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Full Length Article

Using quantum spherical fuzzy decision support system as a novel sustainability index approach for analyzing industries listed in the stock exchange

Mahmut Kayacık [a], Hasan Dinçer [b,*], Serhat Yüksel [b]

[a] *Türkiye Wealth Fund, Social Sciences Institute, İstanbul Medipol University, İstanbul, Turkey*
[b] *School of Business, İstanbul Medipol University, Turkey*

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Abstract

This study aims to identify critical factors of the sustainability index (SI) and evaluate the industries listed in the stock exchange based on the performance of this index. For this purpose, a new fuzzy decision-making model has been created. Firstly, 12 different criteria for the SI are weighted by decision using trial and evaluation laboratory (DEMATEL) methodology based on quantum spherical fuzzy sets (QFS) with golden cut. Secondly, SI performances of the 10 industry alternatives are ranked by extended technique for order of preference: according to similarity through an ideal solution (TOPSIS) with QFS. The main novelty of this study is to identify significant sustainability criteria for the companies to join this index with an original fuzzy decision-making methodology. For this purpose, the analysis results help the companies to act without incurring extreme costs. It is determined that the usage of renewable energy has a significant impact on all other criteria, and while using clean energy, the companies get a chance to improve other criteria of SI. Additionally, based on the weighting results, the use of renewable energy is the most critical criterion to be included in SI. Similarly, recovery of the resources also has a significant contribution. Finally, the ranking results indicate that communication and IT is the most successful industry for SI. Hence, it would be appropriate for businesses to attach importance to the use of renewable energy. In this way, the carbon emission problem would be minimized, and the image of businesses will rise in the eyes of both consumers and investors. In this framework, companies can join microgrid energy management systems to handle high-cost problems of renewable energy investment projects. Owing to microgrid energy applications, the costs of using renewable energy can be shared with other companies, and since this situation can reduce the cost per unit, it will be possible to increase the use of renewable energy.

Keywords: Sustainability index; Stock exchange; Environmental factors; Decision making models; Fuzzy logic

1. Introduction

The concept of sustainability has become very popular, especially in recent years. In its simplest definition, sustainability means taking into consideration the needs of future generations while meeting both economic and social needs. In other words, it means not unconsciously consuming existing resources while meeting today's needs. The most important issue in this process is the effective and efficient use of environmental factors (Yürek et al., 2021), wherein difficulties may arise in accessing natural resources. As a result of the insufficient amount of natural resources, future generations will experience difficulties both socially and economically (Meo & Abd Karim, 2022).

The concept of sustainability is related to many other critical issues, including economic development. Every country aims to develop economically to increase the quality of life of its

* Corresponding author.
E-mail addresses: mahmut.kayacik@tvf.com.tr (M. Kayacık), hdincer@medipol.edu.tr (H. Dinçer), serhatyuksel@medipol.edu.tr (S. Yüksel).
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citizens. On the other hand, it is understood that the economic growth of countries, especially in recent years, is not enough. In fact, the continuity of the economic growth of the countries should be ensured (Usubiaga-Liano & Ekins, 2021) since unsustainable economic growth poses a significant risk for countries. Therefore, while trying to develop their economies, countries should effectively use their natural resources in order to have long-term economic growth (Khan et al., 2022).

Sustainability is also an important concept for businesses as the brand image of enterprises that are positively viewed are also preferred by customers. In other words, the implementation of sustainability provides businesses with a significant competitive advantage (Azari & Tabesh, 2022). Another advantage of sustainability for businesses is that costs can be reduced. One of the main purposes of the concept of sustainability is to use resources effectively, thus contributing to the reduction of costs and ensuring the long-term profitability of companies. In summary, businesses are more preferred by investors, thanks to the fulfillment of sustainability criteria (Ahmed et al., 2022).

SI can express the index of companies that are traded on the stock exchange and can fulfill the sustainability criteria, all of which businesses aim to achieve (Vuong, 2022). However, there are some issues that businesses that want to be included in SI should pay attention to. For example, having an effective risk management mechanism and making innovative investments are very important for companies to be included in SI (Hosseini et al., 2021). Moreover, being transparent in their management activities and operating in accordance with the rules are also managerial issues that businesses should pay attention to within the scope of SI. Furthermore, environmental factors, such as the use of renewable energy, the recycling of products and the efficiency of production processes, also play an important role for SI inclusion (Akbar et al., 2022).

Yet, meeting all the sustainability criteria at the same time is quite challenging since improvements to these criteria involve extra costs for companies. Indeed, the measures to be taken in tackling multiple criteria may cause unmanageable cost increases for companies. Therefore, it would be appropriate to determine the most important sustainability criteria and to give priority to those criteria (Agarwal & Singh, 2022). In the literature, there are many studies on the importance of SI issues, many of which attempt to determine the key factors for SI (Raedo, 2021). Even still, there are only a limited number of studies regarding which criteria a business should prioritize to be included in SI. In this context, a new study to determine the integral criteria among SI criteria was initiated (Chen et al., 2021).

For this purpose, a new fuzzy decision-making model has been generated. In the first stage of this model, 12 different criteria for SI are weighted. Within this context, the examination has been conducted by decision making trial and evaluation laboratory (DEMATEL) methodology based on quantum spherical fuzzy sets (QFS) with golden cut. In the second stage, SI performances of the 10 industry alternatives are ranked by extended technique for order of preference by similarity to ideal solution (TOPSIS) with QFS.

The main novelty of this study is to identify significant sustainability criteria for the companies to join this index with an original fuzzy decision-making methodology. The analysis results can pave the way for companies to take action without incurring extreme costs. Additionally, the proposed model has some key advantages. Firstly, integrating the probability of quantum theory to the Spherical fuzzy sets. Generally, the decision-making problems cannot be satisfied with classical models. And, because of the uncertainty problem, new fuzzy numbers were introduced to solve this issue. Within this context, in this proposed model, Spherical fuzzy sets are considered. With the help of these sets, both membership and non-membership degrees and hesitancy parameters can be used so that a larger domain can be considered in the evaluation process. This condition has a positive influence on reaching appropriate findings.

Another originality of this proposed model is integrating quantum theory to these sets whereby the probabilities of several conditions using different angles can be identified so that uncertainties in this process can be handled in a more effective way. Calculating the degrees in the fuzzy set is also a critical issue in this process, having a positive influence on the originality of the proposed model and resulting in more accurate results. Using DEMATEL methodology in the proposed model also provides some advantages. Namely, this technique creates an impact relation map between the criteria, in addition to finding the weights of them.

With these techniques, it is aimed to determine the important criteria that affect the companies' entry into SI, taking into consideration how these factors can influence each other. For example, thanks to the use of renewable energy, businesses can use their own energy. In this way, it is less affected by the uncertainty in energy prices and contributes to effective risk management-one of SI criteria. As can be seen, in the process of analyzing the criteria for this issue, it would be appropriate to analyze the causality relationship between these criteria, instead of just determining the weights of the criteria. Hence, the DEMATEL method is much more suitable for the studies to be carried out for this purpose. Conversely, considering the distances to both positive and negative optimal solutions in the analysis process is the main reason for selecting this technique to rank the alternatives.

In the next part of the study, the details of similar studies in the literature will be examined, after which the theoretical steps of the techniques considered in the analysis process will be included. In the following part of the study, the results of the analysis will be shared. The conclusion and discussion sections are at the end.

2. Literature review

The factors necessary for companies to be included in SI have been covered in many other studies, while the importance of environmental issues has been emphasized in some of the studies. Most importantly, the energy used by companies must be clean to be included in SI. Fossil fuels such as coal and oil produce carbon gas that creates significant environmental

pollution (Kolosok et al., 2021). So, it is necessary for businesses to use renewable energy to achieve their sustainability goals (Razmjoo et al., 2021). Zhaedi et al. (2022) evaluated the important points to reach sustainability purposes in Iran. They stated that renewable energy investment is a crucial issue to reach this objective. Mukhtarov et al. (2022) and Li et al. (2022) also identified that companies should increase renewable energy investments to join SI and that high-cost problems of the renewable energy projects should mainly be solved with the help of effective financial sources. On the other hand, recycling of resources is also necessary for businesses to be included in SI (Lee et al., 2021). One of the most important issues in the concept of sustainability is the effective use of natural resources (Martins et al., 2021). If the products are not recycled, the increase in the production process will cause the depletion of natural resources, all of which is contrary to the purpose of sustainability (Tabelin et al., 2021). Roy et al. (2022) focused on the key indicators of sustainability for the companies and concluded that green recycling methods should be taken into consideration for this situation. Kumar et al. (2021) also stated that recycling technology investments should be prioritized by the companies to reach this purpose.

Factors related to personnel can also be effective in the inclusion of companies in SI. Qualified personnel are of vital importance for the effective execution of company activities. For the activities to be carried out in an environmentally friendly manner, the personnel must have the necessary knowledge in this area (Olatayo et al., 2022). To ensure sustainability, these issues should be considered in all company activities (Yakovleva & Miller, 2021). Accordingly, necessary training should be given to the personnel (Mercader-Moyano et al., 2021). Kavga et al. (2021) aimed to explain the main determinants of economic and environmental sustainability and identified that companies need qualified personnel to reach sustainability purposes more effectively. Deev et al. (2021) also underlined the significance of this situation. Another important issue here is the necessity of employing these competent personnel for the *best fit* based on their skill set and the dynamics of the department. Otherwise, even if the personnel are qualified, their performance in the company will not be high (Soundararajan et al., 2021). Furthermore, the suitability of working conditions at the workplace is also very important for companies to be included in SI (Fabiani et al., 2021). To ensure the satisfaction of the personnel, the employees must be able to continue their activities in good conditions (Duval et al., 2021). Park and Jeong (2021) made a study to better understand the key issues for sustainability, concluding that effective working conditions should be provided to the employees; in addition, Petrudi et al. (2021) examined significant sustainability factors and identified that fair working conditions play an important role in this regard.

Financial factors are also important for companies to be included in SI. In this framework, enterprises should have an effective risk management mechanism as there will be multiple risks that companies face due to their activities (Nobanee et al., 2021). To achieve the goal of sustainability, companies must accurately identify their risks and take appropriate measures against them (Ozturk & Ullah, 2022). This will provide a significant advantage to the company, particularly in times of financial crises (Landi et al., 2022). In this context, companies that take effective measures against these risks get through crisis periods much more smoothly. Settembre-Blundo et al. (2021) tried to define the ways in which companies can reach sustainability and noted effective risk management systems should be designed for this condition. Dias et al. (2021) also focused on the automotive industry to define sustainability criteria and established an effective risk management department with qualified people as necessary steps. Furthermore, innovative investments also affect companies' inclusion in SI. The effective management of costs is a prerequisite for the continuity of the activities of the companies (Di Simone et al., 2022), and without this cost management, companies are likely to experience financial difficulties (Erdoğan et al., 2022). Principally, technological investments ensure that costs can be reduced (Ferrari et al., 2022). Luo et al. (2022), in evaluating important points of sustainability in China, determined that technological investments should be increased to achieve sustainability. As well, Lopez-Cabrales and DeNisi (2021) pointed out the significance of innovative investments for the companies to be included in SI.

Equally important for companies to be included in SI, some managerial issues should also be considered. In this context, it is vital that the management be transparent, clearly sharing issues and activities with both employees and external stakeholders (Duan et al., 2021). This will help companies gain confidence in the eyes of investors (Navas et al., 2021). Moreover, it is important for the company management to operate in accordance with the rules to be included in SI (Gonçalves & Silva, 2021). Jestratijevic et al. (2021) focused on strategic points for companies to provide sustainability, reaching the conclusion that companies should firstly take necessary actions to have transparency through financial reporting. Cuadrado-Ballesteros and Bisogno (2022) also evaluated the key indicators for the companies to be included in SI, identifying budget transparency as crucial for the purpose of financial sustainability.

In terms of methodology, the main advantage of this model is the consideration of DEMATEL in the criteria weighting process for understanding the causal relationship between the items, in addition to finding the weights of them. In some studies, the analytical hierarchy process (AHP) method was taken into consideration to compute the weights of the criteria. For instance, Hassan et al. (2012), Harik et al. (2015) and Dinçer and Yüksel (2018) considered AHP techniques to evaluate the sustainability factors in different industries. Additionally, Silahtaroğlu et al. (2021) and Yüksel et al. (2021) also used this methodology to weigh the determinants of the currency exchange rate risk and energy investments. Although the weights of the criteria can be calculated in these studies, the

impact relation map could not be created. Additionally, the Spherical fuzzy sets used in the analysis process allow both membership and non-membership degrees and hesitancy parameters to be considered. This situation provides an opportunity to focus on a larger domain in the evaluation process that contributes to reaching appropriate findings. Ngan et al. (2018) and Ocampo et al. (2016) tried to evaluate the SI performance of the companies with the help of triangular fuzzy sets; however, in these studies, the hesitancy condition could not be taken into consideration.

In this study, it is aimed to identify critical factors of SI and evaluate the industries listed in the stock exchange based on the performance of this index. Hence, with the help of this evaluation, it might be possible to begin to grow the literature in this field.

3. Methodology

This section explains the steps of the techniques used in the analysis process.

3.1. Quantum spherical fuzzy sets (QFS) with golden cut

Decision-making techniques help to solve problems by selecting the most optimal ones among many different alternatives. However, the complexity of these problems is increasing in a radical manner. Due to this issue, some improvements are needed to these approaches to reach more appropriate solutions. For this purpose, these methods were considered with fuzzy numbers since Quantum mechanics provides a new outlook to these techniques (Hou et al., 2022). Quantum theory gives an opportunity to consider the probability by using the amplitude and the phase angle items. Equations (1)–(3) explain the details of them. In these equations, $|Q(|u>)| = \varphi^2$ is the amplitude result for the probability of event $|u>$ where the condition is $0 \leq \varphi^2 \leq 1$. Additionally, θ^2 demonstrates the phase angle of event (Afradi & Ebrahimabadi, 2021). Also, ς indicates the set of collective exhaustive events and θ refers to the phase angle. Finally, $|\varphi_1|^2$ explains the belief degree (Wang et al., 2021).

$$Q(|u>) = \varphi e^{j\theta} \tag{1}$$

$$|\varsigma> = \{|u_1>, |u_2>, \ldots, |u_n>\} \tag{2}$$

$$\sum_{|u>\subseteq|\varsigma>} |Q(|u>)| = 1 \tag{3}$$

New fuzzy sets were also introduced to minimize the complexity problem of the decision-making process. Spherical fuzzy sets ($\tilde{A}_S$) were also generated for this purpose (Kutlu Gündoğdu & Kahraman, 2019). The main benefit of these sets is considering membership, non-membership, and hesitancy degrees at the same time (Kahraman, 2021). This situation helps to reach the appropriateness of the analysis process. Equations (4) and (5) give information about the details of these sets (Ashraf et al., 2019).

$$\tilde{A}_S = \left\{\langle u, \left(\mu_{\tilde{A}_S}(u), v_{\tilde{A}_S}(u), h_{\tilde{A}_S}(u)\right)|u \in U\right\} \tag{4}$$

$$0 \leq \mu^2_{\tilde{A}_S}(u) + v^2_{\tilde{A}_S}(u) + h^2_{\tilde{A}_S}(u) \leq 1, \forall_u \in U \tag{5}$$

In this study, quantum theory is integrated with Spherical fuzzy sets to increase the effectiveness and originality of this process. Equation (6) identifies the details of this process in which $\varsigma_{\mu_{\tilde{A}_S}}$, $\varsigma_{v_{\tilde{A}_S}}$, and $\varsigma_{h_{\tilde{A}_S}}$ represent the degrees of QFS.

$$\left|\varsigma_{\tilde{A}_S}>\right. = \left\{\langle u, \left(\varsigma_{\mu_{\tilde{A}_S}}(u), \varsigma_{v_{\tilde{A}_S}}(u), \varsigma_{h_{\tilde{A}_S}}(u)\right)|u \in 2^{\left|\varsigma_{\tilde{A}_S}>\right.}\right\} \tag{6}$$

Equations (7) and (8) shows the formulization of QFS with the amplitude and phase angles. In this scope, ς_μ, ς_v, and ς_h explain the degrees and α, γ, and β are the set of θ phase angles.

$$\varsigma = \left[\varsigma_\mu.e^{j2\pi.\alpha}, \varsigma_v.e^{j2\pi.\gamma}, \varsigma_h.e^{j2\pi.\beta}\right] \tag{7}$$

$$\varphi^2 = \left|\varsigma_\mu(|u_i>)\right| \tag{8}$$

In the decision-making process, the correct definition of the degrees is crucial. In this study, the golden ratio (G) is taken into consideration to compute these values. Equations (9) and (10) identifies the details of this ration where a and b indicate the large and small quantities (Xu et al., 2022).

$$G = \frac{a}{b} \tag{9}$$

$$G = \frac{1+\sqrt{5}}{2} = 1.618\ldots \tag{10}$$

Equations (11) and (12) define the amplitude of non-membership and hesitancy degrees of QFS with golden cut.

$$\varsigma_v = \frac{\varsigma_\mu}{G} \tag{11}$$

$$\varsigma_h = 1 - \varsigma_\mu - \varsigma_v \tag{12}$$

Equation (13) demonstrates the phase angle of QFS in which α refers to the phase angle of the membership degrees for the probability of event.

$$\alpha = \left|\varsigma_\mu(|u_i>)\right| \tag{13}$$

Equations (14) and (15) demonstrate the phase angles of non-member and hesitancy degrees (γ, β).

$$\gamma = \frac{\alpha}{G} \tag{14}$$

$$\beta = 1 - \alpha - \gamma \tag{15}$$

Equations 16–19 define the operations of QFS.

$$\lambda^{*}\tilde{A}_{\varsigma}=\left\{\left(1-\left(1-\varsigma_{\mu_{\tilde{A}}}^{2}\right)^{\lambda}\right)^{\frac{1}{2}}e^{j2\pi.\left(1-\left(1-\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^{2}\right)^{\lambda}\right)^{\frac{1}{2}}},\varsigma_{v_{\tilde{A}}}^{\lambda}e^{j2\pi.\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{\lambda}},\left(\left(1-\varsigma_{h_{\tilde{A}}}^{2}\right)^{\lambda}-\left(1-\varsigma_{\mu_{\tilde{A}}}^{2}-\varsigma_{h_{\tilde{A}}}^{2}\right)^{\lambda}\right)^{\frac{1}{2}}e^{j2\pi.\left(\left(1-\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^{2}\right)^{\lambda}-\left(1-\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^{2}-\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^{2}\right)^{\lambda}\right)^{\frac{1}{2}}}\right\},\lambda>0 \tag{16}$$

$$\tilde{A}_{\varsigma}^{\lambda}=\left\{\varsigma_{\mu_{\tilde{A}}}^{\lambda}e^{j2\pi.\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^{\lambda}},\left(1-\left(1-\varsigma_{v_{\tilde{A}}}^{2}\right)^{\lambda}\right)^{\frac{1}{2}}e^{j2\pi.\left(1-\left(1-\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{2}\right)^{\lambda}\right)^{\frac{1}{2}}},\left(\left(1-\varsigma_{v_{\tilde{A}}}^{2}\right)^{\lambda}-\left(1-\varsigma_{v_{\tilde{A}}}^{2}-\varsigma_{h_{\tilde{A}}}^{2}\right)^{\lambda}\right)^{\frac{1}{2}}e^{j2\pi.\left(\left(1-\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{2}\right)^{\lambda}-\left(1-\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{2}-\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^{2}\right)^{\lambda}\right)^{\frac{1}{2}}}\right\},\lambda>0 \tag{17}$$

$$\begin{aligned}\tilde{A}_{\varsigma}\oplus\tilde{B}_{\varsigma}=&\left\{\left(\varsigma_{\mu_{\tilde{A}}}^{2}+\varsigma_{\mu_{\tilde{B}}}^{2}-\varsigma_{\mu_{\tilde{A}}}^{2}\varsigma_{\mu_{\tilde{B}}}^{2}\right)^{\frac{1}{2}}e^{j2\pi.\left(\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^{2}+\left(\frac{\alpha_{\tilde{B}}}{2\pi}\right)^{2}-\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^{2}\left(\frac{\alpha_{\tilde{B}}}{2\pi}\right)^{2}\right)^{\frac{1}{2}}},\varsigma_{v_{\tilde{A}}}\varsigma_{v_{\tilde{B}}}e^{j2\pi.\left(\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)\left(\frac{\gamma_{\tilde{B}}}{2\pi}\right)\right)},\right.\\&\left.\left(\left(1-\varsigma_{\mu_{\tilde{B}}}^{2}\right)\varsigma_{h_{\tilde{A}}}^{2}+\left(1-\varsigma_{\mu_{\tilde{A}}}^{2}\right)\varsigma_{h_{\tilde{B}}}^{2}-\varsigma_{h_{\tilde{A}}}^{2}\varsigma_{h_{\tilde{B}}}^{2}\right)^{\frac{1}{2}}e^{j2\pi.\left(\left(1-\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^{2}\right)\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^{2}+\left(1-\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)^{2}\right)\left(\frac{\beta_{\tilde{B}}}{2\pi}\right)^{2}-\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^{2}\left(\frac{\beta_{\tilde{B}}}{2\pi}\right)^{2}\right)^{\frac{1}{2}}}\right\}\end{aligned} \tag{18}$$

$$\begin{aligned}\tilde{A}_{\varsigma}\otimes\tilde{B}_{\varsigma}=&\left\{\varsigma_{\mu_{\tilde{A}}}\varsigma_{\mu_{\tilde{B}}}e^{j2\pi.\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)\left(\frac{\alpha_{\tilde{B}}}{2\pi}\right)},\left(\varsigma_{v_{\tilde{A}}}^{2}+\varsigma_{v_{\tilde{B}}}^{2}-\varsigma_{v_{\tilde{A}}}^{2}\varsigma_{v_{\tilde{B}}}^{2}\right)^{\frac{1}{2}}e^{j2\pi.\left(\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{2}+\left(\frac{\gamma_{\tilde{B}}}{2\pi}\right)^{2}-\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{2}\left(\frac{\gamma_{\tilde{B}}}{2\pi}\right)^{2}\right)^{\frac{1}{2}}},\right.\\&\left.\left(\left(1-\varsigma_{v_{\tilde{B}}}^{2}\right)\varsigma_{h_{\tilde{A}}}^{2}+\left(1-\varsigma_{v_{\tilde{A}}}^{2}\right)\varsigma_{h_{\tilde{B}}}^{2}-\varsigma_{h_{\tilde{A}}}^{2}\varsigma_{h_{\tilde{B}}}^{2}\right)^{\frac{1}{2}}e^{j2\pi.\left(\left(1-\left(\frac{\gamma_{\tilde{B}}}{2\pi}\right)^{2}\right)\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^{2}+\left(1-\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)^{2}\right)\left(\frac{\beta_{\tilde{B}}}{2\pi}\right)^{2}-\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)^{2}\left(\frac{\beta_{\tilde{B}}}{2\pi}\right)^{2}\right)^{\frac{1}{2}}}\right\}\end{aligned} \tag{19}$$

3.2. The extension of DEMATEL

DEMATEL methodology aims to find the weights of the different items so that the most significant factor can be identified. The main advantage of this technique is that the causal directions can be determined. In this study, DEMATEL model is extended with QFS (Yuan et al., 2021). In the first step, linguistic evaluations are provided from the expert team (Yüksel et al., 2022). Secondly, the relation matrix is generated by the help of Equations (20) and (21) (Gül, 2020).

$$\varsigma_{k}=\begin{bmatrix}0&\varsigma_{12}&\cdots&\cdots&\varsigma_{1n}\\\varsigma_{21}&0&\cdots&\cdots&\varsigma_{2n}\\\vdots&\vdots&\ddots&\cdots&\cdots\\\vdots&\vdots&\vdots&\ddots&\vdots\\\varsigma_{n1}&\varsigma_{n2}&\cdots&\cdots&0\end{bmatrix} \tag{20}$$

$$\begin{aligned}\varsigma=&\left\{\left[1-\prod_{i=1}^{k}\left(1-\varsigma_{\mu_{i}}^{2}\right)^{\frac{1}{k}}\right]^{\frac{1}{2}}e^{2\pi.\left[1-\prod_{i=1}^{k}\left(1-\left(\frac{\alpha_{i}}{2\pi}\right)^{2}\right)^{\frac{1}{k}}\right]^{\frac{1}{2}}},\prod_{i=1}^{k}\varsigma_{v_{i}}^{\frac{1}{k}}e^{2\pi.\prod_{i=1}^{k}\left(\frac{\gamma_{i}}{2\pi}\right)^{\frac{1}{k}}},\right.\\&\left.\left[\prod_{i=1}^{k}\left(1-\varsigma_{\mu_{i}}^{2}\right)^{\frac{1}{k}}-\prod_{i=1}^{k}\left(1-\varsigma_{\mu_{i}}^{2}-\varsigma_{h_{i}}^{2}\right)^{\frac{1}{k}}\right]^{\frac{1}{2}}e^{2\pi.\left[\prod_{i=1}^{k}\left(1-\left(\frac{\alpha_{i}}{2\pi}\right)^{2}\right)^{\frac{1}{k}}-\prod_{i=1}^{k}\left(1-\left(\frac{\alpha_{i}}{2\pi}\right)^{2}-\left(\frac{\beta_{i}}{2\pi}\right)^{2}\right)^{\frac{1}{k}}\right]^{\frac{1}{2}}}\right\}\end{aligned} \tag{21}$$

Thirdly, Equation (22) is used to compute the defuzzified values.

$$Def\varsigma_i = \varsigma_{\mu_i} + \varsigma_{h_i}\left(\frac{\varsigma_{\mu_i}}{\varsigma_{\mu_i}+\varsigma_{v_i}}\right) + \left(\frac{\alpha_i}{2\pi}\right) + \left(\frac{\gamma_i}{2\pi}\right)\left(\frac{\left(\frac{\alpha_i}{2\pi}\right)}{\left(\frac{\alpha_i}{2\pi}\right)+\left(\frac{\beta_i}{2\pi}\right)}\right) \quad (22)$$

Fourthly, the normalization procedure is implemented with Equations (23) and (24).

$$B = \frac{\varsigma}{max_{1\le i\le n}\sum_{j=1}^{n}\varsigma_{ij}} \quad (23)$$

where,

$$0 \le b_{ij} \le 1 \quad (24)$$

Fifthly, Equation (25) is considered to calculate the total relation matrix.

$$\lim_{k\to\infty}\left(B + B^2 + \ldots + B^k\right) = B(I-B)^{-1} \quad (25)$$

Sixthly, the sums of columns and rows (E and D) are computed with Equations (26) and (27).

$$D = \left[\sum_{j=1}^{n} e_{ij}\right]_{nx1} \quad (26)$$

$$E = \left[\sum_{i=1}^{n} e_{ij}\right]_{1xn} \quad (27)$$

The difference of these values is used to find causal directions and the sum values give information about the significance of the items. The threshold value in Equation (28) is considered for the calculation of the impact relation degrees.

$$\alpha = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}[e_{ij}]}{N} \quad (28)$$

3.3. The extension of TOPSIS

TOPSIS methodology is used to identify the most optimal alternative. The main superiority of this technique is that the distances to both negative and positive ideal solutions are considered in the evaluation process (Akram et al., 2021). In this proposed model, this methodology is integrated with QFS (Barukab et al., 2019). The first step is related to obtaining the evaluations. In the second step, Equation (29) is taken into consideration to create decision matrix (Kahraman et al., 2019).

$$X_k = \begin{bmatrix} 0 & X_{12} & \cdots & \cdots & X_{1m} \\ X_{21} & 0 & \cdots & \cdots & X_{2m} \\ \vdots & \vdots & \ddots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ X_{n1} & X_{n2} & \cdots & \cdots & 0 \end{bmatrix} \quad (29)$$

Thirdly, Equation (21) is used for the defuzzification process. The fourth step includes the normalization as in Equation (30).

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \quad (30)$$

The weighted values are computed with Equation (31).

$$v_{ij} = w_{ij} \times r_{ij} \quad (31)$$

Equations (32) and (33) show the calculation of the positive (A^+) and negative (A^-) ideal solutions.

$$A^+ = \{v_{1j}, v_{2j}, \ldots, v_{mj}\} = \{\max v_{1j}\, for \forall j \in n\}, \quad (32)$$

$$A^- = \{v_{1j}, v_{2j}, \ldots, v_{mj}\} = \{\min v_{1j}\, for \forall j \in n\}. \quad (33)$$

Next, the distances to the best (D_i^+) and worst alternatives (D_i^-) are calculated as in Equations (34) and (35).

$$D_i^+ = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - A_j^+\right)^2}, \quad (34)$$

$$D_i^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - A_j^-\right)^2}. \quad (35)$$

Finally, Equation (36) includes the calculation of the relative closeness to the ideal solutions.

$$RC_i = \frac{D_i^-}{D_i^+ + D_i^-}. \quad (36)$$

4. Analysis

A new fuzzy decision-making model has been created to evaluate the industries listed in the stock exchange with respect to SI. The first stage of this model includes weighting the criteria for SI. For this purpose, the examination has been conducted by DEMATEL methodology based on QFS with golden cut. In the second part, SI performances of the industry alternatives are ranked by extended TOPSIS technique with QFS. Fig. 1 represents the flowchart of this proposed model.

The following parts of the section gives information about the analysis results of each stage.

4.1. Stage 1: weighting the criteria for SI

Step 1 is related to the selection of the criteria for SI. For this purpose, similar studies in the literature have been reviewed. Finally, 12 different factors are identified based on four different dimensions. Table 1 explains the details of these items.

As noted, for companies to be included in SI, it is necessary to pay attention to financial factors. For example, companies

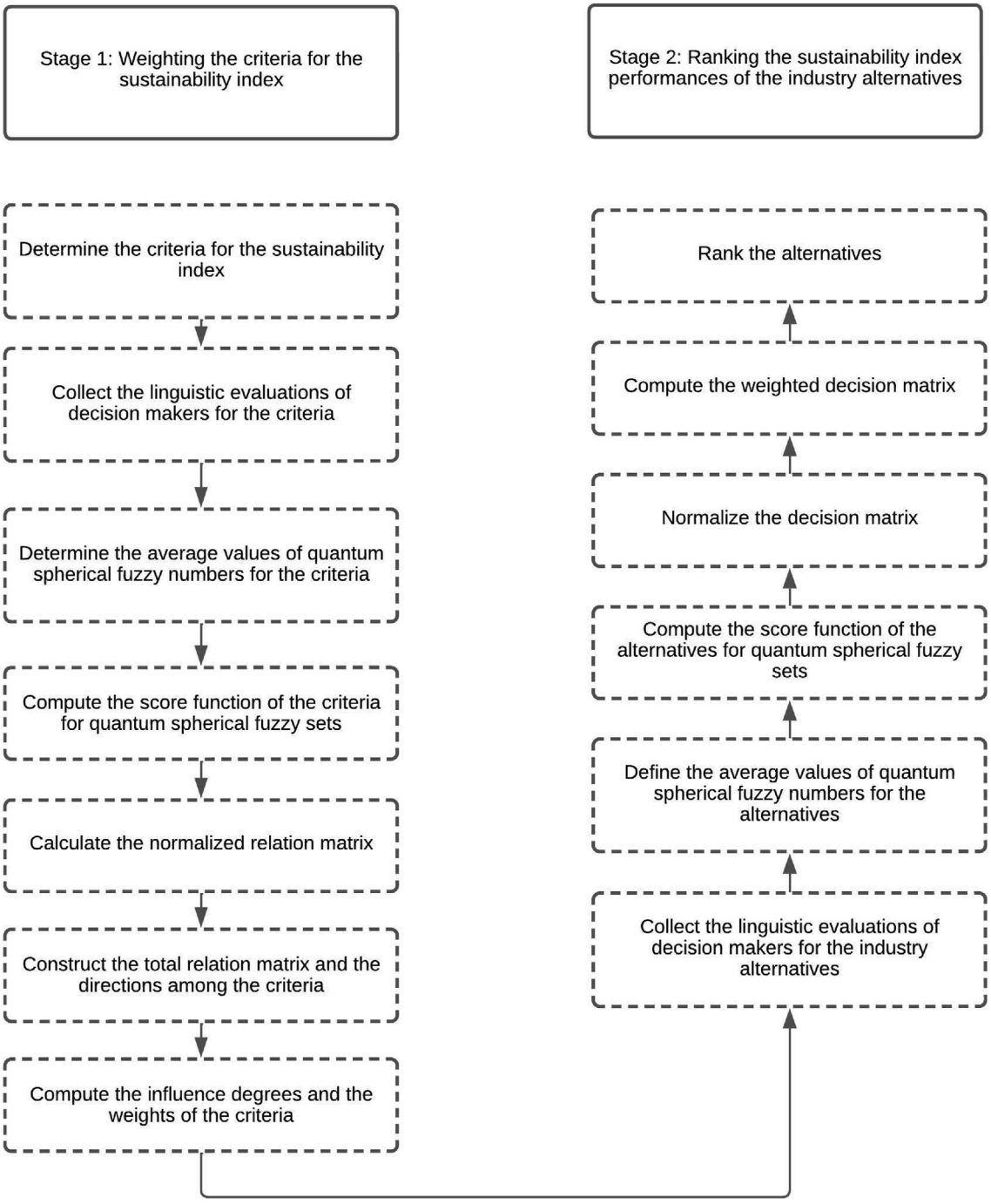

Fig. 1. The flowchart.

must have an effective risk management mechanism. This is especially important in times of financial crisis. Risks emerge more clearly during a financial crisis in the country or around the world, and in this context, companies that take effective measures against these risks get through crisis periods much more smoothly. Moreover, the fact that companies have different income alternatives is also very important in this process as companies that depend on a single type of income take a very serious risk in times of crisis, directly affecting this income channel. In other words, no matter how profitable the companies with a single income type are, they are at risk of losing this income channel. Finally, innovative investments also affect companies' inclusion in SI. For companies to maintain their performance over a long period of time, their costs must be at a reasonable level. Otherwise, it will not be possible for companies to survive financially in the long term. Therefore, companies *need* to invest in technology. Thanks to the investments to be made in this field, it will be possible for companies to learn new practices related to their activities, thereby contributing to reducing their costs.

Table 1
Selected dimensions and criteria for SI.

Dimensions	Criteria	Supported Literature
Finance (D1)	Risk management in the crisis period (RCP)	(Landi et al., 2022); (Ozturk & Ullah, 2022)
	Alternative income policies (AIP)	(Erdoğan et al., 2022); (Ferrari et al., 2022)
	Innovation investments and flexibility in costs (IIF)	(Nobanee et al., 2021); (Di Simone et al., 2022)
Management (D2)	Transparency (TNS)	(Navas et al., 2021); (Jestratijevic et al., 2021)
	Diversification (DFC)	(Duan et al., 2021); (Cuadrado-Ballesteros & Bisogno, 2022)
	Compliance with the Rules (CWR)	(Gonçalves & Silva, 2021); (Duan et al., 2021)
Personnel (D4)	Talent Management (TGE)	(Yakovleva & Miller, 2021); (Fabiani et al., 2021)
	Equal opportunity in the workforce (EOW)	(Olatayo et al., 2022); (Duval et al., 2021)
	Suitability of workplace conditions (SWD)	Soundararajan et al. (2021)
Environment (D3)	Recovery of Resources (RVR)	Lee et al. (2021)
	Actions for Production Efficiency (APF)	(Razmjoo et al., 2021); (Martins et al., 2021)
	Use of Renewable Energy (URW)	(Kolosok et al., 2021); (Zhaedi et al., 2022)

Administrative issues are also very important for companies to be included in SI. In this framework, the company must be transparent in its management activities. To achieve this goal, companies should clearly share aspects of their activities with both their employees and external stakeholders. This will help companies gain confidence in investors and help to increase the range of investments: another issue that comes to the fore since a single investment focus is a huge risk. Therefore, it is essential to provide diversity to minimize risks. In this way, companies will be less affected by a possible financial crisis. Finally, it is important for the company management to operate in accordance with the rules to be included in SI. Management acting in accordance with the rules helps to increase the trust of both personnel and external stakeholders in the company. Furthermore, companies may be subject to high penalties because of not acting in accordance with laws and regulations, putting companies in financial difficulties.

Factors related to personnel can also be effective in the inclusion of companies in SI. Qualified personnel are needed for companies to have high profitability. In this context, competent personnel should be employed. Another important issue here is the necessity of employing these competent personnel for the right job. Otherwise, even if the personnel are qualified, their performance in the company will not be high. Giving equal opportunities to those working in the workforce is also very important in this context. In other words, it is necessary to act with fairness among the personnel while providing job opportunities. This will increase the confidence of both personnel and external stakeholders in the company. Finally, the suitability of working conditions at the workplace is also very important for companies to be included in SI. Employees working in bad conditions will not be satisfied with their work. This will lead to a decrease in the motivation and performance of the employees. This will naturally affect the financial performance of companies negatively. The solution of this mentioned problem is also important for companies to achieve their sustainability goals.

Another issue to be considered for companies to be included in SI is environmental factors. Recycling of resources is another vital issue in this process. The raw materials used in the production process can cause a decrease in natural resources. In this framework, if the production process continues, natural resources will also decrease continuously. This situation negatively affects the concept of sustainability. Therefore, thanks to the recycling of used products, less resources can be used in the production process. This will serve the purpose of sustainability more clearly. The efficiency of the production processes is another important issue in this process. If companies cannot ensure efficiency in the production process, this increases the risk of not being able to control their costs. Uncontrollable costs can put companies in financial difficulties. In other words, inability to control costs can put companies in financial difficulties. This puts the long-term sustainability of companies at risk. The use of clean energy is of vital importance in this respect. The most important issue in terms of sustainability is the effective use of natural resources. Therefore, the use of clean energy sources instead of fossil fuels directly serves this purpose.

Step 2 includes the collection of the linguistic evaluations of decision makers for the criteria. In this context, an expert team is created with three different decision makers. These experts have a minimum 27-year work experience and are currently working as top managers in international companies. They have joined many different projects regarding the subject of sustainability and have sufficient knowledge to make evaluations with respect to SI. The linguistic evaluations are collected by considering five different scales. After that, these evaluations are converted to the possibility degrees and quantum spherical fuzzy numbers by using the values stated in Table 2. Additionally, the evaluations of the decision makers are given in the appendix part (Table A1).

In *Step 3*, the average values of QFS are computed for the criteria. The details of these values are indicated in Table A2. Furthermore, *Step 4* gives information about the calculation of the score function of the criteria for quantum spherical fuzzy sets. Table A3 indicates the details of the score function values for the criteria. *Step 5* includes the normalization process. Normalization procedure is performed by the help of Equations (23) and (24). The details of the values are shown in Table A4. In *Step 6*, the total relation matrix is created with the help of Equation (25). This matrix is used for the identification of the impact directions. The details of this matrix are given in Table A5. Moreover, the causal relationship between the criteria is given in Table 3.

Table 2
Linguistic scales and golden cut based QFS.

for Criteria	for Alternatives	Possibility Degrees	QSFNs
No (n)	Worst (w)	.40	$[\sqrt{0.16}\,e^{j2\pi.0.4}, \sqrt{0.10}\,e^{j2\pi.0.25}, \sqrt{0.74}\,e^{j2\pi.0.35}]$
some (s)	Bad (p)	.45	$[\sqrt{0.20}\,e^{j2\pi.0.45}, \sqrt{0.13}\,e^{j2\pi.0.28}, \sqrt{0.67}\,e^{j2\pi.0.27}]$
Normal (m)	Normal (f)	.50	$[\sqrt{0.25}\,e^{j2\pi.0.50}, \sqrt{0.15}\,e^{j2\pi.0.31}, \sqrt{0.60}\,e^{j2\pi.0.19}]$
High (h)	Well (g)	.55	$[\sqrt{0.30}\,e^{j2\pi.0.55}, \sqrt{0.19}\,e^{j2\pi.0.34}, \sqrt{0.51}\,e^{j2\pi.0.11}]$
Very High (vh)	Perfect (b)	.60	$[\sqrt{0.36}\,e^{j2\pi.0.6}, \sqrt{0.22}\,e^{j2\pi.0.37}, \sqrt{0.42}\,e^{j2\pi.0.03}]$

Table 3
Total relation matrix and the impact directions.

Influencing Criteria	Influenced Criteria
RCP	AIP, IIF, TNS, DFC, CWR, RVR, APF
AIP	TNS, DFC, RVR, APF
IIF	AIP, TNS, DFC, CWR, RVR, APF
TNS	AIP, IIF, RVR, APF
DFC	TNS, RVR, APF
CWR	TNS, DFC, RVR, APF
TGE	TNS, DFC, RVR, APF
EOW	TNS, DFC, RVR, APF
SWD	AIP, IIF, TNS, DFC, CWR, RVR, APF
RVR	None
APF	None
URW	RCP, AIP, IIF, TNS, DFC, CWR, TGE, EOW, SWD, RVR, APF

Table 3 explains that the usage of renewable energy has a significant impact on all other criteria. This situation gives information that for inclusion of companies in SI, renewable energy investments play a crucial role. While using clean energy, the companies get a chance to improve other criteria of SI. Another important point in Table 3 is that risk management in the crisis period, innovation investments, and flexibility in costs and suitability of workplace conditions have also impacted other criteria. In this step, the weights of the criteria are also computed by considering Equations (26) and (27). The weighting results are stated in Table 4.

Table 4 demonstrates that use of renewable energy is the most critical criterion to be included in SI. Similarly, recovery of the resources has also a significant contribution to each of these purposes. The results indicate that environmental issues have a greater importance in comparison with other dimensions and that companies should focus on the usage of clean energy. Of equal significance, Production energy with fossil fuels creates a carbon emission problem, which in turn creates environmental pollution that can threaten the health of the people. To reach sustainability purposes, natural resources should be used effectively. Hence, in this framework, renewable energy alternatives should be selected instead of fossil fuels. Within this scope, companies should focus on renewable energy technology investments. Additionally, resources should be recycled to reach sustainability purposes, and because the production process decreases natural resources, this situation negatively affects the concept of sustainability. Due to this issue, recycling of used products has a positive contribution to sustainability.

Table 4
Weights.

	D	E	D + E	D-E	Weights	Weighting priorities
RCP	21.791	21.542	43.332	.249	.0831	8
AIP	21.663	21.666	43.329	−.002	.0831	9
IIF	21.719	21.673	43.393	.046	.0832	5
TNS	21.670	21.801	43.471	−.131	.0834	3
DFC	21.622	21.777	43.399	−.155	.0832	4
CWR	21.687	21.672	43.359	.015	.0832	7
TGE	21.642	21.521	43.164	.121	.0828	12
EOW	21.623	21.569	43.192	.053	.0828	11
SWD	21.714	21.559	43.273	.155	.0830	10
RVR	21.427	22.453	43.880	−1.026	.0842	2
APF	21.488	21.875	43.363	−.387	.0832	6
URW	22.629	21.569	44.198	1.060	.0848	1

4.2. Stage 2: ranking SI performances of the industry alternatives

Secondly, the industry alternatives are ranked with respect to SI performances. In *Step 7*, linguistic evaluations are collected regarding the alternatives. In this framework, 10 different sectors are selected as alternatives that are food (FOO), real estate and construction (RST), mining (MNN), finance (FCE), chemistry and petroleum (CPO), communication and IT (CMM), metal (MAL), textile (TXL), tourism (TRS) and transportation (TTI). By using the scales stated in Table 2, linguistic evaluations are obtained from the expert team. These evaluations are indicated in Table A6. In *Step 8*, the average values of QFS are defined for the alternatives by using Equation (21). The results are demonstrated in Table A7. *Step 9* is related to the computation of the score function of the alternatives QFS. By using Equation (22), the defuzzified values of the alternatives are represented as the score function. Table A8 explains the details of these values. Normalization procedure is employed with Equation (30) in *Step 10*. Table A9 defines the normalized values of the decision matrix. In *Step 11*, the weighted decision matrix is computed by Equation (31). Table A10 expresses the weighted decision matrix. *Step 12* is related to the ranking of the alternatives. In this framework, Equations 32–36 are considered. In Table 5, the final ranking results are illustrated according to the descending order of the RCi values.

Table 5 defines that communication and IT is the most successful industry for SI. Similarly, finance is another key

Table 5
Ranking results.

Alternatives	D+	D+	RCi	Ranking
FOO	.005	.001	.2267	10
RST	.004	.002	.3819	5
MNN	.004	.003	.4368	3
FCE	.004	.003	.4369	2
CPO	.004	.003	.3858	4
CMM	.003	.003	.4924	1
MAL	.005	.001	.2307	9
TXL	.004	.002	.2705	8
TRS	.004	.002	.3316	6
TTI	.004	.002	.3170	7

industry in this framework. Nonetheless, textile, metal and food are on the last ranks. In the first part of the proposed model, the significant points are identified to be included in SI. These results pave the way especially for the industries at the bottom of the ranking.

5. Discussion

The climate crisis has become a threat to the whole world, leading to an increase in sensitivity to environmental factors. In this context, both governments and businesses are trying to take action to reduce the damage to the environment. In this framework, companies try to continue their activities without harming environmental factors, hence the need for the SI criteria for companies trading in the stock exchange. Companies that meet certain criteria can be included in this index, providing some advantages to companies. For example, the brand image of the companies in this index will be positively affected and thus, it would be preferred by more investors.

Considering the results obtained in this study, it is understood that the use of renewable energy is the most important criterion for companies to enter SI. The carbon emission problem arises due to the preference of fossil fuels in energy consumption, a situation that creates significant air pollution, threatens people's health, and contributes to the problem of global warming (Malik et al., 2022). Therefore, it would be appropriate for businesses to attach importance to the use of renewable energy, and in this way, the carbon emission problem will be minimized while the image of businesses will rise in the eyes of both consumers and investors (Ari & Koc, 2021).

However, there are some negativities in renewable energy investments. High initial cost of these investments poses a serious obstacle to the use of clean energy. But, there are some actions that businesses can take to minimize this cost. First, enterprises should be able to reduce the costs of these projects with long-term research and development studies. This will increase the use of clean energy so that companies can be accepted into SI more easily. Zhong et al. (2020) aimed to identify investment strategies for renewable energy projects, stating that research and development investments have a powerful contribution in decreasing the cost of this project. Dinçer and Yüksel (2019) also made a study to understand which renewable energy alternative is optimal for investment. In this study, the significance of the technology investments was also highlighted to have cost effectiveness. Igliński et al. (2022) assessed the renewable energy sector in Poland and stated that the high-cost problem is the key issue of these projects and new technologies should be adopted to handle this problem more effectively.

Clearly, though, it is necessary to develop a short-term solution proposal for this problem. In this context, it should be ensured that costs can be reduced by using government incentives for these investments. Smirnova et al. (2021) and Zebra et al. (2021) defined that governments should support renewable energy projects, such as loans with low interest rates and tax incentives. Moreover, new applications such as small-scale solar panels may be more useful for businesses-another phenomenon that can increase the use of clean energy. Dinçer et al. (2022) and Li et al. (2022) also highlighted the essence of small-scaled solar panels to minimize the cost of clean energy projects. Furthermore, thanks to microgrid energy applications, the costs of using renewable energy can be shared with other companies. Since this situation can reduce the cost per unit, it will be possible to increase the use of renewable energy (Wu et al., 2022).

6. Conclusions

In this study, the industries listed in the stock exchange are examined with respect to SI, and a new fuzzy decision-making model has been created in this regard. Firstly, 12 different criteria for SI are weighted by DEMATEL methodology based on QFS with a golden cut. Secondly, SI performances of the 10 industry alternatives are ranked using TOPSIS technique with QFS. According to the causal direction results, it is defined that the usage of renewable energy has a significant impact on all other criteria. While using clean energy, the companies get a chance to improve other criteria of SI. It is also concluded that risk management in the crisis period, innovation investments, and flexibility in costs and suitability of workplace conditions have also impacted other criteria. On the other hand, based on the weighting results, it is found that use of renewable energy is the most critical criterion to be included in SI. Similarly, recovery of the resources has also a significant contribution to each of these purposes. The results indicate that environmental issues have a greater importance in comparison with other dimensions. Finally, the ranking results indicate that communication and the IT department are the most successful industry for SI. Similarly, finance is another key industry in this framework. Nonetheless, textile, metal, and food are on the last ranks.

The main novelty of this study is to identify significant sustainability criteria for companies to join within this index using an original fuzzy decision-making methodology. The analysis results have a leading impact for companies with minimal costs. Additionally, with the help of new improvements, a novel fuzzy decision-making model can be created that increases the originality of the study. In this study, evaluations were made on 10 different sectors (this turns out to be an important limitation). Therefore, in future studies, the concept of sustainability can be examined on a sectoral basis.

In this way, it will be possible to develop criteria specific to the examined sector. The model developed in this study can also be improved in new studies. In this context, a comparative analysis can be performed with different fuzzy numbers, allowing the consistency of the results obtained to be tested.

Furthermore, many policy implications for different parties based on the analysis results of this study are necessary. Firstly, policymakers should design effective regulations to improve renewable energy investments in the countries. Within this framework, they should offer subsidies to the renewable energy investors since reducing the tax for these investors provides an opportunity to get tax advantages-an attractive characteristic for increased investment in clean energy projects. The policymakers can also generate a carbon tax for fossil fuel usage: fossil fuel consumption can be decreased due. In addition to this issue, investors should mainly focus on technology improvements related to renewable energy generation, especially as renewable energy production technology has been significantly developing and provides essential cost advantages to the investors. Investors will be able to use clean energy more effectively and efficiently thanks to new technologies, both helping the image of businesses and facilitating their acceptance into the SI index.

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