technology selection. Karasan et al. (2019b) performed a risk analysis of autonomous vehicle driving systems using Pythagorean fuzzy AHP. Gundogdu and Kahraman (2019) modified the AHP by

using spherical fuzzy sets for industrial robot selection. Hesitant fuzzy sets, which enable multiple evaluations to be assigned to represent the hesitancy in decision making, have also been used to modify the AHP. Hesitant AHP methods usually use hesitant linguistic term sets in which the linguistic expressions such as "more than", "between", or "at least" can be modelled. Öztayşi et al. (2019a) created an innovative teaching feedback system design using hesitant fuzzy AHP. Öztayşi et al. (2019b) weighted performance indicators of debt collection offices using hesitant fuzzy AHP. Other fuzzy extensions such as Z-numbers and neutrosophic sets have also been used for the extension of AHP. Yildiz and Kahraman (2019) used a Z-numbers-based AHP for evaluating social sustainable development factors.

The AHP is used with other methods such as QFD to define the criteria weights to satisfy customer needs. Seker et al. (2019) used a combined fuzzy AHP and QFD methodology for retail chain evaluation. Cinar and Cebi (2019) assessed risks of the mining industry using a fuzzy logic-based combined QFD and AHP approach.

At INFUS 2019, even though fuzzy ANP is more complex and has some computational indistinctness, it was used as well as the AHP. Three papers utilized fuzzy ANP to evaluate various multi-criteria decision-making methods. Maden (2019) used fuzzy ANP to evaluate the suitability of blockchain–based systems. This approach was applied to evaluate the systems in a logistics company. Aydogan and Bereketli Zafeirakopoulos (2019) evaluated the leg base airline flight carbon emission performance using fuzzy ANP. Kılıç and Kabak (2019) analyzed the relationship between human development and competitiveness using fuzzy ANP and data envelopment analysis (DEA).

3. INFUS 2020 AHP/ANP papers

At INFUS 2020, a total of 16 papers on fuzzy AHP were presented. These papers developed some new fuzzy extensions of AHP and applied them to some popular problems such as assessment of freight transportation alternatives, beacon technology selection, food waste management, sustainable supplier selection and others.

Jaller and Otay (2020) proposed AHP and TOPSIS based on spherical fuzzy sets to evaluate the sustainable vehicle technology alternatives for freight transportation. The authors evaluated the alternatives using the following five criteria: financial; business and market-related; environmental and legal; maintenance and repair availability; and safety and vehicle performance factors. Twenty-one sub-criteria were also evaluated. Öztayşi et al. (2020) tackled a beacon technology selection problem which enables applications providing location-based services such as notifications, tracking, and navigation via smart mobile devices. One of the most commonly adopted business models based on beacon technology is location-based advertisements. In their paper, target customers were defined, and the most appropriate advertisement was sent to the customer based on his/her location. While the conversion rates of this model are high, there is a need for a dynamic pricing model that calculates the value of an advertisement to an advertiser in a given location. They proposed an advertisement pricing model using the spherical fuzzy AHP scoring method with four main criteria, namely the content quality, daily potential, frequency of communication and user

interest. Buyuk and Temur (2020) proposed a spherical fuzzy AHP method for food waste management since this decision involves multi-faceted dimensions simultaneously under a linguistic and uncertain environment. A numerical example was conducted in order to indicate how the model can be used for food waste management. With the help of the proposed model, a supportive tool for decision makers was created in related institutions such as municipalities. Unal and Temur (2020) used the spherical fuzzy AHP method for the selection of sustainable suppliers. The proposed method takes into consideration the following four main criteria: traditional, economic, social and environmental. Interviews were conducted with three experts who have valuable experiences in this field of study. Otay and Yildiz (2020) studied a cloud service provider selection problem under a fuzzy environment. In the proposed model, a hierarchical structure with six criteria (financial, performance, security and privacy, assurance, agility and usability), and four alternatives, was designed based on a comprehensive literature review. The weights of the criteria were obtained using Pythagorean fuzzy AHP. To rank the alternatives, the Pythagorean fuzzy VIKOR method was used. Bakioglu and Atahan (2020) obtained the weights of factors affecting the adoption of self-driving vehicles using interval-valued Pythagorean fuzzy AHP. The study considered psychological, safety, driving-related and external factors. Alem (2020) assessed four different types of agriculture including traditional farming, artificial intelligence aided farming, vertical farming and plant-based meat. In the study, cost, ecology and customers were selected as the three main criteria. No dependency could be found between these criteria; therefore, interval type-2 fuzzy AHP was selected to determine the weight of the factors. After the weights were found, hesitant fuzzy TOPSIS was used to rank the alternatives. Hasgul and Aytore (2020) solved a road selection problem for autonomous trucks in Turkey. Although self-driving trucks have not yet been introduced, the aim of this study was to be a pioneer in the field by examining truck roads between industrial areas to decide which road would be the best fit to invest in for autonomous trucking. Since there are many uncertainties in this decision, the fuzzy AHP method was used. Cost and maintenance, traffic, demands in the region, trade potential, and weather conditions were the considered criteria. Otay and Atik (2020) concentrated on a location evaluation and selection problem of an oil station. The location was comprised of several quantitative and qualitative criteria such as environmental, economic, and traffic-related factors. The spherical fuzzy AHP and spherical fuzzy WASPAS methods were used to provide a solution for the problem. Karayazi and Bereketli (2020) proposed a multi-criteria decision model to assist a global logistics company on the blockchain software selection problem based on Buckley's fuzzy AHP. Six main criteria and 13 sub-criteria were used in the hierarchy. Sahin et al. (2020) presented an application in which companies within the country can be individually categorized according to the logistic performance index (LPI). Using classical AHP and fuzzy AHP, the most important criteria were also found. These results provided a practical application that shows which areas are behind the LPI index and which criteria can improve their performances. Demir and Koca (2020) compared the applications of intuitionistic multi-criteria supplier selection methods under a fuzzy environment. The intuitionistic fuzzy AHP and TOPSIS methods were thoroughly discussed and utilized to complete a green supplier evaluation. Three alternative green suppliers and 10 sub-criteria under the three main-criteria, including supplier performance, environmental protection and supplier risk

were considered. The intuitionistic fuzzy TOPSIS and AHP methods were used to rank alternatives from best to worst. Keivanpour (2020) proposed a model for benchmarking and visualization of the ergonomic risks in manufacturing. The joint application of the fuzzy AHP and treemap was applied for benchmarking and mapping these risks. Ilbahar et al. (2020) identified risks in research and development projects and evaluated them using interval-valued intuitionistic fuzzy AHP and a fuzzy inference system. Alkan (2020) examined the risks of the advancement of technology more closely on sustainable supply chain environments. The aim was to create a model that evaluated the risks that are encountered under the digitalization perspective of the sustainable supply chain. The main and sub-criteria of the risk assessment model were determined by a comprehensive literature review and experts' opinions. Subsequently, the interval-valued Pythagorean fuzzy AHP method was used to evaluate the related risks arising in the sustainable supply chain with digitalization. Mizrahi et al. (2020) developed the prioritization-based taxonomy of the accounting information systems (AIS)'s information quality factors using the fuzzy AHP approach. The information production processes of AIS directly affect the quality of the information produced. For this reason, critical factors affecting the information quality were determined by focusing on the information production processes of AIS. Nineteen information quality factors were extracted from the literature. Then, fuzzy AHP was used to prioritize and develop the taxonomy of the identified factors.

4. INFUS 2021 AHP/ANP papers

At INFUS 2021, a total of 13 papers on fuzzy AHP and one paper on fuzzy ANP were presented. These papers developed some new fuzzy extensions of AHP and applied them to popular problems such as a software selection problem, green hospital attribute prioritization, clean energy evaluation, sustainable supply chain development.

Konyalıoğlu et al. (2021) proposed an assessment technique to develop an innovative multi-criteria decision-making approach that incorporates the ANP method under a fuzzy environment. The authors provided a decision model with four criteria and 11 sub-criteria which are dependent on each other. The authors prioritized the criteria and the results revealed that the highest weight belongs to energy-related factors as criteria and as sub-criteria, the highest weight belongs to renewable material usage. Altıntaşlı et al. (2021) focused on prioritization of significant criteria of service quality and evaluation of different business-to-customer (B2C) websites using fuzzy AHP and fuzzy TOPSIS. The authors used eight criteria namely, agility, responsiveness towards customers, website appearance, easy-to-use interface, variety of payment options, security of payment options, product variety and product prices. The authors determined the weights of the criteria using fuzzy AHP and evaluated the alternatives using fuzzy TOPSIS. Miloševic et al. (2021) focused on the problem of internet and communication technologies in smart cities and provided a comparative study using fuzzy AHP and interval type-2 fuzzy sets. The decision model used for comparison involved six criteria, namely, governance, environment, buildings, mobility, education, and healthcare. The results of the study revealed that the methods are significantly similar. Yel et al. (2021) focused on selecting a project

management process based on technical and managerial criteria by considering the skills of the teams. The authors found the weights of the criteria using fuzzy AHP and then utilized the fuzzy EDAS and WASPAS methods for ranking. Mukul et al. (2021) proposed a framework for evaluating clean energy alternatives using hesitant fuzzy sets. The evaluation criteria weights were found by hesitant AHP and then, clean energy alternatives were assessed by the hesitant EDAS method. The authors proposed a decision model involving five criteria, namely, environment, social, security and governance, economic, and technical and 15 sub-criteria. By using hesitant fuzzy sets, the decision makers could express their hesitance using linguistic terms such as *between* or *at least*. Cubukcu and Cantekin (2021) proposed using fuzzy AHP for determining the best firewall selection problem. The decision model involved three criteria, namely, cost, capacity, and productivity and nine sub-criteria. The model was solved using fuzzy AHP and five firewall alternatives were ranked. Cevik Onar and Ibil (2021) focused on personal treatment methods for Type-2 diabetes. The authors proposed a model for determining the best oral anti-diabetic combination for patients in different risk groups. Spherical fuzzy AHP was used in the study to solve the decision model which included six criteria and five alternatives. Menekşe and Akdag (2021) studied an information technology governance problem as a multicriteria decision making problem and proposed using the spherical fuzzy AHP and ELECTRE methods. The decision model involved five criteria and four alternatives. In the proposed solution, the criteria weights were determined with the spherical fuzzy AHP technique and the alternatives were ranked with ELECTRE by constructing outranking relationships utilizing score and accuracy functions developed for spherical fuzzy sets. Ariöz et al. (2021) concentrated on barriers to the big data driven fight against the COVID-19 pandemic. After a literature survey, the authors provided a decision model with four criteria and 17 sub-criteria. The criteria involved in the study are socio-economic structure, technological incompetence, data-related characteristics, and governmental policies. The authors used spherical fuzzy AHP to solve the problem and the results revealed that data related characteristics are the most important barrier. Buran and Erçek (2021) applied spherical fuzzy AHP to evaluate the public transportation business model taking into account internal and external perspectives with a political, economic, social, technological, legal, and environmental (PESTLE) analysis. The authors solved the problem with a decision model involving two main criteria, nine sub-criteria and 26 sub-sub-criteria. Cizmecioglu et al. (2021) focused on a software project management model selection problem. In order to evaluate the different models such as Waterfall, Prototype, Spiral, Incremental, Iterative and Agile they used an interval-valued neutrosophic AHP methodology. The decision model involved five criteria, namely, requirement determination, cost, success guarantee, making changes, and time. The results of the case study showed that an agile project management methodology was the best alternative for the given case. Ilbahar et al. (2021) concentrated on a social acceptability problem, and the factors affecting social acceptance were listed first. The authors used a BOCR model to categorize the factors as benefits, opportunities, costs and risks. The decision model involved four criteria and 10 sub-criteria. The social acceptance assessment problem was solved using interval-valued intuitionistic fuzzy (IVIF) AHP. Yıldızbaş et al. (2021) emphasized the importance of a circular economy and focused on key challenges of the lithium-ion battery recycling process. The authors approached the problem with a decision model involving four criteria,

namely, technical, economic, social, and environmental and 30 sub-criteria. The results of the study showed that economic challenges have relatively more importance during the lithium-ion battery recycling process.

5. INFUS 2022 AHP/ANP papers

At INFUS 2022, a total of 200 papers were presented and 17 of these papers utilized the AHP method to solve the problems. Eleven of these AHP-based papers preferred extensions of fuzzy sets, while four articles included the application of ordinary fuzzy sets. Only two of these papers were related to the classical AHP method. These papers developed some new fuzzy extensions of the AHP and applied them to some popular problems such as supply chain evaluation, site selection, risk assessment, human resources, and IT technology.

Yalcinkaya and Cebi (2022) used Pythagorean fuzzy AHP to handle risks in the pharmaceutical supply chain under four main criteria (delivery reliability, quality, operational, communication and technology) and 28 sub-criteria. In the study, the Pythagorean fuzzy AHP method was used to determine the importance degrees of the criteria. Tunc and Tasdemir (2022) proposed a study to predict the daily amount of money that should be in ATM devices. In the study, the fuzzy AHP method was used to determine importance degrees of the parameters affecting the cash flow. Coban and Cevik Onar (2022) used an integrated method including the fuzzy AHP and TOPSIS methods to determine the appropriate site for Grid-Connected Photovoltaic Power Plants. In the paper, fuzzy AHP was used to define importance degrees of the five criteria including social, technical, economic, environmental, and political factors. Oturakci and Konyalioglu (2022) proposed an objective risk assessment method and prioritized precautionary actions that must be taken. In the study, a fuzzy AHP-based TOPSIS method was used to prioritize actions which were developed for the hazards defined by a Fuzzy Failure Mode Effect Analysis. Yel et al. (2022) proposed a study to determine the competencies of system analysts at a participating bank using fuzzy AHP-based neutrosophic Z-number sets. In the study, fuzzy AHP was used to determine the importance weights of the competencies while rankings of system analysts were made using neutrosophic Z-number sets. Bal and Ucal (2022) discussed the importance degrees of decision criteria on remote-working preferences of companies using picture fuzzy AHP. Ilhan, Gundogdu, and Karasan (2022) considered a spaceport site selection problem using spherical fuzzy AHP. In the study, five main criteria and twenty sub-criteria and the method were applied to determine the importance degrees of these criteria. Aslan and Tolga (2022) conducted a study to determine the most appropriate area in which artificial intelligence (AI) technology can be used in aviation maintenance-repair-overhaul activities and to detect the most suitable AI tool. For the first aim, eleven criteria were determined and an AHP-based VIKOR method was used, while for the second aim, twelve criteria were determined and an AHP-based TOPSIS method was used. In the study, AHP was utilized to determine the importance degrees of the criteria. Cakir and Tas (2022) conducted a study to present the challenges of remote working for businesses using circular intuitionistic fuzzy AHP. Alkan and Kahraman (2022) proposed a spherical fuzzy Z-AHP method and the method was applied to a supplier selection problem. Kose et al. (2022) used a spherical fuzzy AHP method to prioritize the factors causing

rheumatoid arthritis and to select the best treatment alternative. In the study, three main criteria and a total of twenty-three sub-criteria are evaluated. Seker (2022) utilized interval-valued Pythagorean fuzzy AHP to determine importance degrees of the agility factors considering the fuel oil supply chain. In the paper, a total of nine criteria were considered. Ilbahar et al. (2022) proposed an integrated method including interval-valued intuitionistic fuzzy (IVIF) AHP and safety and critical effect analysis (SCEA) to evaluate and prioritize the risk in waste-to-energy (WtE) plants. In the study, after risks in a WtE plant were categorized, IVIF AHP was used to obtain the probability, severity, frequency, and detectability weights of these risks, and then SCEA was utilized to prioritize the risk. Soygüder et al. (2022) studied a supplier selection problem under the selected seven criteria using fuzzy AHP. Yaman and Yaylali (2022) used twelve criteria and a spherical fuzzy AHP-based TOPSIS method for the selection of relevant locations of cargomatics. Zakieh et al. (2022) developed a decision support system for investments in cryptocurrencies. In the study, the AHP method was used to understand the individual preferences of the investors. Dalyan et al. (2022) utilized an interval-valued Pythagorean fuzzy (IVPF) AHP-based TOPSIS method for the selection of an enterprise resource planning system under four main criteria and twenty-two sub-criteria. In the study, IVPF AHP was utilized to determine weights of the criteria while the TOPSIS method was used to evaluate alternatives.

6. Conclusion

Figure 1 illustrates the distributions of AHP papers at each INFUS conference. It is clear that AHP papers using extensions of ordinary fuzzy sets have significantly increased from year to year (8 to 11), whereas ordinary fuzzy AHP papers have decreased (9 to 4). Classical fuzzy AHP has only been used 2 times at INFUS 2022.

The usage of vague data in AHP/ANP methods has caused new scales to be defined for pairwise comparisons including a scale for interval-valued intuitionistic fuzzy AHP, a scale for interval-valued spherical fuzzy AHP, and a scale for interval-valued picture fuzzy sets. Usage of different extensions and different fuzzy numbers in AHP made it necessary to develop a consistency measurement for each fuzzy AHP method. This approach has received a large amount of criticism in the literature since the consistency measurement is made by a defuzzification method, leaving the fuzziness very early, as in the classical AHP. Consistency measurement is an important problem area of fuzzy AHP methods. Conducting research on this problem provides important opportunities for researchers. Since the membership degrees are between 0-1, it is necessary to investigate which value the fuzzy numbers correspond to on the 1-9 scale and to develop solutions for this.

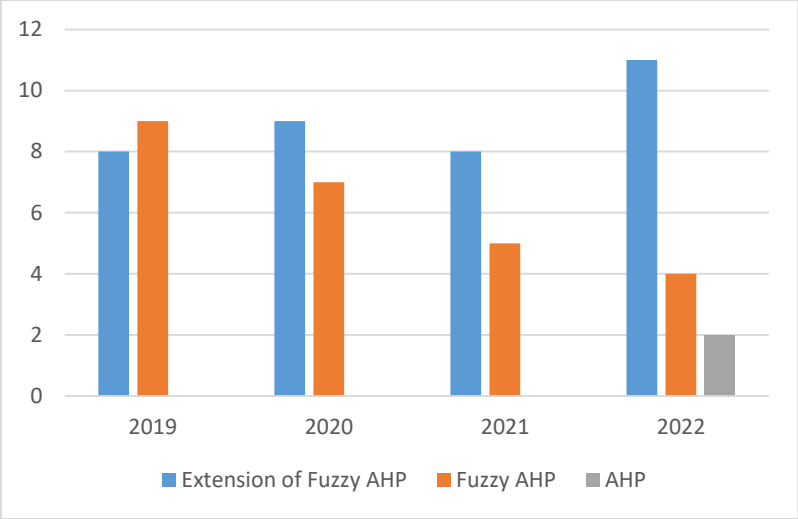

Figure 1 Distributions of AHP papers at INFUS conferences

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