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Consensus-Based Public Acceptance and Mapping of Nuclear Energy Investments Using Spherical and Pythagorean Fuzzy Group Decision Making Approaches

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ABSTRACT The purpose of the study is to identify the ways to improve the public acceptance for nuclear energy investment in energy importing countries. In this framework, 4 different factors are identified that have an influence on this situation. After that, consensus model is applied for obtaining the fuzzy preference relations at the most consistency level. Next, the criteria are weighted by using DEMATEL (Decision Making Trial and Evaluation Laboratory) methodology based on the Spherical fuzzy sets. Additionally, another evaluation has also been made by considering the Pythagorean fuzzy sets to check the consistency and coherency of the analysis results. It is identified that the results of both Spherical and Pythagorean fuzzy sets are almost the same. This situation gives information about the consistency of the analysis results. Also, sensitivity analysis is also applied by using the different values of δ with 4 cases. It is determined that there is significant coherency in the consensus-based group decision-making process. The findings indicate that security conditions play the most crucial role to improve the public acceptance for nuclear energy investments in energy importing countries. In addition, it is also identified that economic benefit and environmental issues also have importance influence on this situation. It is recommended that countries should be able to convince their citizens that nuclear energy is safe. Within this context, necessary measures should be taken for security in nuclear power plants and this situation should be clearly explained to citizens. It is obvious that priority should be mainly given to the security issues to improve public perception of nuclear energy investments in energy importing countries. One of the issues most worried by the public is the possibility of an explosion of the nuclear reactor. Hence, for this purpose, the nuclear power plant should be open to international inspection.

INDEX TERMS Consensus decision making, spherical fuzzy sets, Pythagorean fuzzy sets, DEMATEL, nuclear energy investments, public acceptance.

I. INTRODUCTION

Protons and neutrons in the nucleus of an atom are tightly connected to each other. In order to obtain nuclear energy, neutrons are thrown into the nucleus of the atom and the protons and neutrons connected to each other are separated. By using the steam of the heat provided in this process, electricity can be obtained [1]. There are many advantages of nuclear energy. Countries can produce their own energy by using nuclear energy. This situation contributes to the energy supply security of countries. Furthermore, owing to the use of nuclear energy, countries will not have to import the energy they need from abroad. This issue will positively affect the current account balance of the countries [2]. In addition,

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no carbon gas is released into the atmosphere during the use of nuclear energy. This situation is accepted as a significant advantage of using nuclear energy since it does not cause environmental pollution. Also, with the help of the nuclear energy, it is possible to generate electricity any time in a day. Since the energy production process can be acted more planned, this stated issue increases energy efficiency [3].

On the other hand, there are some disadvantages in using nuclear energy. After obtaining nuclear energy, radioactive wastes occur. These wastes need to be disposed of effectively. Otherwise, this situation seriously threatens the health of living things. However, how nuclear waste generated by nuclear power plants should be disposed of is still a question mark [4]. Furthermore, the risk of explosion of the nuclear power plant is accepted as one of the most important disadvantages of nuclear energy. The reactions in the nuclear reactor also need to be controlled to minimize the risk of the nuclear reactor explosion. As a result of the explosion of the nuclear reactor in Chernobyl in 1986, many people lost their lives. Moreover, the possibility of natural disasters and terrorist attacks should be taken into consideration in the selection of the location where nuclear power plants will be established [5]. These situations increase the possibility of explosion of nuclear reactors. After the earthquake and tsunami, radioactive material leakage occurred in the Fukushima nuclear power plant in 2011.

As can be understood from these examples, nuclear energy has very important advantages and disadvantages at the same time. Thus, nuclear energy has been the subject of serious discussion among people. Nuclear energy is of vital importance especially for countries that do not have their own energy resources [6]. The main reason for this situation is that these countries have to import most of their energy needs from abroad. As a result, countries are faced with the current account deficit problem which increases the economic fragility of the country. On the other hand, by constantly importing energy from abroad, it becomes politically dependent on that country. In summary, the use of nuclear energy will contribute to the social and economic development of energy-importing countries [7]. However, due to mainly considering its disadvantages, there is a serious opposition among the public regarding the use of nuclear energy. This issue poses a serious obstacle to the establishment of nuclear power plants. In other words, public acceptance of nuclear energy is vital for the efficiency of this energy [8].

It is very important to make some studies to increase the acceptance of the public about nuclear energy. Another important issue in this process is the methodology used. Applying methods that are not suitable for the subject lead to reaching inappropriate results and suggesting incorrect strategies. Consensus method is an approach that can be taken into consideration to achieve this goal. Consensus, in its most general definition, means making decisions that will be accepted by all interlocutors on a subject in dispute. In this process, a suggestion is evaluated by considering both its positive and negative aspects. In this way, it provides the opportunity to share information among people regarding a controversial subject [9]. This situation contributes to achieving a more accurate result. Additionally, the consensus approach allows more ideas to be generated on the subject and more creativity in problem solving. Hence, the details regarding the subject can be explained in all aspects. This will help to reach more effective results, especially in solving complex problems. However, the biggest disadvantage of the consensus method is that there are problems due to differences of opinion between experts. Because the communication between all experts cannot be very strong, it may not be possible to reach a common consensus in this process in some cases [10].

Multi-criteria decision-making methods (MCDM) are also other approaches that can be taken into consideration to increase public acceptance in nuclear energy investments. With these methods, it can be determined which of the different factors are more important [11]. Moreover, these methodologies can be used to determine the most optimal of different alternatives. As can be seen from the definitions, these approaches can yield useful results in cases where there are many different factors affecting an issue. In addition, owing to these methods, it is possible to make more effective decisions in complex processes [12]. In the literature, these approaches can also be taken into consideration with fuzzy logic. Thanks to the use of fuzzy numbers, it can be more possible to handle the uncertainty in decision making process [13], [14].

In this study, it is aimed to improve the public acceptance for nuclear energy investment in energy importing countries. Within this context, firstly, a detailed literature review has been conducted for the subject. As a result, 4 different factors are identified that have an influence on the public acceptance of nuclear energy investments which are health, economic, security and environmental issues. After that, 4 different experts who are competent in nuclear energy are asked to evaluate these criteria. In this process, consensus decision-making procedure has been applied. In this framework, group consensus levels of the evaluations of decision makers are analyzed. Within this scope, the feedback mechanism is implemented so that the fuzzy preference relations can be obtained at the most consistency level. Then, these evaluations are converted to Spherical fuzzy sets. In the final process, DEMATEL methodology is implemented by considering these fuzzy sets to understand which factors are more significant to improve the public acceptance regarding the nuclear energy investments. Additionally, another analysis has also been performed with the help of the Pythagorean fuzzy sets in order to check the coherency and consistency of the results.

The most significant contribution of the study to the literature is related to the methodology. In multi-criteria decision analysis, there is not always a consensus in the evaluations of decision makers regarding the criteria. This situation adversely affects the efficiency of the analysis process. By using the consensus decision-making method, more effective and accurate results can be achieved in the decision-making process [15]. In addition, by taking this approach into account, it will be possible to solve this problem more effectively in issues that have a lot of public reaction, such as nuclear energy. For this purpose, the application of the consensus-based decision-making process to MCDM methods is now a necessity. There is no consensus on the opinions of different experts in the analyzes made with these methods. However, this problem is solved to a great extent with the consensus-based decision-making method. One of the most important novelties of this study is that the consensus-based decision-making process is adapted to MCDM methods [16].

On the other hand, considering the DEMATEL approach in the analysis process is another motivation of the study. There are other methods such as analytic hierarchy process (AHP) and analytic network process (ANP) to calculate the importance weights of different criteria. The most important advantage of the DEMATEL approach compared to these methods is that the impact relationship analysis can be performed [17]. Owing to this analysis, the causality relationship between variables can also be determined [18]. As a result, it will be possible to present more effective strategies for the solution of the problem [19]. In other words, priority actions can be determined to increase public acceptance for nuclear energy investments.

Also, using Spherical fuzzy numbers will help to achieve more effective results. The use of fuzzy sets in MCDM methods is also an important issue recently. However, the increasing uncertainty environment and the complexity of real-world data made it necessary to examine fuzzy logic methods in a more complicated way. The biggest advantage of Spherical fuzzy numbers is that different parameters are used in membership functions [20]. Unlike traditional fuzzy numbers, Spherical fuzzy numbers consider membership, non-membership, and hesitancy [21]. This will contribute to achieving more consistent results.

Furthermore, an evaluation has also been performed by using the Pythagorean fuzzy sets. Hence, it is aimed to examine the consistency and coherency of the analysis results. These fuzzy sets provide a stronger representation of uncertainty in comparison with the traditional ones [22], [23]. Additionally, it can be identified how public acceptance in nuclear energy investments can be improved in energy-importing countries. Nuclear energy investments are vital for the economic growth of these countries because they have current account deficit problems mainly due to high imports for the energy. Hence, public acceptance is very important to increase the efficiency of these investments. With the help of the results to be obtained, it will be understood what should be focused on to improve public acceptance for these investments.

There are 6 different sections in this study. Firstly, general information about the subject is given. Moreover, the second section of the study is related to the literature review. Moreover, in the third part of the study, the theoretical information regarding the methods used in the study is identified. The fourth section includes the analysis regarding public acceptance of nuclear energy investments for energy importing countries. The fifth section focuses on the analysis results and strategies to improve this situation are given in the sixth section.

II. LITERATURE REVIEW

Under this heading, studies parallel to our research topic in the literature are examined. In this context, firstly, studies on public acceptance in nuclear energy production are included. In the last part, the missing area in the literature on the subject will be specified.

A. LITERATURE ON PUBLIC ACCEPTANCE FOR NUCLEAR ENERGY INVESTMENTS

There are many studies on nuclear energy in the literature. The subject of public acceptance is one of the most popular of these studies. According to a significant part of these studies, a significant portion of the public opposes nuclear power plants because they do not find it safe. Kim *et al.* [24] focused on the public acceptance situation of the nuclear power plants in South Korea. While using logistic regression methodology, it is identified that security plays the most significant role to improve public acceptance for these investments. Furthermore, they underlined that education level, income level, political ideology and other demographic factors are effective on the public opinion for this situation. Ho *et al.* [25] made a similar analysis for Singapore. In this study, a survey analysis has been conducted with 600 participants. They concluded that people give importance to the risk factors in these plants. Moreover, Xia *et al.* [26] tried to understand the determinants of public acceptance for nuclear energy usage in China. They determined that to achieve this objective, the dangerous perception of the public towards nuclear energy must be corrected. Wang *et al.* [27] and Berényi *et al.* [28] evaluated the public acceptance of nuclear power plants for different countries, such as China and Hungary. They defined that states should give confidence that all precautions are taken for the security.

According to some studies, the most important way to increase public acceptance for nuclear energy investments is to emphasize that nuclear energy is environmentally friendly. Fossil fuels emit significant carbon gas into the atmosphere. Because this situation leads to environmental pollution, it causes the public to be sick [29]. This issue harms the country both socially and economically. Especially in recent years, sensitivity to the environment has been increasing all over the world because of this situation [2]. There is no carbon emission in the use of nuclear energy. Increasing awareness of this advantage in the use of nuclear energy also strengthens public acceptance of this issue. Vossen [30] made an evaluation to understand the main indicators of public acceptance for nuclear energy investments. According to the results of the analysis, it is necessary to emphasize that this type of energy does not pollute the environment primarily to increase public acceptance in nuclear energy investments.

In addition, Liao *et al.* [31] also identified that in order for the social perception to be positive, it should be stated that nuclear energy is environmentally friendly.

On the other hand, one of the most important ways to increase public acceptance for nuclear energy investments is emphasizing the economic advantages. Nuclear energy has many economic benefits. First, countries will be able to produce their own energy thanks to nuclear energy [32], [33]. As a result, energy will not be imported, and the current account deficit problem will be minimized [34], [35]. According to many studies in the literature, the economic benefits should be highlighted to improve the perception of nuclear energy among the public [36]–[38]. Gupta *et al.* [39] focused on this subject for United States (US). They determined that nuclear energy supports are raising when oil, gas and coal become expensive and scarce in US. This situation explains that when there is an economic advantage, the public accepts nuclear energy investments more easily. Parallel to this study, Prăvălie and Bandoc [40] also underlined the significance of economic advantage for improving the public acceptance in nuclear energy investments.

Some of the researchers also stated that the perception of nuclear power plants is negative because there are health fears of the local population. As a result of obtaining nuclear energy, radioactive wastes are formed. These wastes cause both air and water pollution. Hence, especially the people living in the region are worried about being sick. Because of this situation, the people of the region oppose the establishment of the nuclear power plant [4]. Thus, in some studies in the literature, the importance of this issue has been emphasized. Liu and Wei [41] focused on the waste management strategies of nuclear power plants. They identified that the radioactive wastes generated because of nuclear energy should be disposed of effectively.

B. LITERATURE ON THE METHODOLOGY

In the consensus decision-making method, the opinions of experts are primarily provided. Subsequently, these evaluations are evaluated, and the group consensus level is calculated [42]. When this level is below the threshold value, feedback mechanism is applied. This process continues until the consensus level exceeds the threshold [43]. Hence, it is accepted that the analysis results obtained using the consensus decision-making method are more consistent. This is the most important advantage of this method compared to others [44]. Due to this positive aspect, this method has been preferred by many researchers in the literature. For example, Gao *et al.* [45] considered this approach with the aim of the selection of the green suppliers in electronics manufacturing. Furthermore, Lu *et al.* [46] focused on the selection of the energy-saving technology in hotels with the help of this approach. Additionally, Dong *et al.* [47] evaluated social network by using consensus decision making methodology.

Spherical fuzzy numbers also have some advantages over traditional fuzzy numbers. In the analysis process, three different parameters are taken into consideration which are membership, non-membership and hesitancy [48]. In this framework, the indecision of experts is also taken into consideration by including hesitancy in the analysis process [49]. It is accepted that the results will be more consistent by using more parameters in the analysis process [50]. Because of this positive aspect, especially in recent years, there has been an increase in studies using Spherical fuzzy numbers in the literature. For example, Liu *et al.* [51] used Spherical fuzzy sets for public evaluation of shared bicycles in China. Moreover, important environmental factors for the child development are examined with these fuzzy sets by Ashraf *et al.* [52]. Furthermore, Kahraman *et al.* [53] considered Spherical fuzzy numbers to select the optimal locations for the hospitals.

In this study, the DEMATEL method is used to determine the criterion weights. There are other approaches in the literature that are considered in determining the significance levels of criteria, such as AHP and ANP. The DEMATEL method has many benefits compared to other methods. By using DEMATEL, an impact relationship map of factors can be created. Thus, the causality relationship between variables can be defined [54], [55]. Because of these points, many researchers in the literature used the DEMATEL method in their analysis. As an example, Dalvi-Esfahani *et al.* [56] evaluated social media addiction by applying DEMATEL methodology. Additionally, Abdel-Basset *et al.* [57] focused on the selection of the best suppliers. In this study, the criteria are weighted by DEMATEL approach. Furthermore, Büyüközkan and Güleryüz [58] aimed to examine the resource selection for renewable energy investments in Turkey by considering DEMATEL methodology.

C. THE RESULTS OF LITERATURE REVIEW

The literature review provides the opportunity to understand some issues. There has been an important increase in studies on nuclear energy investments, especially in recent years. In a significant part of these studies, factors affecting public acceptance for nuclear energy were examined. The main reason is that there is a significant opposition to nuclear energy investments worldwide. This situation adversely affects the efficiency of nuclear energy investments. This issue is more important especially for energy-importing countries. These countries pay huge amounts to import energy which causes them to have a current account deficit problem. Therefore, it is obvious that nuclear energy is vital especially for these countries. As a result, it is thought that studies addressing increasing public acceptance for nuclear energy investments in energy-importing countries are needed. In this study, it is intended to understand the ways to improve the public acceptance for nuclear energy investments. Within this context, an evaluation has been performed by consensus-based Spherical fuzzy DEMATEL methodology. The results of the analysis will help determine which issue should be prioritized in order to improve public perception on nuclear energy. Also, this methodology is firstly applied in this study for the public acceptance of nuclear energy investments. Thus, it is obvious that this study has methodological originality.

III. METHODOLOGY

Under this section, firstly, consensus decision-making methodology is explained. Later, Spherical and Pythagorean fuzzy sets are detailed. In the next part, necessary information is given with respect to DEMATEL approach. Finally, necessary information is provided for the proposed model.

A. CONSENSUS MODEL FOR GROUP DECISION MAKING

Consensus is one of the most important issues for decision making problems [59]. Especially, difficulties in the group decision making process make the consensus necessary for the right decisions in the expert team [60]. The main problem of group decision making approach is to provide the consistency among the decision makers and reach a consensus for the preference relations [61]. There are several procedures defining the consensus model for group decision making. Group decision making approaches including the consensus and consistency measurements could give more comprehensive and accurate results with an appropriate feedback mechanism. Proposed consensus model is summarized for group decision making below [62].

A fuzzy preference relation (P) gives information about the relation degrees of criteria by a membership function $\mu_p : X \times X \rightarrow [0, 1]$. The preference matrix is defined as in the equation (1).

$$P = (P_{ik}) \quad \text{and } P_{ik} = \mu_p(x_i, x_k), (\forall i, k \in \{1, \ldots, n\}) \tag{1}$$

Corresponding fuzzy preferences among the criteria are computed to define the consistency levels of criteria with the equation (2).

$$CP_{ik} = \frac{\sum_{j=1; i \neq k \neq j}^{n} (CP_{ik})^{j1} + \ldots + (CP_{ik})^{j(n-1)}}{(n-1) * (n-2)} \tag{2}$$

Consistency level for each pair of criteria is defined using the corresponding fuzzy preferences with the equations (3) and (4).

$$CL_{ik} = 1 - \left(\frac{2 * |CP_{ik} - P_{ik}|}{(n-1)} \right) \tag{3}$$

$$CL_i = \frac{\sum_{k=1; i \neq k}^{n} (CL_{ik} + CL_{ki})}{2(n-1)} \tag{4}$$

Global consistency level (GCL) is generated with the equation (5).

$$GCL = \frac{\sum_{i=1}^{n} CL_i}{n} \tag{5}$$

Similarity matrices for pairs of decision makers and collective results are determined with the equations (6) and (7) respectively.

$$SM_{ik}^{hl} = 1 - \left| P_{ik}^{h} - P_{ik}^{l} \right| \tag{6}$$

$$SM_{ik} = \phi \left(SM_{ik}^{hl} \right) \tag{7}$$

where, ϕ is the aggregation function, e_h and e_l are the pairs of experts, $(h < l), \forall h, l = 1, \ldots, m$. Global consensus degrees among the decision makers are defined as in the equation (8).

$$CR = \frac{\sum_{i=1}^{n} \frac{\sum_{k=1; k \neq i}^{n} (SM_{ik} + SM_{ki})}{2(n-1)}}{n} \tag{8}$$

The consensual degrees of each decision maker are calculated with the equation (9).

$$Z_{ik}^{h} = (1-\delta) * CL_{ik}^{h} + \delta * \left(\frac{\sum_{l=h+1}^{n} SM_{ik}^{hl} + \sum_{l=1}^{h-1} SM_{ik}^{lh}}{n-1} \right) \tag{9}$$

In these equations,δ refers to the control parameter of consistency and consensus degrees. $\delta \in [0, 1]$ and the greater values than 0.5 show that it is given more importance to the consensus than the lower values than 0.5. In this study, the value of δ is determined as 0.75 for defining the importance of consensus among the decision makers. Collective fuzzy preference relations P_{ik}^{c} are employed by using the consistent and consensual individual fuzzy preferences with the equations (10)-(12). In these equations, σ is a permutation of $\{1, \ldots, m\}$, $Z_{ik}^{\sigma(h)} \geq Z_{ik}^{\sigma(h+1)}$, $\forall h = 1, \ldots, m-1$. $\langle Z_{ik}^{\sigma(h)}, P_{\sigma(i)} \rangle$ is two-tuple with $Z_{ik}^{\sigma(h)}$ the hth largest value in $\{Z_{ik}^{1}, \ldots, Z_{ik}^{m}\}$.

$$P_{ik}^{c} = \Phi w \left(\langle Z_{ik}^{1}, P_{ik}^{1} \rangle, \ldots, \langle Z_{ik}^{m}, P_{ik}^{m} \rangle \right) = \sum_{h=1}^{m} w_h * P_{ik}^{\sigma(h)} \tag{10}$$

$$w_h = Q(h/n) - Q(h-1)/n) \tag{11}$$

$$(r) = \begin{cases} 0 & if\ r < a \\ \dfrac{r-a}{b-a} & if\ a \leq r \leq b \\ 1 & if\ r > a \end{cases} \tag{12}$$

Proximity levels PP_{ik}^{h} for each pair of criteria and the relation between criteria Pr^{h} are given in the equation (13) and (14) respectively.

$$PP_{ik}^{h} = 1 - \left| P_{ik}^{h} - P_{ik}^{c} \right| \tag{13}$$

$$Pr^{h} = \frac{\sum_{i=1}^{n} \frac{\sum_{k=1; k \neq i}^{n} (PP_{ik}^{h} + PP_{ki}^{h})}{2(n-1)}}{n} \tag{14}$$

Consensus control level (CCL) is computed to understand whether decision makers reach a consensus on the fuzzy preference relations by the equation (15).

$$CCL = (1-\delta) * GCL + \delta * CR \tag{15}$$

The final consensus result can be obtained by considering the value of consensus control level. Accordingly, the result should be compared with a threshold value $\gamma \in [0.1]$. Threshold is generally selected as 0.85 for the consensus satisfaction. The feedback mechanism is also considered to appoint the revised values of fuzzy preference relation if it is necessary. The procedure of consensus model is repeated in several rounds by changing the preference relations based on the directions of feedback mechanism until the value of CCL is higher than the threshold. For this purpose, the values of EXPCH, ALT, and APS are computed by the equations (16)-(18).

$$EXPCH = \left\{h \left| (1-\delta) * CL^h + \delta * Pr^h < \gamma \right.\right\} \tag{16}$$

$$ALT = \left\{(h, i) \left| e_h \in EXPCH \wedge (1-\delta) * CL_i^h + \delta * \frac{\sum_{k=1;k\neq i}^{n} (PP_{ik}^h + PP_{ki}^h)}{2(n-1)} < \gamma \right.\right\} \tag{17}$$

$$APS = \left\{(h, i, k) \left| (h, i) \in ALT \wedge (1-\delta) * CL_{ik}^h + \delta * PP_{ik}^h < \gamma \right.\right\} \tag{18}$$

B. SPHERICAL FUZZY SETS

Vagueness and complex problems of multi-criteria decision-making models brings on the agenda for the several extensions of the fuzzy sets even if the linguistic evaluations of decision makers do not dramatically change in this process. Zadeh introduced the fuzzy sets and the earlier extensions for providing more accurate results in the uncertain environment [63]. Type-2, interval-valued, and intuitionistic fuzzy sets are among the main contributions to the literature of decision making under the uncertainty [64], [65]. Nowadays, one of the most prominent extensions of fuzzy sets is Spherical fuzzy sets that is the generalized form of Neutrosophic and Pythagorean fuzzy numbers [66]. This method is similar to the second type-intuitionistic fuzzy sets, and it also aims to use the hesitancy degree of fuzzy set in the decision-making process properly. Characteristics of Spherical fuzzy sets and their essential operations are defined as follows [67]. In this method, the squared sum of membership μ, non-membership ν, and hesitancy π parameters are between 0 and 1. They are also presented at the same scale individually. Hence, it is aimed to provide more comprehensive and accurate results by using all items in the decision-making process at the same time. Spherical fuzzy sets $\tilde{A}_S$ are defined as in the equations (19) and (20).

$$\tilde{A}_S = \left\{\langle u, (\mu_{\tilde{A}_S}(u), v_{\tilde{A}_S}(u), \pi_{\tilde{A}_S}(u)) | u \in U\right\} \tag{19}$$

$$0 \le \mu_{\tilde{A}_S}^2(u) + v_{\tilde{A}_S}^2(u) + \pi_{\tilde{A}_S}^2(u) \le 1, \quad \forall_u \in U \tag{20}$$

The membership, non-membership, and hesitant degrees of Spherical fuzzy sets are illustrated in Figure 1 [66].

X_1 and X_2 are two universes and $\tilde{A}_S = (\mu_{\tilde{A}_S}, v_{\tilde{A}_S}, \pi_{\tilde{A}_S})$ and $\tilde{B}_S = (\mu_{\tilde{B}_S}, v_{\tilde{B}_S}, \pi_{\tilde{B}_S})$ are two Spherical fuzzy sets from the universe of discourse X_1 and X_2. The details are demonstrated in the equations (21)-(24).

$$\tilde{A}_S \oplus \tilde{B}_S = \left\{\left(\mu_{\tilde{A}_S}^2 + \mu_{\tilde{B}_S}^2 - \mu_{\tilde{A}_S}^2\mu_{\tilde{B}_S}^2\right)^{\frac{1}{2}}, v_{\tilde{A}_S}v_{\tilde{B}_S}, \left(\left(1-\mu_{\tilde{B}_S}^2\right)\pi_{\tilde{A}_S}^2 + \left(1-\mu_{\tilde{A}_S}^2\right)\pi_{\tilde{B}_S}^2 - \pi_{\tilde{A}_S}^2\pi_{\tilde{B}_S}^2\right)^{\frac{1}{2}}\right\} \tag{21}$$

$$\tilde{A}_S \otimes \tilde{B}_S = \left\{\left(\mu_{\tilde{A}_S}\mu_{\tilde{B}_S}, (v_{\tilde{A}_S}^2 + v_{\tilde{B}_S}^2 - v_{\tilde{A}_S}^2 v_{\tilde{B}_S}^2\right)^{\frac{1}{2}}, \left(\left(1-v_{\tilde{B}_S}^2\right)\pi_{\tilde{A}_S}^2 + \left(1-v_{\tilde{A}_S}^2\right)\pi_{\tilde{B}_S}^2 - \pi_{\tilde{A}_S}^2\pi_{\tilde{B}_S}^2\right)^{\frac{1}{2}}\right\} \tilde{A}_S \otimes \tilde{B}_S = \left\{\left(\mu_{\tilde{A}_S}\mu_{\tilde{B}_S}, (v_{\tilde{A}_S}^2 + v_{\tilde{B}_S}^2 - v_{\tilde{A}_S}^2 v_{\tilde{B}_S}^2\right)^{\frac{1}{2}}, \left(\left(1-v_{\tilde{B}_S}^2\right)\pi_{\tilde{A}_S}^2 + \left(1-v_{\tilde{A}_S}^2\right)\pi_{\tilde{B}_S}^2 - \pi_{\tilde{A}_S}^2\pi_{\tilde{B}_S}^2\right)^{\frac{1}{2}}\right\} \tag{22}$$

$$\lambda * \tilde{A}_S = \left\{\left(1-\left(1-\mu_{\tilde{A}_S}^2\right)^{\lambda}\right)^{\frac{1}{2}}, v_{\tilde{A}_S}^{\lambda}, \left(\left(1-\mu_{\tilde{A}_S}^2\right)^{\lambda} - \left(1-\mu_{\tilde{A}_S}^2 - \pi_{\tilde{A}_S}^2\right)^{\lambda}\right)^{\frac{1}{2}}\right\}, \quad \lambda > 0 \tag{23}$$

$$\tilde{A}_S^{\lambda} = \left\{\mu_{\tilde{A}_S}^{\lambda}, \left(1-\left(1-v_{\tilde{A}_S}^2\right)^{\lambda}\right)^{\frac{1}{2}}, \left(\left(1-v_{\tilde{A}_S}^2\right)^{\lambda} - \left(1-v_{\tilde{A}_S}^2 - \pi_{\tilde{A}_S}^2\right)^{\lambda}\right)^{\frac{1}{2}}\right\}, \quad \lambda > 0 \tag{24}$$

The aggregated values of Spherical fuzzy sets are given with the Spherical weighted arithmetic mean (SWAM) operator with the equation (25).

$$SWAM_w\left(\tilde{A}_{S1}, .., \tilde{A}_{Sn}\right) = w_1\tilde{A}_{S1} + \ldots + w_n\tilde{A}_{Sn} = \left\{\left[1-\prod_{i=1}^{n}\left(1-\mu_{\tilde{A}_{Si}}^2\right)^{w_i}\right]^{\frac{1}{2}}, \prod_{i=1}^{n} v_{\tilde{A}_{Si}}^{w_i}, \times\left[\prod_{i=1}^{n}\left(1-\mu_{\tilde{A}_{Si}}^2\right)^{w_i} - \prod_{i=1}^{n}\left(1-\mu_{\tilde{A}_{Si}}^2 - \pi_{\tilde{A}_{Si}}^2\right)^{w_i}\right]^{\frac{1}{2}}\right\} \tag{25}$$

C. PYTHAGOREAN FUZZY SETS

Pythagorean fuzzy sets (P) are generated by Yager [68] with the aim of identifying a new class of non-standard fuzzy membership grades. They are defined as a set of pairs over a universal set ϑ. The details are demonstrated on the equation (26).

$$P = \{\langle\vartheta, \mu_P(\vartheta), n_P(\vartheta)\rangle / \vartheta \epsilon U\} \tag{26}$$

In this equation, μ_P and n_P: $U \rightarrow [0, 1]$ indicate the membership and nonmembership of the element $\vartheta \epsilon U$ in the Pythagorean fuzzy set form. They are detailed on the equation (27).

$$(\mu_P(\vartheta))^2 + (n_P(\vartheta))^2 \le 1 \tag{27}$$

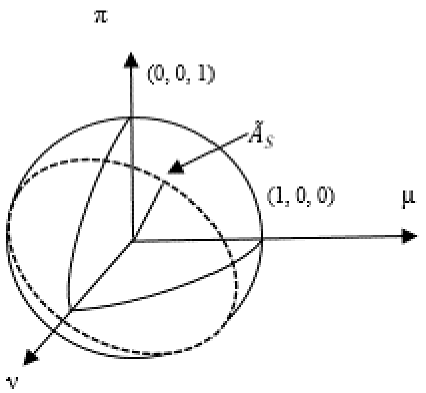

FIGURE 1. Illustration of Spherical fuzzy sets.

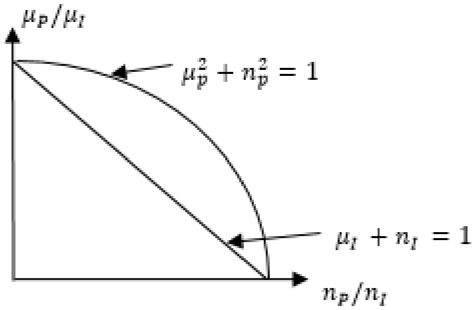

FIGURE 2. Membership and Nonmembership degrees of IFS and PFS.

Furthermore, the equation (28) gives information about the degree of indeterminacy.

$$\pi_P(\vartheta) = \sqrt{1 - (\mu_P(\vartheta))^2 - (n_P(\vartheta))^2} \tag{28}$$

On the other side, the equations (29)-(32) demonstrate he essential operations of Pythagorean fuzzy sets.

$P_1 = \left\{\langle \vartheta, P_1(\mu_{P_1}(\vartheta), n_{P_1}(\vartheta))\rangle / \vartheta \epsilon U\right\}$ and $P_2 = \left\{\langle \vartheta, P_2(\mu_{P_2}(\vartheta), n_{P_2}(\vartheta))\rangle / \vartheta \epsilon U\right\}$

$$P_1 \oplus P_2 = P\left(\sqrt{\mu_{P_1}^1 + \mu_{P_2}^2 - \mu_{P_1}^1 \mu_2^2}, n_{P_1} n_{P_1}\right) \tag{29}$$

$$P_1 \otimes P_2 = P\left(\mu_{P_1}\mu_{P_2}, \sqrt{n_{P_1}^2 + n_{P_2}^2 - n_{P_1}^2 n_{P_2}^2}\right) \tag{30}$$

$$\lambda P = P\left(\sqrt{1 - \left(1 - \mu_p^2\right)^\lambda}, (n_p)^\lambda\right), \quad \lambda > 0 \tag{31}$$

$$P^\lambda = P\left((\mu_p)^\lambda, \sqrt{1 - \left(1 - n_p^2\right)^\lambda}\right), \quad \lambda > 0 \tag{32}$$

Additionally, Figure 2 illustrates the relationship between intuitionistic (IFS) and Pythagorean fuzzy sets (PFS).

Moreover, the deffuzzied values are computed as in the equation (33) [69].

$$S(\vartheta) = (\mu_P(\vartheta))^2 - (n_P(\vartheta))^2 \tag{33}$$

where $S(\vartheta) \in [-1, 1]$

D. DEMATEL

DEMATEL approach is used to calculate the weights of the criteria. In this method, impact relation map can be generated, and this is accepted as the main superiority of this approach [55]. This situation provides an opportunity to understand the causality relationship among the items. In the first step, expert opinions are collected by considering 5 different scales that are 0 (no influence), 1 (low influence), 2 (medium influence), 3 (high influence) and 4 (very high influence) [56]. By considering the average values of these evaluations, the direct relation matrix (A) is calculated as in the equation (34).

$$A = \begin{bmatrix} 0 & a_{12} & a_{13} & & \cdots & a_{1n} \\ a_{21} & 0 & a_{23} & & \cdots & a_{2n} \\ a_{31} & a_{32} & 0 & & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & & \vdots \\ a_{n1} & a_{n2} & a_{n3} & & \cdots & 0 \end{bmatrix} \tag{34}$$

After that, this matrix is normalized by considering the equations (35) and (36).

$$B = \frac{A}{max_{1 \le i \le n} \sum_{j=1}^{n} a_{ij}} \tag{35}$$

$$0 \le b_{ij} \le 1(36) \tag{36}$$

In the next step, total relation matrix (C) is created by using the equation (37). In this equation, I gives information about the identity matrix [57].

$$C = B(I - B)^{-1} \tag{37}$$

Additionally, the sums of rows and columns (D and E) are calculated with the equations (38) and (39).

$$D = \left[\sum_{j=1}^{n} e_{ij}\right]_{nx1} \tag{38}$$

$$E = \left[\sum_{i=1}^{n} e_{ij}\right]_{1xn} \tag{39}$$

The values of D+E give information about the significance weights of the criteria whereas the causal relationship is calculated by considering the values of D-E. Additionally, in order to calculate the impact-relation map, a threshold value (α) is calculated as in the equation (40).

$$\alpha = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \left[e_{ij}\right]}{N} \tag{40}$$

E. PROPOSED MODEL

While considering the methods discussed in the previous section, a new hybrid model has been proposed in this study. It is an integrated group decision making approach is proposed based on the consensus model, Spherical and Pythagorean fuzzy DEMATEL. The flowchart of the proposed model is illustrated in Figure 3.

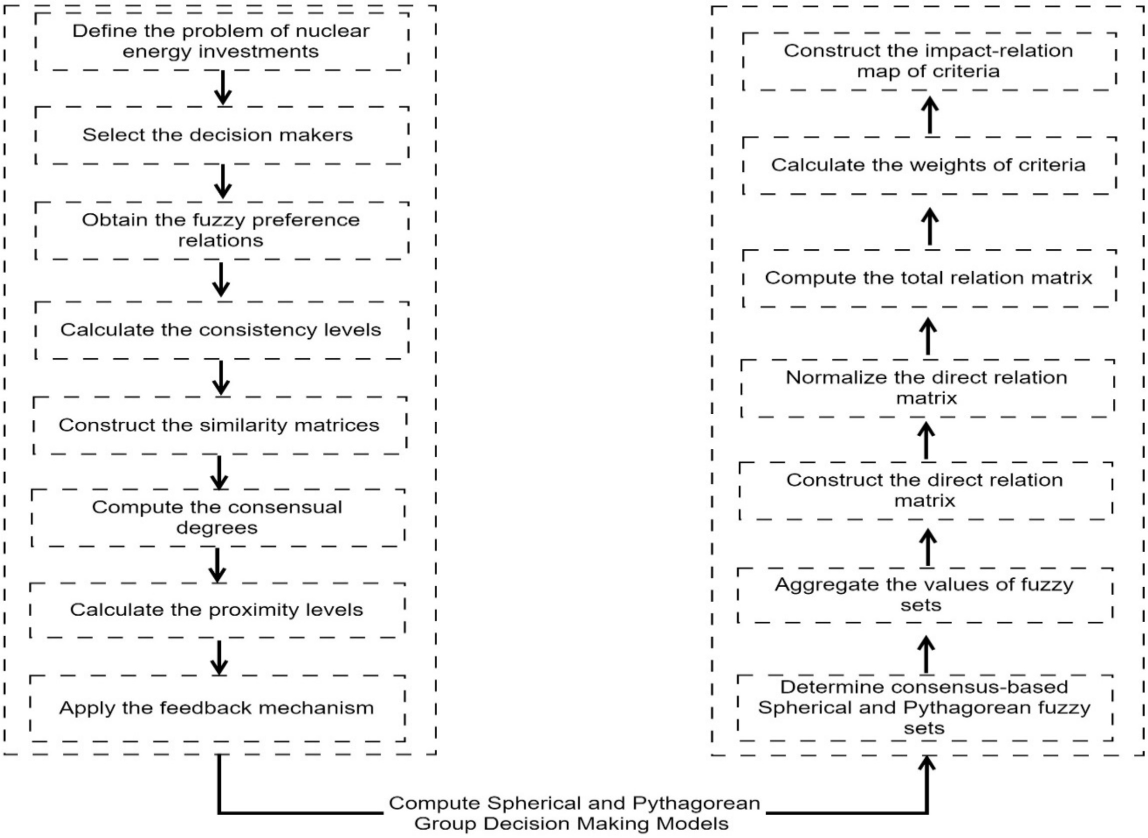

FIGURE 3. **The flowchart of the proposed model.**

This proposed model includes two different stages. Firstly, consensus-based evaluations of the decision makers are calculated. Within this framework, firstly, by conducting a detailed literature review, the problem of nuclear energy investment is defined. In the second step, the decision makers are appointed to evaluate the criteria. Next, the fuzzy preference relations of each decision maker are obtained by considering the equation (1). After that, consistency level for each pair of criteria is calculated by considering the equations (3)-(5). Additionally, collective similarity matrix is generated in the fifth step. Later, consensus degrees for criterion (cc_i) are identified with the equations (8)-(9). Moreover, proximity levels for each pair of criteria are determined to demonstrate the relation between criteria while considering the equations (13)-(14). Finally, feedback mechanism is implemented to change the values of fuzzy preference with the help of the equations (16)-(18).

The second stage of the proposed model is related to the weighting the criteria with Spherical and Pythagorean DEMATEL methods. In this context, firstly, the consensus-based fuzzy preference relations are used for constructing the Spherical fuzzy sets by the equation (19)-(20). Next, aggregated values of Spherical fuzzy sets from decision makers are calculated by considering SWAM operator using the equation (25). In the third step, the deffuzification procedure is applied by the score function. After that, normalization procedure is implemented by the equations (35)-(36). Total relation matrix is generated with the equation (37) in the fifth step. Later, the impact and relation directions as well as the weights of criteria are identified for both Spherical and Pythagorean fuzzy sets by the equations (38)-(39). Also, impact-relation map of criteria is constructed in the final step.

Hence, the main novelty of this proposed model is the integration of consensus-based group decision-making results with Spherical fuzzy DEMATEL. One of the most important aspects in MCDM models is that decision makers do not always reach a consensus in their evaluation of the criteria. This situation leads to a decrease in the effectiveness of decision-making processes. It is possible to minimize this problem by using the consensus group decision making method. By taking Spherical fuzzy numbers into account in the analysis process, more accurate results can be obtained. The main reason is that membership, non-membership, and hesitancy issues are taken into account at the same time in the analysis process. Additionally, an analysis has also been performed by using Pythagorean fuzzy DEMATEL methodology. With the help of this situation, the consistency of the analysis results can be evaluated.

IV. ANALYSIS RESULTS

Two-stage consensus-based group decision making approach based on Spherical and Pythagorean fuzzy sets is applied

TABLE 1. Proposed criteria.

Criteria	References
Health Factors (criterion 1)	[4],[41]
Economic Benefit (criterion 2)	[32],[39]
Security Conditions (criterion 3)	[20],[24]
Environmental Issues (criterion 4)	[26],[30]

for analyzing the public acceptance of the nuclear energy investments. The first stage is to construct the fuzzy preference relations based on consensus model for group decision making. The second stage uses the consensus-based fuzzy preferences to measure the weights of criteria using Spherical and Pythagorean fuzzy DEMATEL methods consecutively. Analysis results are given in detail as follows

STAGE 1: COMPUTING THE CONSENSUS-BASED EVALUATIONS OF DECISION MAKERS

Step 1: The problem of nuclear energy investments is defined with supported literature. The criteria regarding the public acceptance of nuclear energy investments are defined based on the literature review. In this evaluation, 4 different criteria are identified for this situation. The details of them are given on Table 1.

Table 1 indicates that there are mainly 4 different items that affect the public acceptance of the nuclear energy investments. Firstly, health conditions can play a very significant role in this context. Especially people living in the region where the nuclear power plant will be established are worried that this power plant will adversely affect their health. Therefore, proving that nuclear energy does not have too many negative effects on health plays an important role in terms of public acceptance. In addition, emphasizing the economic benefits of nuclear energy could positively affect the public image. Another important issue in this process is safety factors. Convincing the public that necessary security measures will be taken in nuclear power plants will increase public acceptance. Finally, it should be noted that nuclear energy is an environmentally friendly type of energy. The situation that nuclear energy does not emit carbon gas into the atmosphere can improve the public's acceptance of nuclear energy.

Step 2: The decision makers are appointed to obtain the evaluation. 4 decision makers who are the experts in the field of energy economics, nuclear engineering, risk management, and renewable energy are appointed to provide the preferences defining membership degrees within [0, 1]. Table 2 gives the information about the decision makers in detail.

Step 3: The fuzzy preference relations of each decision maker are collected using the equation (1). The results are represented in Table 3.

By using the equation (2), corresponding fuzzy preferences of each decision maker are computed in Table 4.

TABLE 2. Profiles of decision makers.

Decision Makers (DM)	Education Status	Experience	Areas of Expertise
DM 1	PhD	16 years	Energy Economics
DM 2	PhD	14 years	Nuclear Engineering
DM 3	PhD	21 years	Risk Management
DM 4	PhD	18 years	Renewable Energy

TABLE 3. Fuzzy preference relations for criteria.

Decision Maker 1					Decision Maker 2				
P^1	C1	C2	C3	C4	P^2	C1	C2	C3	C4
C1		0.40	0.50	0.80	C1		0.40	0.50	0.80
C2	0.30		0.60	0.60	C2	0.30		0.60	0.60
C3	0.40	0.80		0.30	C3	0.40	0.80		0.30
C4	0.50	0.60	0.70		C4	0.50	0.60	0.70	
Decision Maker 3					**Decision Maker 4**				
P^3	C1	C2	C3	C4	P^4	C1	C2	C3	C4
C1		0.40	0.50	0.80	C1		0.40	0.50	0.80
C2	0.30		0.60	0.60	C2	0.30		0.60	0.60
C3	0.40	0.80		0.30	C3	0.40	0.80		0.30
C4	0.50	0.60	0.70		C4	0.50	0.60	0.70	

TABLE 4. Corresponding fuzzy preference relations for criteria.

Decision Maker 1					Decision Maker 2				
CP^1	C1	C2	C3	C4	CP^2	C1	C2	C3	C4
C1		0.72	0.68	0.43	C1		0.58	0.53	0.62
C2	0.42		0.58	0.43	C2	0.53		0.57	0.38
C3	0.38	0.38		0.67	C3	0.58	0.47		0.83
C4	0.53	0.63	0.47		C4	0.42	0.73	0.28	
Decision Maker 3					**Decision Maker 4**				
CP^3	C1	C2	C3	C4	CP^4	C1	C2	C3	C4
C1		0.73	0.58	0.70	C1		0.48	0.82	0.52
C2	0.48		0.65	0.53	C2	0.63		0.77	0.67
C3	0.53	0.35		0.68	C3	0.37	0.27		0.43
C4	0.30	0.58	0.53		C4	0.52	0.52	0.68	

TABLE 5. Consistency levels of decision makers.

Decision Maker 1 (CL^1:0.87)					Decision Maker 2 (CL^2:0.84)				
CL^1	C1	C2	C3	C4	CL^2	C1	C2	C3	C4
C1		0.79	0.88	0.76	C1		0.92	0.84	0.94
C2	0.92		0.99	0.89	C2	0.98		0.89	0.66
C3	0.99	0.72		0.76	C3	0.88	0.71		0.71
C4	0.98	0.98	0.84		C4	0.88	0.84	0.86	
Decision Maker 3 (CL^3:0.86)					**Decision Maker 4 (CL^4:0.92)**				
CL^3	C1	C2	C3	C4	CL^4	C1	C2	C3	C4
C1		0.91	0.92	0.87	C1		0.99	0.92	0.81
C2	0.99		0.97	0.82	C2	0.98		0.91	0.89
C3	0.84	0.70		0.74	C3	0.98	0.91		0.98
C4	0.73	0.94	0.84		C4	0.88	0.86	0.92	

Step 4: Consistency level for each pair of criteria is computed with the equations (3)-(5) and the results are given in Table 5.

Table 5 indicates that global consistency level (GCL) are computed as 0.87. In the next step, similarity matrices for the pairs of decision makers are constructed for defining the collective similarity matrix by the equations (6)-(7). Table 6 shows the similarity matrices for each pair of decision makers.

TABLE 6. Similarity matrices for pairs of decision makers.

DM1-DM3					DM1-DM4				
SM^{13}	C1	C2	C3	C4	SM^{14}	C1	C2	C3	C4
C1		0.80	0.80	0.90	C1		0.90	0.80	1.00
C2	0.80		1.00	0.80	C2	0.70		0.70	0.90
C3	0.90	1.00		1.00	C3	1.00	0.60		0.90
C4	0.80	0.90	0.60		C4	0.80	0.70	0.90	
DM2-DM3					DM2-DM4				
SM^{23}	C1	C2	C3	C4	SM^{24}	C1	C2	C3	C4
C1		0.90	0.60	0.80	C1		0.80	0.60	0.90
C2	1.00		0.80	0.90	C2	0.90		0.50	0.60
C3	0.90	0.90		0.90	C3	1.00	0.50		1.00
C4	0.90	1.00	0.80		C4	0.90	0.80	0.70	

TABLE 7. Collective similarity matrix.

SM	C1	C2	C3	C4
C1		0.85	0.70	0.90
C2	0.85		0.75	0.80
C3	0.95	0.75		0.95
C4	0.85	0.85	0.75	

TABLE 8. Consensual fuzzy preference degrees of decision makers.

Decision Maker 1					Decision Maker 2				
Z^1	C1	C2	C3	C4	Z^2	C1	C2	C3	C4
C1		0.80	0.82	0.89	C1		0.83	0.71	0.89
C2	0.81		0.87	0.82	C2	0.92		0.75	0.71
C3	0.97	0.81		0.89	C3	0.94	0.75		0.88
C4	0.87	0.87	0.79		C4	0.89	0.89	0.79	
Decision Maker 3					Decision Maker 4				
Z^3	C1	C2	C3	C4	Z^4	C1	C2	C3	C4
C1		0.88	0.83	0.87	C1		0.90	0.83	0.90
C2	0.92		0.87	0.81	C2	0.87		0.70	0.77
C3	0.89	0.80		0.89	C3	0.97	0.65		0.94
C4	0.86	0.91	0.69		C4	0.89	0.79	0.76	

TABLE 9. Collective fuzzy preference relations for criteria.

P^c	C1	C2	C3	C4
C1		0.83	0.80	0.89
C2	0.85		0.82	0.79
C3	0.95	0.77		0.90
C4	0.88	0.87	0.77	

Step 5: collective similarity matrix is calculated as seen in Table 7.

Step 6: Consensus degrees for criterion (cc_i) are determined by the equations (8)-(9) and relation degree for global consensus (CR) is calculated as 0.83. The consensual degrees of each decision maker for fuzzy preference relations are computed in Table 8.

Collective fuzzy preference relations $P^c$is computed by using the consensual fuzzy preferences and the weighting results with the fuzzy linguistic quantifier ''most'' defined as $Q(r) = r^{1/2}$. Using the equations (10)-(12), the collective results are given in Table 9.

Step 7: Proximity levels PP^h_{ik} for each pair of criteria are defined to illustrate the relation between criteria Pr^h with the equations (13)-(14). The proximity results are given in Table 10.

The consensus control level (CCL) is computed to decide on the consensus level among the decision makers using the equation (15). If CCL is higher than threshold level γ, it is demonstrated that the satisfaction on the consensus are provided between the decision makers. Otherwise, the consensus process should be repeated with the revised fuzzy preference relations in several rounds until the value of CCL exceeds the threshold level. In this study, the value of γ is defined as 0.85 to provide the satisfaction. Consensus control level of this study is calculated as 0.84 and it is seen that the second-round consensus process should be constructed to increase the level.

Step 8: Feedback mechanism is applied to change the values of fuzzy preference relation that do not satisfy the values

TABLE 10. Proximity levels of decision makers for criteria.

Decision Maker 1 (Pr^1: 0.69)					Decision Maker 2 (Pr^2: 0.68)				
PP^1	C1	C2	C3	C4	PP^2	C1	C2	C3	C4
C1		0.57	0.70	0.91	C1		0.87	0.50	0.81
C2	0.45		0.78	0.81	C2	0.65		0.58	0.89
C3	0.45	0.97		0.40	C3	0.45	0.87		0.50
C4	0.62	0.73	0.93		C4	0.72	0.63	0.73	
Decision Maker 3 (Pr^3: 0.73)					Decision Maker 4 (Pr^4: 0.72)				
PP^3	C1	C2	C3	C4	PP^4	C1	C2	C3	C4
C1		0.77	0.90	0.99	C1		0.67	0.90	0.91
C2	0.65		0.78	0.99	C2	0.75		0.92	0.71
C3	0.35	0.97		0.40	C3	0.45	0.63		0.50
C4	0.82	0.63	0.53		C4	0.82	0.43	0.97	

TABLE 11. Fuzzy preference relations for the second round.

Decision Maker 1					Decision Maker 2				
P^1	C1	C2	C3	C4	P^2	C1	C2	C3	C4
C1		0.80	0.77	0.80	C1		0.70	0.30	0.70
C2	0.30		0.60	0.60	C2	0.50		0.40	0.90
C3	0.40	0.80		0.30	C3	0.86	0.90		0.88
C4	0.50	0.60	0.70		C4	0.60	0.50	0.50	
Decision Maker 3					Decision Maker 4				
P^3	C1	C2	C3	C4	P^4	C1	C2	C3	C4
C1		0.60	0.70	0.90	C1		0.50	0.70	0.80
C2	0.50		0.60	0.80	C2	0.60		0.90	0.50
C3	0.85	0.80		0.84	C3	0.40	0.40		0.40
C4	0.70	0.80	0.71		C4	0.70	0.78	0.80	

TABLE 12. Fuzzy preference relations for the third round.

Decision Maker 1					Decision Maker 2				
P^1	C1	C2	C3	C4	P^2	C1	C2	C3	C4
C1		0.80	0.77	0.80	C1		0.70	0.72	0.70
C2	0.30		0.60	0.60	C2	0.50		0.40	0.90
C3	0.40	0.80		0.30	C3	0.86	0.90		0.88
C4	0.77	0.60	0.70		C4	0.60	0.50	0.50	
Decision Maker 3					Decision Maker 4				
P^3	C1	C2	C3	C4	P^4	C1	C2	C3	C4
C1		0.60	0.70	0.90	C1		0.80	0.70	0.80
C2	0.79		0.60	0.80	C2	0.60		0.90	0.50
C3	0.85	0.80		0.84	C3	0.40	0.40		0.40
C4	0.70	0.80	0.71		C4	0.70	0.78	0.80	

TABLE 13. Fuzzy preference relations for the fourth round.

Decision Maker 1					Decision Maker 2				
P^1	C1	C2	C3	C4	P^2	C1	C2	C3	C4
C1		0.80	0.77	0.80	C1		0.70	0.72	0.70
C2	0.30		0.60	0.60	C2	0.50		0.75	0.90
C3	0.40	0.80		0.30	C3	0.86	0.90		0.88
C4	0.77	0.60	0.70		C4	0.60	0.79	0.75	
Decision Maker 3					Decision Maker 4				
P^3	C1	C2	C3	C4	P^4	C1	C2	C3	C4
C1		0.86	0.70	0.90	C1		0.80	0.70	0.80
C2	0.79		0.60	0.80	C2	0.60		0.90	0.50
C3	0.85	0.80		0.84	C3	0.65	0.73		0.40
C4	0.70	0.80	0.71		C4	0.70	0.78	0.80	

TABLE 14. Consensus-based Spherical fuzzy sets for criteria.

	Decision Maker 1											
	C1			C2			C3			C4		
	μ	ν	Π	μ	ν	π	μ	ν	π	μ	ν	π
C1				0.72	0.08	0.08	0.69	0.09	0.09	0.72	0.08	0.08
C2	0.27	0.22	0.22				0.54	0.14	0.14	0.54	0.14	0.14
C3	0.36	0.19	0.19	0.72	0.08	0.08				0.27	0.22	0.22
C4	0.69	0.09	0.09	0.54	0.14	0.14	0.63	0.11	0.11			
	Decision Maker 2											
	C1			C2			C3			C4		
	μ	ν	Π	μ	ν	π	μ	ν	π	μ	ν	π
C1				0.63	0.11	0.11	0.65	0.11	0.11	0.63	0.11	0.11
C2	0.45	0.17	0.17				0.67	0.10	0.10	0.81	0.06	0.06
C3	0.78	0.07	0.07	0.81	0.06	0.06				0.79	0.06	0.06
C4	0.54	0.14	0.14	0.71	0.09	0.09	0.67	0.10	0.10			
	Decision Maker 3											
	C1			C2			C3			C4		
	μ	ν	Π	μ	ν	π	μ	ν	π	μ	ν	π
C1				0.78	0.07	0.07	0.63	0.11	0.11	0.81	0.06	0.06
C2	0.71	0.09	0.09				0.54	0.14	0.14	0.72	0.08	0.08
C3	0.76	0.07	0.07	0.72	0.08	0.08				0.76	0.07	0.07
C4	0.63	0.11	0.11	0.72	0.09	0.09	0.64	0.11	0.11			
	Decision Maker 4											
	C1			C2			C3			C4		
	μ	ν	π	μ	ν	π	μ	ν	π	μ	ν	π
C1				0.72	0.08	0.08	0.63	0.11	0.11	0.72	0.08	0.08
C2	0.54	0.14	0.14				0.81	0.06	0.06	0.45	0.17	0.17
C3	0.59	0.12	0.12	0.65	0.10	0.10				0.36	0.19	0.19
C4	0.63	0.11	0.11	0.70	0.09	0.09	0.72	0.08	0.08			

TABLE 15. Aggregated Spherical fuzzy sets for criteria.

	C1			C2			C3			C4		
	μ	**ν**	**π**	**μ**	**ν**	**π**	**μ**	**ν**	**π**	**μ**	**ν**	**π**
C1				0.72	0.08	0.09	0.65	0.10	0.10	0.73	0.08	0.08
C2	0.54	0.14	0.15				0.67	0.10	0.11	0.67	0.10	0.11
C3	0.67	0.10	0.11	0.73	0.08	0.08				0.63	0.12	0.13
C4	0.63	0.11	0.11	0.68	0.10	0.10	0.67	0.10	0.10			

of EXPCH, ALT, and APS respectively using the equations (16)-(18). Accordingly, the fuzzy preference relations are revised for the second round as seen in Table 11.

The values of GCL, CR, and CCL are computed as 0.91, 0.80, and 0.82 respectively for the second round. Once the consensus control level is lower than the threshold value, the third-round consensus process should be applied. In Table 12, the fuzzy preference relations are illustrated, and the analysis results are represented for the third round below.

The analysis results of the third-round relation values are computed as 0.90 for GCL, 0.81 for CR, 0.84 for CCL. The fourth-round evaluation process should be initiated because of the unsatisfied consensus result. The revised fuzzy preference relations for the fourth round are presented in Table 13.

In this round, the value of GCL is calculated as 0.92 while CR is 0.86 and CCL is 0.87. These results demonstrate that the consensus among the decision makers is provided for the fuzzy preference relations. Because the value of CCL is greater than the value of threshold γ.

STAGE 2: WEIGHTING THE CRITERIA WITH SPHERICAL AND PYTHAGOREAN DEMATEL METHODS

Step 1: The consensus-based fuzzy preference relations that define the membership degrees μ are used for constructing the Spherical fuzzy sets with the equation (19)-(20). For this

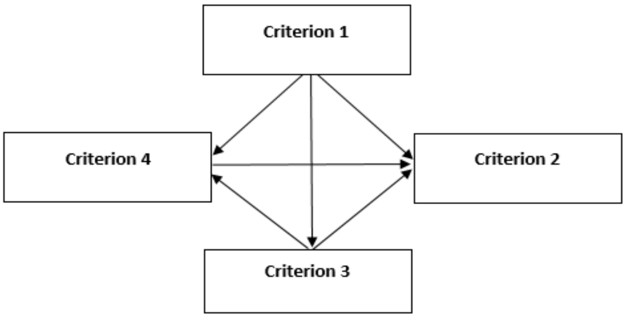

FIGURE 4. Direction mapping of criteria.

purpose, the fuzzy preference relations for the fourth round are selected because of the satisfied consensus level and the membership degrees μ are converted into the Spherical fuzzy sets by considering the Spherical fuzzy evaluation metrics from Gundogdu and Kahraman's study [66]. Accordingly, ν is the difference between 1 and μ while π is the lowest degree from the values of μ and ν for each criterion. The normalized values are obtained with the boundaries of $0\leq \mu_p^2(u) + \nu_p^2(u) + \pi_p^2(u) \leq 1$ for Spherical fuzzy sets and the values are normalized into the limitation of $\mu_p^2 + n_p^2 = 1$ for Pythagorean fuzzy sets. Accordingly, consensus-based Spherical fuzzy preference relations are represented in Table 14.

Step 2: Aggregated values of Spherical fuzzy sets from decision makers are computed with SWAM operator using the equation (25). The weights are assumed equally for each item. The aggregated Spherical fuzzy evaluations are given in Table 15.

Step 3: The deffuzification procedure is applied by the score function. By the equation (34), direct-relation matrix that is the defuzzified values of fuzzy sets are illustrated in Table 16.

Step 4: Normalization procedure is applied by the equations (35)-(36). Table 17 shows the normalization values of direct relation matrix.

Step 5: Total relation matrix is calculated with the equation (37). The results are given in Table 18.

Similar weighting procedures are also applied for Pythagorean fuzzy sets with the formula (26)-(37).

Step 6: By the equations (38)-(39), the impact and relation directions as well as the weights of criteria are illustrated for both Spherical and Pythagorean fuzzy sets in Table 19.

Table 19 identifies that the results of both Spherical and Pythagorean fuzzy sets are quite similar. This situation gives information about the consistency of the analysis results. It is identified that security conditions play the most crucial role to improve the public acceptance for nuclear energy investments in energy importing countries. Moreover, it is also determined that economic benefit and environmental issues also have importance influence on this situation. Nevertheless, it is concluded that health factors have lower impact on this issue in comparison with other items.

TABLE 16. Deffuzified values of relation matrix.

Criteria	C1	C2	C3	C4
C1	0.000	0.400	0.299	0.417
C2	0.148	0.000	0.316	0.313
C3	0.309	0.425	0.000	0.251
C4	0.266	0.332	0.322	0.000

TABLE 17. Normalized values of direct relation matrix.

Criteria	C1	C2	C3	C4
C1	0.000	0.358	0.268	0.374
C2	0.133	0.000	0.283	0.281
C3	0.277	0.381	0.000	0.225
C4	0.239	0.297	0.288	0.000

TABLE 18. Total relation matrix.

Criteria	C1	C2	C3	C4
C1	1.038	1.783	1.514	1.603
C2	0.903	1.137	1.196	1.206
C3	1.152	1.652	1.176	1.384
C4	1.087	1.537	1.345	1.140

Step 7: Impact-relation map of criteria is constructed. By the equation (32), the averaged value of total relation matrix is defined as threshold and higher values than the threshold shows that there is an influence among the criteria. Accordingly, the directions among the criteria are given in Figure 4.

Figure 4 illustrates that health factors affect all other items. On the other side, it is also defined that economic situation is affected by all other criteria. Moreover, sensitivity analysis is also applied for illustrating the coherencies of group decision making results by using the different values of δ with 4 cases. The ranking results of criteria by the cases are given in table 20.

Table 20 indicates that the analysis results of both Spherical and Pythagorean fuzzy sets are almost the same for 4 different cases. Thus, as a result of the sensitivity analysis, it has been determined that there is significant consistency in the consensus-based group decision-making process.

V. CONCLUSION

This study aims to improve the public acceptance for nuclear energy investment in energy importing countries. Within this framework, 4 different criteria are identified while analyzing similar studies in the literature. After that, these criteria are evaluated by 4 different experts. Later, consensus decision-making procedure has been implemented to these evaluations. Owing to this situation, the feedback mechanism is applied to obtain fuzzy preference relations at the most consistency level. In the next step, these evaluations are converted to

TABLE 19. The weights of the criteria.

Criteria	D		E		D+E		D-E		Weights	
	SFSs	PFSs	SFSs	PFSs	SFSs	PFSs	SFSs	PFSs	SFSs	PFSs
Health Factors (criterion 1)	5.939	5.266	4.180	3.649	10.119	8.915	1.759	1.616	0.243	0.247
Economic Benefit (criterion 2)	4.442	3.780	6.109	5.292	10.550	9.072	-1.667	-1.512	0.253	0.251
Security Conditions (criterion 3)	5.363	4.363	5.231	4.690	10.594	9.053	0.133	-0.327	0.254	0.252
Environmental Issues (criterion 4)	5.110	4.664	5.333	4.370	10.443	9.033	-0.224	0.294	0.250	0.250

TABLE 20. Ranking results by Cases.

Criteria	Case 1 (δ: 0.75)		Case 2 (δ: 0.80)		Case 3 (δ: 0.85)		Case 4 (δ: 0.90)	
	SFSs	PFSs	SFSs	PFSs	SFSs	PFSs	SFSs	PFSs
Health Factors (criterion 1)	4	4	4	4	4	4	4	4
Economic Benefit (criterion 2)	2	2	2	2	2	3	2	3
Security Conditions (criterion 3)	1	1	1	1	1	1	1	1
Environmental Issues (criterion 4)	3	3	3	3	3	2	3	2

Spherical fuzzy sets. Finally, DEMATEL methodology is considered to find more important factors. Moreover, another evaluation has been performed by using the Pythagorean fuzzy sets to make a comparative analysis. It is concluded that the results of both Spherical and Pythagorean fuzzy sets are quite similar. Hence, it is identified that the results are consistent. Additionally, sensitivity analysis is also applied for illustrating the coherencies of group decision making results. For this purpose, different values of δ with 4 cases are considered. It is determined that the analysis results of both Spherical and Pythagorean fuzzy sets are almost the same for 4 different cases. This situation gives information about the coherency in the consensus-based group decision-making process. The results illustrate that security conditions have the most important influence on the improvement of the public acceptance for nuclear energy investments in energy importing countries. Furthermore, it is concluded that economic benefit and environmental issues are also important for this situation. However, it is identified that health factors have lower impact on this issue in comparison with other items. On the other side, health factors affect all other items whereas economic situation is affected by all other criteria.

VI. LIMITATIONS AND IMPLICATIONS

According to the results obtained, in order to improve public perception of nuclear energy investments in energy importing countries, priority should be paid attention to security issues. In other words, to have a positive view of nuclear energy, the public must believe that nuclear power is a safe investment. In this process, both the investor company and the state have some duties. The reaction occurring in nuclear power plants should be brought under control. Otherwise, there is a risk of a very powerful explosion occurring in the nuclear reactor. If this situation cannot be brought under control, the lives of many living things will be endangered. One of the issues most worried by the public is the possibility of an explosion of the nuclear reactor. In this framework, it is necessary to assure the public that the necessary security measures have been taken. In this context, it is very important that the nuclear power plant is open to international inspection. This will help the public to believe that security measures have been taken. Kratochvíl and Mišík [70] focused on nuclear energy investments in the Czech Republic and Slovakia. For the effectiveness of these investments, necessary controls should be adopted to overcome the risks in the nuclear power plants. Jenkins *et al.* [71] also underlined the importance of the same issues for the nuclear power plants in Canada. On the other hand, an independent and autonomous organization can be established within the country, responsible for the security of nuclear power plants. This institution to be established will be able to independently conduct security audits at nuclear power plants with its own team. Son *et al.* [72] and Kang [73] also highlighted the significance of the independency in the audit works for nuclear power plants.

One of the most important risks in nuclear energy investments is an explosion in nuclear power plants due to natural disasters. In this context, nuclear power plants should not be built on the fault line. Seismic earthquake data of the region where nuclear power plants will be established should be shared with the public transparently. In this way, it will be easier for the public to be convinced that there is no natural disaster risk in the nuclear power plant. Choi and Kim [74], Song *et al.* [75] and Rao and Choudhury [76] also identified that necessary precautions should be taken to minimize the risks of the earthquake while building the nuclear power plants. In parallel, it must be proven that the nuclear power plant construction is sound. For this purpose, it is important to present construction inspection reports. On the other hand, personnel who will work in nuclear power plants must also have the necessary knowledge. In this context, some standards should be determined for the personnel who will work in these plants. In this context, personnel who cannot complete certain training should not be allowed to work in these plants. This will help the public to believe that more security measures are being taken at nuclear power plants. Lee *et al.* [77] and Alam *et al.* [78] focused on the effectiveness of the nuclear power plants in different country groups. They mainly discussed that personnel, who work in the nuclear power plants, should have necessary qualifications so that in the event of a possible risk, it will be possible to make quick and correct decisions. It is also important to establish the policies and procedures required by the state in order to manage these processes effectively.

The biggest constraint in this study is that it focuses solely on public acceptance for nuclear energy. Nuclear energy investments are very important for the social and economic development of countries. In this context, cost-benefit analysis in nuclear energy investments is also an issue that needs to be examined. In addition, it is thought that a study to increase the security measures in nuclear power plants will contribute to the literature. On the other hand, different methodologies can be taken into consideration in new studies. As an example, AHP, ANP and Entropy approaches can be taken into consideration in determining the weights of the criteria. This will help comparative analysis.

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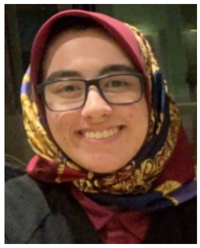

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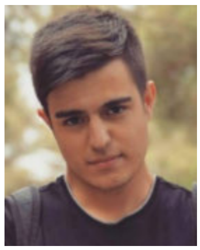

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