Received 26 February 2023, accepted 9 April 2023, date of publication 12 April 2023, date of current version 20 April 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3266524

RESEARCH ARTICLE

Analysis of Environmental Impact for Material Production Investments Using a Novel Soft Computing Methodology

HASAN DİNÇER[1,2], SERKAN ETİ[3], TAMER AKSOY[2], SERHAT YÜKSEL[1], ÜMİT HACIOĞLU[2], ALEXEY MIKHAYLOV[4], AND S. M. MUYEEN[5], (Senior Member, IEEE)
[1]School of Business, Istanbul Medipol University, 34810 Istanbul, Turkey
[2]School of Business, Ibn Haldun University, 34480 Istanbul, Turkey
[3]Vocational School, Istanbul Medipol University, 34810 Istanbul, Turkey
[4]Financial Faculty, Financial University under the Government of the Russian Federation, 125993 Moscow, Russian Federation
[5]Department of Electrical Engineering, Qatar University, Doha, Qatar

Corresponding authors: S. M. Muyeen (sm.muyeen@qu.edu.qa) and Serhat Yuksel (serhatyuksel@medipol.edu.tr)

This study is is supported by the Russian Science Foundation grant No. 23-41-10001, https://rscf.ru/project/23-41-10001/. Open Access funding provided by the Qatar National Library.

ABSTRACT The purpose of this study is to evaluate the environmental impacts of material production investments. The factors of Higg Materials Sustainability Index are defined as the parameters. These factors are weighted by considering T-SF TOPSIS-DEMATEL. Moreover, the items of the life cycle process are defined as alternative set for measuring the environmental effects of each process in the sustainable production investments. These alternatives are ranked with interval valued SF MAIRCA. The calculations are also made for different t, u and d values with the aim of making comparative evaluations. The main contribution of this study is that a priority analysis has been made so that the most significant indicators are defined for the companies to increase sustainability in material production investment process. Another important novelty of this paper is that a new model is created by the name of TOPSIS-DEMATEL. This situation has a positive influence on both increasing methodological originality and overcoming criticized issues of DEMATEL. The results are quite similar for all conditions, so it is understood that the proposed model provides consistent and coherent findings. It is concluded that chemistry is the most critical factor for environmental impact for material production investments. Moreover, recycle is determined as the most optimal alternative.

INDEX TERMS Material production, environmental impact, energy investments, clean energy, TOPSIS-DEMATEL, MAIRCA, spherical fuzzy sets.

NOMENCLATURE

DEMATEL: decision making trial and evaluation laboratory.
MAIRCA: multi attributive ideal-real comparative analysis.
SF: Spherical fuzzy.
TOPSIS: technique for order preference by similarity to ideal solution.

I. INTRODUCTION

Raw materials play a key role in industrial production. In order not to interrupt the production process, raw materials must be supplied both on time and in sufficient quantity. The industrial production of countries will increase rapidly that contributes to economic growth. Businesses need to give importance to material production processes, which include the acquisition of raw materials and logistics to the relevant place [1]. Otherwise, customer dissatisfaction will arise, and this will reduce the efficiency of production processes. However, there are some issues that businesses should pay attention to during the material production investment process. Otherwise, there is a possibility that these investments will harm the environment. Economic growth will not be sustainable in this case [2]. Issues such as air and water pollution will lead to problems that threaten the whole world, such as global warming.

The associate editor coordinating the review of this manuscript and approving it for publication was Kuo-Ching Ying.

Higg Materials Sustainability Index is generated to compute the environmental impacts of material production investments. With the help of this index, it can be possible to improve manufacturing process so that more sustainable products can be generated [3]. This index considers five different parameters that are global warming, water pollution, water scarcity, resource depletion and chemistry. In this index, scores are created by considering the environmental impact of the material on each of these parameters. Based on these results, appropriate strategies can be developed for the manufacturers to increase the performance of sustainability [4]. However, the important point in this process is to determine which actions are more important because these improvements create extra costs for businesses. Therefore, it is not very reasonable for businesses to make improvements for all factors together to ensure sustainability [5]. It is vital for businesses to make a priority analysis for these factors and use their budgets accordingly.

In this study, it is aimed to examine the environmental impacts of material production investments. A model has been constructed to make this evaluation. Firstly, the factors of Higg Materials Sustainability Index are selected as the parameters and they are weighted by considering T-SF TOPSIS-DEMATEL. Secondly, the items of the life cycle process are defined as alternative set for measuring the environmental effects of each process in the sustainable production investments. In this scope, these alternatives are ranked with interval valued SF MAIRCA. In the final step, E7 countries (Brazil, China, India, Indonesia, Mexico, Russia, and Turkey) are ranked for the performance of the environmental impacts of material production investments.

The main contributions of this study are demonstrated as follows.

(i) There are limited studies in literature that determine which actions are more important regarding the environmental impacts of material production investments. A priority analysis has been made so that the most significant indicators are defined for the companies to increase sustainability in material production investment process. This situation helps to use the budget of these companies efficiently while taking actions to reach this purpose. Because the improvements create extra costs for businesses, it is not very reasonable to make improvements for all factors together. Hence, the analysis results of this study pave the way for the companies to implement the most important strategies.

(ii) Considering Higg Materials Sustainability Index parameters to define criteria list is another essential advantage of this proposed model. This index calculates the scores of the material production process regarding the environmental impacts [6]. This index is considered by many organizations around the world [7]. This gives information about the effectiveness of the index parameters. Therefore, these index parameters will contribute to the presentation of more effective strategies to the enterprises [8].

(iii) DEMATEL technique has many benefits by comparing with other techniques, such as creating impact directions of the indicators. However, this methodology has also been criticized because of some issues [9]. For example, the criteria weights are equal in the case of a symmetrical evaluation [10]. The mathematical background of this disadvantage is related to the weighting process steps of the DEMATEL method [11]. On the other hand, the steps of TOPSIS technique help to solve this problem. Therefore, a new model is created in this study by integrating some steps of TOPSIS to DEMATEL. This new methodology is named by TOPSIS-based DEMATEL method (TOPSIS-DEMATEL). This situation has a positive influence on both increasing methodological originality and overcoming criticized issues of DEMATEL.

(iv) One of the most important issues in the decision-making processes is the selection of the appropriate technique and fuzzy sets for the problem. However, the fact that the problems become more and more complex makes this issue much more difficult. In this study, membership, non-membership and hesitancy parameters could be used considering the SF sets [12]. This also contributes to the more reliable results obtained [13]. In the previously generated model that did not use SF sets, hesitancy conditions could not be taken into consideration. This situation has a negative impact on the accuracy of the model results.

(v) Another advantage of this proposed model is calculating the results for different t values. Hence, it can be possible to compare the results based on different conditions. Hence, the consistency and reliability of the findings can be checked. Owing to this issue, more effective environmentally friendly strategies can be identified.

(vi) Considering the MAIRCA method also provides some benefits. In this technique, the probability of choosing each alternative is considered equal. In other words, the probability of alternatives according to each criterion is taken into consideration. In this way, it will be possible to reach more objective results.

The second part denotes literature evaluation. In this section, similar studies in literature are evaluated. The methodology part is explained in the next section that gives information about the techniques considered in the analysis process. Analysis result part gives information about the findings of the proposed model. Conclusions and discussions are demonstrated in the last parts.

II. LITERATURE REVIEW

Environmental negative effects may occur in material production investments. Global warming is one of the prominent issues in this process. López-Perales et al. [14] stated that especially with the increase in industrial production, more raw materials are used throughout the world. A significant amount of electricity is needed in the production of raw materials. Fischer et al. [15] defined that the carbon gas formed as a result of this electricity being obtained from fossil fuels pollutes the air significantly. Air pollution causes an increase in diseases [16]. This situation puts countries in difficulties both socially and economically. Peiró et al. [17] and Xu et al. [18] studied that fossil fuel-related air pollution causes global warming problem. According to Eštoková et al. [19], Wang et al. [20] and Huang et al. [21], due to global warming, many important problems such as disruption in agricultural production and climate change arise.

Another environmental problem that may occur in raw material production investments is the depletion of natural resources. Lee et al. [22] determined that countries need more raw materials to grow their economies. A significant majority of these raw materials are obtained from natural sources. According to Pevs et al. [23], if these raw materials are used unconsciously, a significant decrease in natural resources may occur. This will cause the problem of not being able to access natural resources [24]. Thus, countries may grow economically, but this growth will not be sustainable. On the other hand, Chien et al. [25], Charlier and Fizaine [26] and Liu et al. [27] emphasized that some natural resources may be damaged in the production of raw materials where the necessary attention is not given. For example, in the unconscious production of wood raw materials, a lot of damage can be done to forests [28]. This situation causes the deterioration of the ecological balance [29].

There is also a risk of damage to water resources in raw material production. Some wastes may occur in raw material production. According to Zhang et al. [30], if this waste is not disposed of properly, water resources can be polluted. Ghosal et al. [31] stated that polluted water also threatens the life of living things. In summary, more critical problems may arise for the countries due to the wrong steps taken while the economies of the countries are growing. In addition, Padilla Fernández et al. [32] highlighted that it may be necessary to use water in the production of some raw materials. If these waters are used unconsciously, water resources can be depleted quickly [33], [34]. Kyriakopoulos et al. [35], Sang et al. [36] and Karimidastenaei et al. [37] claimed that experiencing water scarcity around the world can also cause life-threatening problems. Therefore, it is important to carry out efficiency studies when using water in raw material production.

The use of chemicals is also one of the problems that may arise in raw material production. Almroth et al. [38] defined that the use of chemicals in raw material production has increased significantly in recent years. This increase brings with it a number of threats. Pola et al. [39] identified that chemical substances pose a life-threatening danger to employees in possible accidents that may occur in production facilities. According to Kumar et al. [40], as a result of giving weight to chemical substances in the production of raw materials, harmful wastes may occur. These harmful wastes also cause significant environmental pollution [41]. If this situation cannot be controlled, fatal diseases may occur and thus the life of living things will be endangered. Tickner et al. [42] and Gonzalez et al. [43] emphasized that thanks to effective recycling processes, these hazards caused by chemical products should be minimized.

As a result of the literature review, the following important points can be reached.

(i) More raw materials are used throughout the world with the increase in industrial production.

(ii) A significant amount of electricity is needed in the production of raw materials. The carbon gas formed as a result of this electricity being obtained from fossil fuels pollutes the air significantly.

(iii) The depletion of natural resources is a crucial environmental problem that may occur in raw material production investments.

(iv) In material production investments, there is also a risk of damage to water resources.

(v) The use of chemicals in raw material production has increased significantly in recent years that causes significant problems.

(vi) It is essential for businesses to take some actions to ensure sustainability in material production processes. However, there are limited studies in literature that determine which actions are more important.

(vii) However, it is crucial for businesses to make a priority analysis for these factors and use their budgets accordingly.

By considering these issues, in this study, a comprehensive examination is applied to determine the most critical environmental impacts of material production investments. With the help of this analysis, appropriate strategies can be developed for the manufacturers to increase the performance of sustainability.

III. METHODOLOGY

In this proposed model, T-SF TOPSIS-DEMATEL methodology is used to weight the indicators. Also, interval valued SF MAIRCA is considered for ranking the alternatives. These two techniques are identified separately in this section.

A. T-SF TOPSIS-DEMATEL

Decision makers want to find the most appropriate solution when there is a problem. As the number of criteria increases, making the most appropriate decision becomes more complex. To overcome this problem, scientific methods have been developed. One of these methods is DEMATEL method, which is one of the multi-criteria decision-making techniques. This approach is mainly used to rank the criteria set by pairwise comparison [44]. In other words, it is the preferred method for ranking and weighting from the most important to the least important criteria based on expert opinions [45]. Its superiority over other weighting methods used for this purpose is that it takes into consideration the effect between criteria. In other words, it is one of the biggest advantages of the method that the criteria have an effect on each other and that these effects are taken into account in weighting. Another advantage is that it enables the determination of criteria that are affected by other criteria or that affect other criteria.

TABLE 1. Fuzzy Sets.

Scales	s	U	d
4	,85	,15	,45
3	,6	,2	,35
2	,35	,25	,25
1	0	,3	,15
0	0	0	0

Nevertheless, DEMATEL method has also some disadvantages. The foremost of these is that the criteria weights are equal in the case of a symmetrical evaluation [9], [10]. The mathematical background of this disadvantage is related to the weighting process steps of the DEMATEL method [11]. The TOPSIS-based weighting proposed in this step allows the problem to be solved. In this context, TOPSIS-based DEMATEL method (TOPSIS-DEMATEL) is used in the study. Thus, in this proposed model, originality is achieved by using the TOPSIS-DEMATEL method, in which the DEMATEL method is improved.

In addition, fuzzy number systems have recently been integrated into these methods because they better handle the uncertainty in multi-criteria decision making. In this context, Spherical Fuzzy sets (SFS) are currently preferred in fuzzy number systems [12]. In addition to this, T-SFS method, which can be calculated according to different t values, is used in this study. A T-SFS number is defined as the combination of three restricted functions known as membership (s), abstinence or hesitance (u), and non-membership (d). Equation (1) gives information about this restriction [13].

$$0 \leq s^t + u^t + d^t \leq 1 \tag{1}$$

The advantage of this set of fuzzy numbers is that calculations according to t, d and u values can be converted to other fuzzy number systems. A T-SFS number can be converted to different sets as follows [46].

- SFS when t is taken as 2.
- Picture fuzzy set when t is taken as 1.
- Q-rung orthopair fuzzy set when u value is considered as 0. (For this situation, t values are computed with golden cut)
- Pythagorean fuzzy set when t number is taken as 2 and u value is considered as 0.
- Intuitionistic fuzzy set when t number is taken as 1 and u value is considered as 0.
- Zadeh's fuzzy set when t number is taken as 1 and u and d values are considered as 0.

Thanks to this advantage, TOPSIS-DEMATEL results obtained in different situations can be compared. In other words, the reliability of the results can be tested. The steps of the T-SF TOPSIS-DEMATEL method are as follows.

Step 1: Expert opinions are taken and converted with the fuzzy number equivalents in Table 1.

A matrix (Zi) is created with fuzzy numbers corresponding to the expert opinion. The matrix in question is shown by Equation (2) [47].

$$Z^i = \begin{bmatrix} 0 & \cdots & (s^i_{1n}, u^i_{1n}, d^i_{1n}) \\ \vdots & \ddots & \vdots \\ (s^i_{n1}, u^i_{n1}, d^i_{n1}) & \cdots & 0 \end{bmatrix} \tag{2}$$

Step 2: Using Equation (3), the average (Z) of k experts is taken. The decision matrix where the averages are taken is shown by Equation (4). The weights (w) in Equation (3) are taken as 1/k and the expert opinions are given equal weight [48].

$$TSFWAM_W\left(\tilde{A}_{S1}, \tilde{A}_{S1}, \ldots \tilde{A}_{Sn}\right) = \left\{\left[1 - \prod_{i=1}^{n}\left(1 - s^t_{\tilde{A}_{Si}}\right)^{w_i}\right]^{\frac{1}{t}}, \prod_{i=1}^{n} u^{w_i}_{\tilde{A}_{Si}}, \prod_{i=1}^{n} d^{w_i}_{\tilde{A}_{Si}}\right\} \tag{3}$$

$$Z = \begin{bmatrix} 0 & \cdots & (s^d_{1n}, u^d_{1n}, d^d_{1n}) \\ \vdots & \ddots & \vdots \\ (s^d_{n1}, u^d_{n1}, d^d_{n1}) & \cdots & 0 \end{bmatrix} \tag{4}$$

Step 3: For each component in the T-Spherical fuzzy, 3 separate sub-matrices (X^s, X^u and X^d) are created. Then, these matrices are normalized separately by using Equations (5) and (6) [49].

$$X = sZ \tag{5}$$

$$s = \min\left[\frac{1}{\min_i \sum_{j=1}^{n} |z_{ij}|}, \frac{1}{\min_j \sum_{i=1}^{n} |z_{ij}|}\right] \tag{6}$$

3 submatrices obtained by normalization are represented by Equation (7) [46].

$$X^s = \begin{bmatrix} 0 & \cdots & s_{1n} \\ \vdots & \ddots & \vdots \\ s_{n1} & \cdots & 0 \end{bmatrix} X^u = \begin{bmatrix} 0 & \cdots & u_{1n} \\ \vdots & \ddots & \vdots \\ u_{n1} & \cdots & 0 \end{bmatrix}$$
$$X^d = \begin{bmatrix} 0 & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & 0 \end{bmatrix} \tag{7}$$

Step 4: The total relationship matrix (T) is calculated for each submatrix with Equation (8) [47].

The calculated 3 submatrices are then applied with Euclidean normalization. Thus, Equation (1) required for the t-spherical fuzzy number to be formed is provided.

Step 5: 3 submatrices are combined, and the t-spherical fuzzy total relationship matrix (T) is obtained as in Equation (9) [48].

$$T = \begin{bmatrix} 0 & \cdots & (\mu^T_{1n}, \eta^T_{1n}, \nu^T_{1n}) \\ \vdots & \ddots & \vdots \\ (\mu^T_{n1}, \eta^T_{n1}, \nu^T_{n1}) & \cdots & 0 \end{bmatrix} \tag{8}$$

Step 6: T matrix defuzzification is done with the help of Equation (9) [49].

$$Score = \mu^t - \eta^t - \nu^t \tag{9}$$

Step 7: The criterion weights (W) are obtained by using the T matrix with the defuzzification via Equations (10)-(16) [46].

$$C_j^* = \sqrt{\sum_{i=1}^{n} (t_i - t_i)^2} \quad j = 1, 2, \ldots n \tag{10}$$

$$C_j^- = \sqrt{\sum_{i=1}^{n} (t_i - t_i)^2} \quad j = 1, 2, \ldots n \tag{11}$$

$$R_i^* = \sqrt{\sum_{j=1}^{n} \left(t_j - t_j\right)^2} \quad i = 1, 2, \ldots n \tag{12}$$

$$R_i^- = \sqrt{\sum_{j=1}^{n} \left(t_j - t_j\right)^2} \quad i = 1, 2, \ldots n \tag{13}$$

$$S_i^* = C_i^* + R_i \tag{14}$$

$$S_i^- = C_i^- + R_i^- \tag{15}$$

$$W_i = \frac{S_i^{-}}{S_{\ i}^{-}} + S_i \tag{16}$$

B. INTERVAL VALUED SF MAIRCA

In the second stage of the proposed model in the study, it is aimed to rank the alternatives. In this context, the MAIRCA method has been taken into consideration. The purpose of the MAIRCA method is to rank the alternatives under certain criteria [50]. In other words, with this method, the most suitable alternative can be determined by considering the criteria. In MAIRCA, very reliable results can be obtained thanks to its unique linear normalization algorithm. Also, other sorting methods consider distances from ideal positive to ideal negative values. The MAIRCA method, on the other hand, calculates the selection probability. With this aspect, it is considered to be more advantageous compared to other methods. This method aims to determine the most optimal alternative by calculating the distance between the theoretical and the actual evaluation matrix [51]. The interval valued SF set is given in Equation (17) [50].

$$\tilde{A}_s = \left\{ u, \left(\begin{array}{l} \left[\mu_{\tilde{A}_s}^L(u), \mu_{\tilde{A}_s}^U(u)\right], \\ \left[v_{\tilde{A}_s}^L(u), v_{\tilde{A}_s}^U(u)\right], \\ \left[\pi_{\tilde{A}_s}^L(u), \pi_{\tilde{A}_s}^U(u)\right] \end{array} \right) \middle| u \in U \right\} \tag{17}$$

In this scope, $\mu_{\tilde{A}_s}^U(u)$, $v_{\tilde{A}_s}^U(u)$ and $\pi_{\tilde{A}_s}^U(u)$ refer to the are the upper limit values of memberships, non-membership ve hesitancy degrees. Additionally, the lower and upper limits are given by $0 \le \mu_{\tilde{A}_s}^L(u) \le \mu_{\tilde{A}_s}^U(u) \le 1, 0 \le v_{\tilde{A}_s}^L(u) \le v_{\tilde{A}_s}^U(u) \le 1$, ve $0 \le \pi_{\tilde{A}_s}^L(u) \le \pi_{\tilde{A}_s}^U(u) \le 1$.

When $\langle [a_j, b_j,], [c_j, d_j], [e_j, f_j] \rangle$ is interval valued SF set, the arithmetic mean of k numbers is computed by as in Equation (18), shown at the bottom of the next page, [52]. In this study, the MAIRCA model is integrated with interval SF numbers. The stages of the developed model are as follows.

Step 8: The n criteria matrices with m alternatives created by the evaluations of each expert are calculated by Equation (19). This initial decision matrix (D) is given in Equation (19) [53].

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \cdots & \tilde{x}_{mn} \end{bmatrix}$$
$$\text{where } \tilde{x}_{ij} = \langle [a_j, b_j,], [c_j, d_j], [e_j, f_j] \rangle \tag{19}$$

Step 9: The preference possibilities (P_{Ai}) is the probability of choosing each alternative and is calculated by Equation (20) [50].

$$P_{Ai} = \frac{1}{m}; \sum_{i=1}^{m} P_{Ai} = 1 \tag{20}$$

Step 10: The theoretical evaluation matrix (TPA) is calculated by multiplying the (P_{Ai}) value with the weights obtained from TOPSIS-DEMATEL as in Equation (21) [51].

$$K_p = \begin{bmatrix} k_{p11} & \cdots & k_{p1n} \\ \vdots & \ddots & \vdots \\ k_{pm1} & \cdots & k_{pmn} \end{bmatrix} = \begin{bmatrix} P_{A1}w_1 & \cdots & P_{A1}w_n \\ \vdots & \ddots & \vdots \\ P_{Am}w_1 & \cdots & P_{Am}w_n \end{bmatrix} \tag{21}$$

Step 11: The score function of the $\tilde{D}$ matrix is calculated as in Equation (22) [52].

$$Score\left(\tilde{x}_{ij}\right) = S\left(\tilde{x}_{ij}\right) = \frac{a^2 + b^2 - c^2 - d^2 - \left(\frac{e}{2}\right)^2 - \left(\frac{f}{2}\right)^2}{2} + 1 \tag{22}$$

Step 12: The score values in the decision matrix for each criterion are normalized with Equations (23)-(24) [53].

$$\left(\frac{S\left(\tilde{x}_{ij}\right) - \min(S\left(\tilde{x}_{ij}\right))}{\max\left(S\left(\tilde{x}_{ij}\right)\right) - \min\left(S\left(\tilde{x}_{ij}\right)\right)}\right) \text{if x is a benefit criterion} \tag{23}$$

$$\left(\frac{S\left(\tilde{x}_{ij}\right) - \max(S\left(\tilde{x}_{ij}\right))}{\min\left(S\left(\tilde{x}_{ij}\right)\right) - \max\left(S\left(\tilde{x}_{ij}\right)\right)}\right) \text{if x is a cost criterion} \tag{24}$$

Step 13: With Equations (25) and (26), the actual evaluation matrix (Kr) is calculated. In this process, the normalized decision matrix is multiplied by the theoretical evaluation matrix [50].

$$k_{rij} = k_{pij}\left(\frac{S\left(\tilde{x}_{ij}\right) - \min(S\left(\tilde{x}_{ij}\right))}{\max\left(S\left(\tilde{x}_{ij}\right)\right) - \min\left(S\left(\tilde{x}_{ij}\right)\right)}\right) \times \text{ if x is a benefit criterion} \tag{25}$$

$$k_{rij} = k_{pij}\left(\frac{S\left(\tilde{x}_{ij}\right) - \max(S\left(\tilde{x}_{ij}\right))}{\min\left(S\left(\tilde{x}_{ij}\right)\right) - \max\left(S\left(\tilde{x}_{ij}\right)\right)}\right) \times \text{ if x is a cost criterion} \tag{26}$$

Step 14: The total void matrix (G) matrix is calculated by Equation (27) [51]. The gap between the theoretical and actual evaluation of each alternative according to each criterion is calculated.

$$G = K_p - K_r = \begin{bmatrix} g_{11} & \cdots & g_{1n} \\ \vdots & \ddots & \vdots \\ g_{m1} & \cdots & g_{mn} \end{bmatrix} \tag{27}$$

Step 15: The final values (Q) for the criteria are calculated by Equation (29) [52]. According to the final values obtained from the criteria functions of the alternatives, the alternatives are listed and the best one is selected. The alternative with the lowest clearance distance is selected as the best, while the alternative with the highest clearance distance is considered the worst.

$$Q_i = \sum_{j=1}^{n} g_{ij} \quad i = 1, 2, \ldots, n \tag{28}$$

IV. ANALYSIS RESULTS

In this study, a novel model is created to evaluate the environmental impacts of material production investments. Figure 1 explains the process of this new model.

The proposed model has two different sections. The analysis results are explained for each section separately.

A. WEIGHTING THE INDICATORS

T-SF TOPSIS-DEMATEL method is used for weighting in the application of the study. In the method, six different results are obtained by changing the t, u and d values. In the following parts, the results of the first case (t=2) are shared.

The purpose of the study is to assess the environmental impacts of material production including all life cycle from the production of raw materials to the recycling of the final product for sustainable production investments. For this situation, the factors of Higg Materials Sustainability Index are considered as "Global warming" (GWG), "Nutrient pollution in water" (NPW), "Water scarcity" (WSY), "Abiotic resource depletion" (ABN), and "Chemistry" (CTY) for evaluating the environmental impacts of the material production.

In *Step 1,* expert opinions are taken and converted with the fuzzy number. For this purpose, an expert team is generated from three people (PTOs). These people work as senior managers in the sustainability department of large-scale international industrial companies. Considering their long-term work experience and knowledge on the subject, it is understood that these people are capable of evaluating factors and alternatives. The opinions of these people regarding the criteria are given in Table 2.

Expert matrixes in Equation (2) are created with the evaluations of three experts and their fuzzy number equivalents in Table 1.

In *Step 2,* the average values are computed by using Equation (3). Afterwards, the decision matrix (Z) (Table 3) is calculated with the help of this situation.

In *Step 3,* three separate sub-matrices (X^s, X^u and X^d) are created for each component in the T-SF sets. The normalized matrixes obtained are given in Table 4.

Step 4 includes the construction of the total relationship matrix for each submatrix with Equation (8).

Regarding *Step 5*, three matrixes of the total effect matrix are obtained by applying the operations in Equation (8). By combining these calculated matrixes, the total relationship matrix (Table 5) is formed with Equation (9).

In *Step 6*, the defuzzification process is applied to the T matrix with Equation (9). Afterwards, Equations (10)-(16) is applied for weighting in *Step 7* as in Table 6.

It is concluded that chemistry is the most critical factor for environmental impact for material production investments since the weight (0.23) is the highest. Global warming is another significant issue in this framework. For the material

$$IVSWAM\left(\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_n\right) = \left\{ \begin{array}{c} \left[\begin{array}{c} \left(1 - \prod_{j=1}^{n}\left(1 - a_j^2\right)^{\frac{1}{k}}\right)^{\frac{1}{2}}, \\ \left(1 - \prod_{j=1}^{n}\left(1 - b_j^2\right)^{\frac{1}{k}}\right)^{\frac{1}{2}} \end{array}\right], \\ \left[\prod_{j=1}^{n} c_j^{\frac{1}{k}}, \prod_{j=1}^{n} d_j^{\frac{1}{k}}\right], \\ \left[\begin{array}{c} \left(\prod_{j=1}^{n}\left(1 - a_j^2\right)^{\frac{1}{k}} - \prod_{j=1}^{n}\left(1 - a_j^2 - e_j^2\right)^{\frac{1}{k}}\right)^{\frac{1}{2}}, \\ \left(\prod_{j=1}^{n}\left(1 - b_j^2\right)^{1/k} - \prod_{j=1}^{n}\left(1 - b_j^2 - f_j^2\right)^{1/k}\right)^{1/2} \end{array}\right] \end{array} \right\} \tag{18}$$

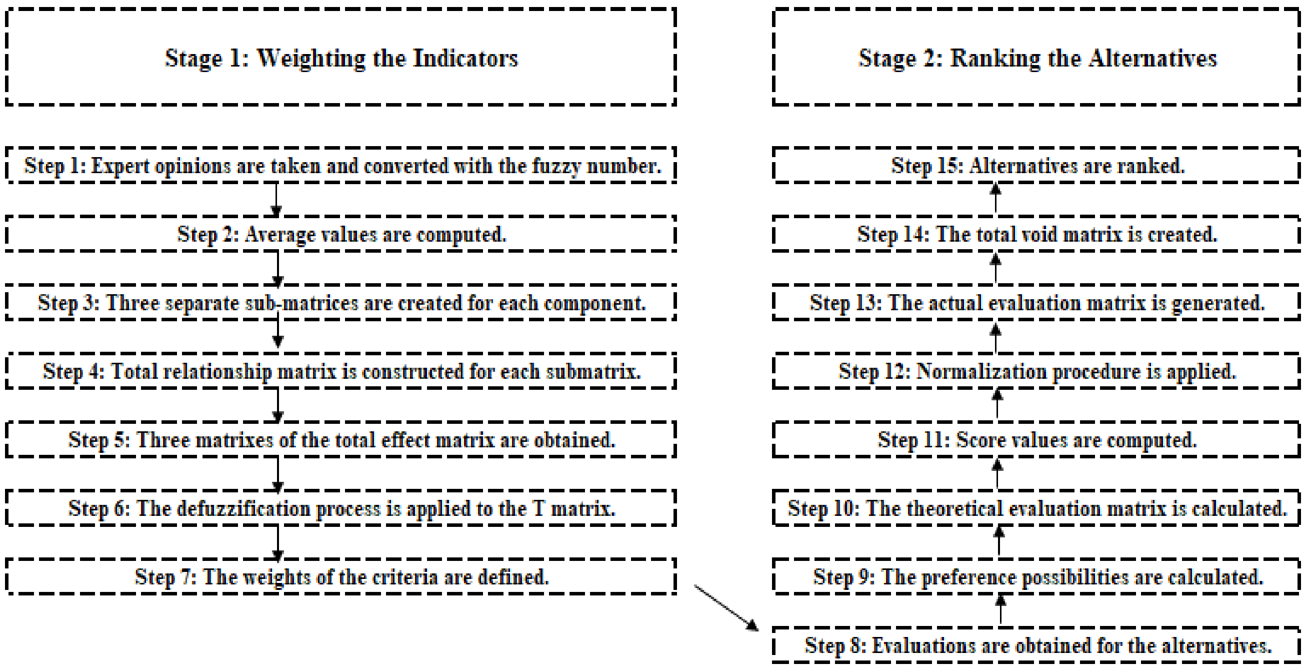


FIGURE 1. The details of the model.

TABLE 2. The linguistic evaluations of the decision makers for the criteria.

PTO 1					
	GWG	**NPW**	**WSY**	**ABN**	**CTY**
GWG		4	4	3	2
NPW	2		4	2	1
WSY	2	3		3	3
ABN	2	3	3		3
CTY	4	3	3	3	
PTO 2					
	GWG	**NPW**	**WSY**	**ABN**	**CTY**
GWG		4	3	3	3
NPW	2		3	2	2
WSY	3	3		3	4
ABN	1	3	3		4
CTY	2	2	2	3	
PTO 3					
	GWG	**NPW**	**WSY**	**ABN**	**CTY**
GWG		4	4	4	1
NPW	1		4	2	1
WSY	2	3		3	2
ABN	3	2	3		3
CTY	4	3	3	3	

TABLE 3. Decision matrix.

Z	GWG			NPW		
GWG	,00	,00	,00	,85	,15	,45
NPW	,29	,27	,21	,00	,00	,00
WSY	,46	,23	,28	,60	,20	,35
ABN	,42	,25	,24	,54	,22	,31
CTY	,77	,18	,37	,54	,22	,31
Z	**WSY**			**ABN**		
GWG	,80	,17	,41	,72	,18	,38
NPW	,80	,17	,41	,35	,25	,25
WSY	,00	,00	,00	,60	,20	,35
ABN	,60	,20	,35	,00	,00	,00
CTY	,54	,22	,31	,60	,20	,35
Z	**CTY**					
GWG	,42	,42	,42			
NPW	,21	,21	,21			
WSY	,68	,68	,68			
ABN	,72	,72	,72			
CTY	,00	,00	,00			

production investments not to harm the environment, attention should be paid to the absence of chemical substances in the most used products. These substances will create a significant amount of waste, and this will cause an increase in environmental pollution. In addition, it is very important that the material used does not cause carbon emissions. In this

TABLE 4. Normalized sub matrixes.

Xs	GWG	NPW	WSY	ABN	CTY
GWG	,00	,31	,29	,26	,15
NPW	,10	,00	,29	,13	,07
WSY	,16	,22	,00	,22	,24
ABN	,15	,19	,22	,00	,26
CTY	,28	,19	,19	,22	,00
XU	**GWG**	**NPW**	**WSY**	**ABN**	**CTY**
GWG	,00	,16	,17	,19	,26
NPW	,28	,00	,17	,26	,29
WSY	,24	,21	,00	,21	,20
ABN	,26	,22	,21	,00	,19
CTY	,18	,22	,22	,21	,00
Xd	**GWG**	**NPW**	**WSY**	**ABN**	**CTY**
GWG	,00	,30	,28	,26	,16
NPW	,14	,00	,28	,17	,12
WSY	,19	,23	,00	,23	,23
ABN	,16	,21	,23	,00	,26
CTY	,25	,21	,21	,23	,00

TABLE 5. Total relation matrix.

T	GWG			NPW		
GWG	,43	,36	,44	,54	,41	,51
NPW	,33	,51	,38	,28	,45	,33
WSY	,46	,45	,47	,46	,46	,46
ABN	,45	,46	,45	,44	,47	,45
CTY	,53	,44	,49	,47	,46	,47
T	**WSY**			**ABN**		
GWG	,53	,41	,51	,54	,41	,51
NPW	,38	,50	,40	,34	,52	,38
WSY	,38	,39	,40	,47	,45	,47
ABN	,45	,46	,45	,37	,40	,39
CTY	,47	,46	,47	,49	,45	,48
T	**CTY**					
GWG	,51	,42	,49			
NPW	,32	,52	,38			
WSY	,49	,45	,47			
ABN	,49	,45	,47			
CTY	,40	,39	,41			

context, it is necessary to pay attention to this issue in the products to be selected. In this way, it will be easier to solve the carbon emission problem. The results for other t, u and d values are given in Table 7.

TABLE 6. Weights.

	C*	C-	R*	R-	S*	S-	Weights
GWG	,04	,05	,20	,25	,23	,30	,22
NPW	,13	,08	,15	,10	,28	,18	,15
WSY	,07	,05	,16	,18	,22	,23	,19
ABN	,08	,06	,18	,25	,25	,31	,21
CTY	,08	,07	,15	,26	,23	,33	,23

TABLE 7. Comparative weighting results.

	t=2	t=1	u=0, t=golden cuts	u=0, t=2	u=0, t=1	u=0, d=0, t=1
GWG	,22	,21	,21	,21	,20	,21
NPW	,15	,17	,19	,19	,20	,20
WSY	,19	,19	,18	,18	,19	,19
ABN	,21	,21	,20	,20	,20	,19
CTY	,23	,22	,21	,22	,21	,21

Moreover, comparative weighting results are shown in Table 8. Table 3 denotes that weighting results are quite similar for all conditions. Therefore, it is understood that the proposed model provides consistent and coherent results.

TABLE 8. Comparative weighting results.

	t=2	t=1	u=0, t=golden cut	u=0, t=2	u=0, t=1	u=0, d=0, t=1
GWG	2	2	2	2	2	2
NPW	5	5	4	4	4	3
WSY	4	4	5	5	5	5
ABN	3	3	3	3	3	4
CTY	1	1	1	1	1	1

B. RANKING THE ITEMS OF THE LIFE CYCLE PROCESS

The items of the life cycle process are defined as alternative set for measuring the environmental effects of each process in the sustainable production investments. These alternatives are given as "Resources" (RRC), "Manufacturing", (MFC), "Storage/Assembly" (SLY), "Retail", (RTA), "Use" (USE), "Recycle" (RYC). Alternatives are ranked by applying SF MAIRCA for 6 different weights obtained. In the following parts, the case results for t=2 are shared.

Step 8 is related to obtaining the evaluations from the experts (Table 9) and construction of initial decision matrix (Table 10) with the help of Equation (19).

TABLE 9. The linguistic evaluations of the decision makers for the alternatives.

PTO 1					
	GWG	NPW	WSY	ABN	CTY
RRC	7	8	6	7	5
MFC	4	7	8	9	4
SLY	6	4	6	5	5
RTA	2	4	5	7	4
USE	4	5	7	6	4
RYC	6	7	8	9	6
PTO 3					
	GWG	NPW	WSY	ABN	CTY
RRC	5	5	6	8	8
MFC	5	6	8	6	6
SLY	4	3	5	4	4
RTA	3	3	5	6	5
USE	4	6	6	6	6
RYC	6	7	8	7	7
PTO 3					
	GWG	NPW	WSY	ABN	CTY
RRC	7	5	5	7	5
MFC	4	7	6	6	6
SLY	5	4	6	5	5
RTA	2	4	5	5	7
USE	4	5	7	6	6
RYC	7	7	8	7	8

In *Step 9*, the preference possibilities (P_{Ai}) are calculated by Equation (20). In *Step 10*, the theoretical evaluation matrix (Table 11) is calculated with the help of Equations (22) and (21).

In *Step 11*, score values (Table 12) are computed by Equation (22). Normalization procedure is applied for the score values in *Step 12*.

Step 13 includes the generation of the actual evaluation matrix (Table 13) by Equations (25) and (26).

In *Step 14,* the total void matrix (Table 14) matrix is calculated by Equation (27). The final values (Q) for the criteria are calculated by Equation (27) in *Step 15*. These values are also indicated in Table 14.

Recycle is determined as the most optimal alternative because it has the lowest Q value. Resources and manufacturing are other critical alternatives in this respect. The same MAIRCA process is carried out with the other weights obtained with T-SF TOPSIS-DEMATEL. Q values obtained with the other weights are given in Table 15.

Furthermore, Table 16 indicates the summary of the comparative ranking results.

TABLE 10. Direct relation matrix.

	GWG						NPW					
	a	b	c	d	e	f	a	b	c	d	e	f
RRC	,61	,70	,26	,33	,23	,30	,61	,70	,31	,39	,25	,32
MFC	,36	,41	,51	,61	,22	,35	,62	,72	,22	,27	,22	,27
SLY	,46	,53	,40	,48	,25	,34	,23	,28	,58	,68	,17	,28
RTA	,17	,22	,72	,82	,17	,22	,23	,28	,58	,68	,17	,28
USE	,25	,30	,55	,65	,15	,30	,52	,59	,37	,45	,28	,37
RYC	,59	,69	,23	,28	,23	,28	,65	,75	,20	,25	,20	,25
	WSY						ABN					
	a	b	c	d	e	f	a	b	c	d	e	f
RRC	,53	,62	,30	,37	,27	,33	,69	,79	,18	,23	,18	,23
MFC	,70	,80	,18	,23	,18	,23	,70	,83	,18	,24	,18	,24
SLY	,53	,62	,30	,37	,27	,33	,44	,49	,48	,58	,27	,38
RTA	,50	,55	,45	,55	,30	,40	,57	,66	,28	,35	,25	,31
USE	,62	,72	,22	,27	,22	,27	,55	,65	,25	,30	,25	,30
RYC	,75	,85	,15	,20	,15	,20	,74	,86	,16	,21	,15	,21
	CTY											
	a	b	c	d	e	f						
RRC	,61	,70	,31	,39	,25	,32						
MFC	,48	,57	,33	,39	,23	,30						
SLY	,44	,49	,48	,58	,27	,38						
RTA	,51	,59	,37	,45	,23	,32						
USE	,48	,57	,33	,39	,23	,30						
RYC	,66	,77	,20	,25	,20	,25						

TABLE 11. TPA.

TPA	GWG	NPW	WSY	ABN	CTY
RRC	,036	,025	,032	,035	,038
MFC	,036	,025	,032	,035	,038
SLY	,036	,025	,032	,035	,038
RTA	,036	,025	,032	,035	,038
USE	,036	,025	,032	,035	,038
RYC	,036	,025	,032	,035	,038

TABLE 12. Score Values.

	GWG	NPW	WSY	ABN	CTY
RRC	1,324	1,284	1,199	1,494	1,284
MFC	,806	1,379	1,515	1,527	1,133
SLY	1,034	,653	1,199	,903	,903
RTA	,44	,653	,993	1,264	1,117
USE	,7	1,11	1,379	1,267	1,133
RYC	1,326	1,428	1,603	1,598	1,451

Figure 2 also illustrates the details of the comparative ranking results.

The ranking results are the same for all different situations. This situation explains the reliability and accuracy of the proposed model. The most accurate strategy to be applied to minimize the damage to the environment in material investments

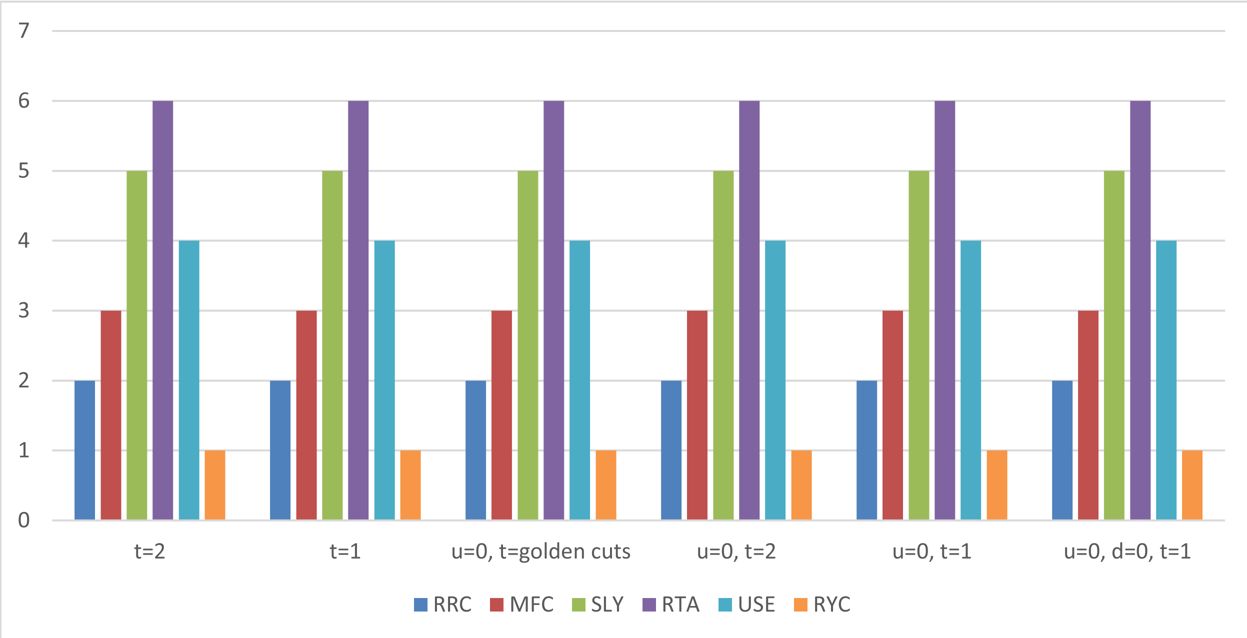


FIGURE 2. Comparative ranking results.

TABLE 13. Kr matrix.

	GWG	NPW	WSY	ABN	CTY
RRC	,036	,021	,011	,030	,026
MFC	,015	,024	,028	,032	,016
SLY	,024	,000	,011	,000	,000
RTA	,000	,000	,000	,018	,015
USE	,011	,015	,021	,018	,016
RYC	,036	,025	,032	,035	,038

TABLE 14. G matrix and Q values.

	GWG	NPW	WSY	ABN	CTY	Q
RRC	,000	,005	,022	,005	,012	,043
MFC	,021	,002	,005	,004	,022	,053
SLY	,012	,025	,022	,035	,038	,131
RTA	,036	,025	,032	,017	,023	,134
USE	,026	,010	,012	,017	,022	,086
RYC	,000	,000	,000	,000	,000	,000

TABLE 15. G matrix.

	GWG	NPW	WSY	ABN	CTY	Q
RRC	,000	,005	,022	,005	,012	,043
MFC	,021	,002	,005	,004	,022	,053
SLY	,012	,025	,022	,035	,038	,131
RTA	,036	,025	,032	,017	,023	,134
USE	,026	,010	,012	,017	,022	,086
RYC	,000	,000	,000	,000	,000	,000

TABLE 16. Comparative ranking results.

	t=2	t=1	u=0, t=golden cuts	u=0, t=2	u=0, t=1	u=0, d=0, t=1
RRC	2	2	2	2	2	2
MFC	3	3	3	3	3	3
SLY	5	5	5	5	5	5
RTA	6	6	6	6	6	6
USE	4	4	4	4	4	4
RYC	1	1	1	1	1	1

is the recycling of products. In this way, much fewer natural resources will be used during production. This will help to have a more environmentally friendly material production time.

C. RANKING E7 COUNTRIES

In the final step, E7 countries (Brazil, China, India, Indonesia, Mexico, Russia, and Turkey) are ranked for the performance of the environmental impacts of material production investments. Table 17 gives information about the linguistic evaluations of the decision makers for these countries.

TABLE 17. The linguistic evaluations of the decision makers for the countries.

PTO 1					
	GWG	NPW	WSY	ABN	CTY
Brazil	5	6	5	5	4
China	9	8	9	9	8
India	6	5	7	5	7
Indonesia	6	3	2	4	5
Mexico	4	4	5	6	5
Russia	5	7	6	8	8
Turkey	7	6	8	7	8
PTO 3					
	GWG	NPW	WSY	ABN	CTY
Brazil	5	6	5	5	4
China	9	8	9	9	8
India	6	5	7	5	7
Indonesia	6	3	2	4	5
Mexico	4	4	5	6	5
Russia	5	7	6	8	8
Turkey	7	6	8	7	8
PTO 3					
	GWG	NPW	WSY	ABN	CTY
Brazil	5	6	5	5	4
China	9	8	9	9	8
India	6	5	7	5	7
Indonesia	6	3	2	4	5
Mexico	4	4	5	6	5
Russia	5	7	6	8	8
Turkey	7	6	8	7	8

Table 18 indicates direct relation matrix.

TPA and score values are presented in Tables 19 and 20.

Tables 21 and 22 demonstrate the Kr matrix, G matrix and Q values.

Finally, comparative ranking results of E7 economies are indicated in Table 23.

The ranking results are also explained in Figure 3.

The results are similar for different conditions that demonstrate the reliability of the proposed model. It is concluded that China is the most successful country regarding the environmental impacts of material production investments. Turkey is another successful country in this context. Nonetheless, Brazil, Mexico and Indonesia have low performance with respect to this situation. The results obtained in this study are especially guiding for low-performing countries. As a result of the improvements to be made in these highlighted issues, it will be possible for these countries to make their material production processes more environmentally friendly.

TABLE 18. Direct relation matrix.

	GWG						NPW					
	a	b	c	d	e	f	a	b	c	d	e	f
Brazil	,50	,55	,45	,55	,30	,40	,55	,65	,25	,30	,25	,30
China	,85	,95	,10	,15	,05	,15	,75	,85	,15	,20	,15	,20
India	,55	,65	,25	,30	,25	,30	,50	,55	,45	,55	,30	,40
Indonesia	,55	,65	,25	,30	,25	,30	,20	,25	,65	,75	,20	,25
Mexico	,25	,30	,55	,65	,15	,30	,25	,30	,55	,65	,15	,30
Russia	,50	,55	,45	,55	,30	,40	,65	,75	,20	,25	,20	,25
Turkey	,65	,75	,20	,25	,20	,25	,55	,65	,25	,30	,25	,30
	WSY						ABN					
	a	b	c	d	e	f	a	b	c	d	e	f
Brazil	,50	,55	,45	,55	,30	,40	,50	,55	,45	,55	,30	,40
China	,85	,95	,10	,15	,05	,15	,85	,95	,10	,15	,05	,15
India	,65	,75	,20	,25	,20	,25	,50	,55	,45	,55	,30	,40
Indonesia	,15	,20	,75	,85	,15	,20	,25	,30	,55	,65	,15	,30
Mexico	,50	,55	,45	,55	,30	,40	,55	,65	,25	,30	,25	,30
Russia	,55	,65	,25	,30	,25	,30	,75	,85	,15	,20	,15	,20
Turkey	,75	,85	,15	,20	,15	,20	,65	,75	,20	,25	,20	,25
	CTY											
	a	b	c	d	e	f						
Brazil	,25	,30	,55	,65	,15	,30						
China	,75	,85	,15	,20	,15	,20						
India	,65	,75	,20	,25	,20	,25						
Indonesia	,50	,55	,45	,55	,30	,40						
Mexico	,50	,55	,45	,55	,30	,40						
Russia	,75	,85	,15	,20	,15	,20						
Turkey	,75	,85	,15	,20	,15	,20						

TABLE 19. TPA.

TPA	GWG	NPW	WSY	ABN	CTY
Brazil	,031	,022	,028	,030	,032
China	,031	,022	,028	,030	,032
India	,031	,022	,028	,030	,032
Indonesia	,031	,022	,028	,030	,032
Mexico	,031	,022	,028	,030	,032
Russia	,031	,022	,028	,030	,032
Turkey	,031	,022	,028	,030	,032

V. DISCUSSIONS

The use of chemicals in material production investments brings some conveniences. In this way, production processes can be completed much faster. However, if the necessary precautions are not taken in this process, very big problems can occur. These chemicals seriously threaten the environment. A high amount of waste occurs in raw material investments where chemicals are used a lot. If this waste is not disposed of effectively, they pollute both the air and the soil. On the other hand, some chemicals also cause pollution of water resources. Therefore, first, these chemical wastes should be destroyed. As a result of this process not being carried out

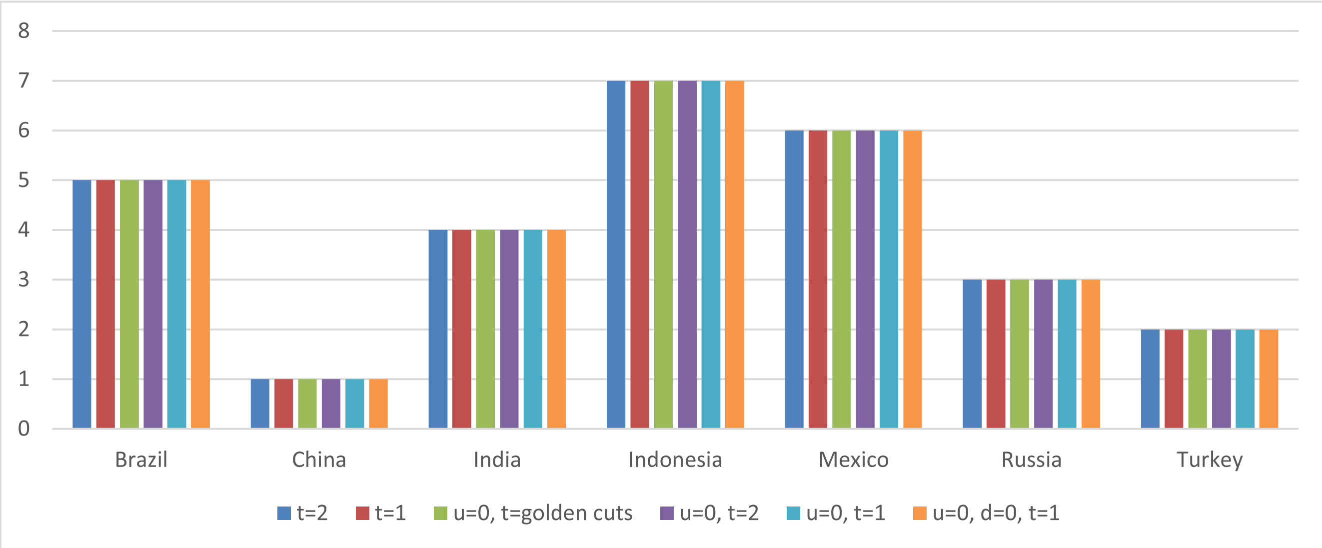


FIGURE 3. Ranking results of E7 economies.

TABLE 20. Score values.

	GWG	NPW	WSY	ABN	CTY
Brazil	,99	1,27	,99	,99	,70
China	1,79	1,60	1,79	1,79	1,60
India	1,27	,99	1,43	,99	1,43
Indonesia	1,27	,55	,38	,70	,99
Mexico	,70	,70	,99	1,27	,99
Russia	,99	1,43	1,27	1,60	1,60
Turkey	1,43	1,27	1,60	1,43	1,60

TABLE 21. Kr matrix.

	GWG	NPW	WSY	ABN	CTY
Brazil	,008	,015	,012	,008	,000
China	,031	,022	,028	,030	,032
India	,016	,009	,021	,008	,026
Indonesia	,016	,000	,000	,000	,010
Mexico	,000	,003	,012	,016	,010
Russia	,008	,018	,017	,025	,032
Turkey	,021	,015	,024	,020	,032

TABLE 22. G matrix and Q values.

	GWG	NPW	WSY	ABN	CTY	Q
Brazil	,023	,007	,016	,022	,032	,100
China	,000	,000	,000	,000	,000	,000
India	,015	,012	,007	,022	,006	,063
Indonesia	,015	,022	,028	,030	,022	,116
Mexico	,031	,018	,016	,014	,022	,102
Russia	,023	,004	,010	,005	,000	,042
Turkey	,010	,007	,004	,010	,000	,031

TABLE 23. Comparative ranking results.

	t=2	t=1	u=0, t=golden cuts	u=0, t=2	u=0, t=1	u=0, d=0, t=1
Brazil	5	5	5	5	5	5
China	1	1	1	1	1	1
India	4	4	4	4	4	4
Indonesia	7	7	7	7	7	7
Mexico	6	6	6	6	6	6
Russia	3	3	3	3	3	3
Turkey	2	2	2	2	2	2

effectively, people's lives are in danger. Therefore, it would be appropriate for states to provide incentives for investments in recycling processes. Sheldon et al. [54] underlined the significance of chemicals with respect to environmental issues. They claimed that green chemicals should be taken into consideration for the purpose of waste minimization. Zhao et al. [55] and Varshney et al. [56] also stated that effective disposals of the chemicals is a very critical issue to minimize the environmental damage of the material production investments.

Another important issue in this process is the adequacy of legal regulations. Material production investments without adequate regulations for the use of chemicals can lead to very serious harmful consequences on the environment and living things. In this context, states should make the necessary legal arrangements for both the amount of use of chemical products in raw material production and the effective management of wastes. In this way, natural resources will be less damaged in the material production process, and this will contribute to the sustainability of economic growth. Sajid et al. [57], Hassan and Saleh [58] and Siril et al. [59] highlighted that legal regulations should be created effectively so that it can be much easier to handle environmental problems created by material production investments.

VI. CONCLUSION

In this study, it is aimed to identify the environmental impacts of material production investments. The factors of Higg Materials Sustainability Index are defined as the parameters. These factors are weighted by considering T-SF TOPSIS-DEMATEL. Furthermore, the items of the life cycle process are defined as alternative set for measuring the environmental effects of each process in the sustainable production investments. For this purpose, these alternatives are ranked with interval valued SF MAIRCA. The calculations are also made for different t, u and d values with the aim of making comparative evaluations. The results are quite similar for all conditions. Therefore, it is understood that the proposed model provides consistent and coherent findings. It is concluded that chemistry is the most critical factor for environmental impact for material production investments. Moreover, recycle is determined as the most optimal alternative.

The main contribution of this study is that a priority analysis has been made so that the most significant indicators are defined for the companies to increase sustainability in material production investment process. Nonetheless, a specific country analysis has not been applied in this study. Instead of this issue, the criteria and alternative list is examined in a general view. For the future research direction, a specific assessment can be made for countries with high carbon emissions. This will help to solve the carbon emission problem more quickly.

REFERENCES

[1] N. M. Clauser, G. González, C. M. Mendieta, J. Kruyeniski, M. C. Area, and M. E. Vallejos, "Biomass waste as sustainable raw material for energy and fuels," *Sustainability*, vol. 13, no. 2, p. 794, Jan. 2021.

[2] P. Ghamisi, "The potential of machine learning for a more responsible sourcing of critical raw materials," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 14, pp. 8971–8988, 2021.

[3] V. Prado, J. Daystar, M. Wallace, S. Pires, and L. Laurin, "Evaluating alternative environmental decision support matrices for future Higg MSI scenarios," *Int. J. Life Cycle Assessment*, vol. 26, no. 7, pp. 1357–1373, Jul. 2021.

[4] M. Alberghini, S. Hong, L. M. Lozano, V. Korolovych, Y. Huang, F. Signorato, S. H. Zandavi, C. Fucetola, I. Uluturk, M. Y. Tolstorukov, G. Chen, P. Asinari, R. M. Osgood, M. Fasano, and S. V. Boriskina, "Sustainable polyethylene fabrics with engineered moisture transport for passive cooling," *Nature Sustainability*, vol. 4, no. 8, pp. 715–724, Mar. 2021.

[5] A. Zanoletti, A. Cornelio, and E. Bontempi, "A post-pandemic sustainable scenario: What actions can be pursued to increase the raw materials availability?" *Environ. Res.*, vol. 202, Nov. 2021, Art. no. 111681.

[6] A. Gonçalves and C. Silva, "Looking for sustainability scoring in apparel: A review on environmental footprint, social impacts and transparency," *Energies*, vol. 14, no. 11, p. 3032, May 2021.

[7] M. Jones, A. Gandia, S. John, and A. Bismarck, "Leather-like material biofabrication using fungi," *Nature Sustainability*, vol. 4, no. 1, pp. 9–16, Sep. 2020.

[8] L. K. Sirotina and M. N. Titova, "Planning the production of chemical fibers and threads from secondary raw materials based on optimization of indicators and development of models of material intensity of production processes," *Fibre Chem.*, vol. 53, no. 3, pp. 208–214, Sep. 2021.

[9] S. Eti, H. Dinçer, S. Yüksel, and Y. Gökalp, "Analysis of the suitability of the solar panels for hospitals: A new fuzzy decision-making model proposal with the T-spherical TOP-DEMATEL method," *J. Intell. Fuzzy Syst.*, 2023.

[10] A. K. Yazdi, P. F. Wanke, T. Hanne, F. Abdi, and A. H. Sarfaraz, "Supplier selection in the oil & gas industry: A comprehensive approach for multi-criteria decision analysis," *Socio-Econ. Planning Sci.*, vol. 79, Feb. 2022, Art. no. 101142.

[11] T. Chakraborty, "A MCDM-NBO approach for selection of installation location for wave energy power plants," in *Application of Geographical Information Systems and Soft Computation Techniques in Water and Water Based Renewable Energy Problems*. Singapore: Springer, 2018, pp. 121–140.

[12] F. K. Gündoğdu and C. Kahraman, "Spherical fuzzy sets and spherical fuzzy TOPSIS method," *J. Intell. Fuzzy Syst.*, vol. 36, no. 1, pp. 337–352, Feb. 2019.

[13] K. Ullah, T. Mahmood, and N. Jan, "Similarity measures for T-spherical fuzzy sets with applications in pattern recognition," *Symmetry*, vol. 10, no. 6, p. 193, Jun. 2018.

[14] J. F. López-Perales, J. E. Contreras, F. J. Vázquez-Rodríguez, C. Gómez-Rodríguez, L. Díaz-Tato, F. Banda-Muñoz, and E. A. Rodríguez, "Partial replacement of a traditional raw material by blast furnace slag in developing a sustainable conventional refractory castable of improved physical-mechanical properties," *J. Cleaner Prod.*, vol. 306, Jul. 2021, Art. no. 127266.

[15] H. Fischer, F. Frühwald, and A. Korjenic, "Ecological comparison of hygrothermally safe floor constructions based on renewable raw materials for multi-storey buildings," *J. Building Eng.*, vol. 57, Oct. 2022, Art. no. 104899.

[16] A. Vilén, P. Laurell, and R. Vahala, "Comparative life cycle assessment of activated carbon production from various raw materials," *J. Environ. Manage.*, vol. 324, Dec. 2022, Art. no. 116356.

[17] L. T. Peiró, N. Martin, G. V. Méndez, and C. Madrid-López, "Integration of raw materials indicators of energy technologies into energy system models," *Appl. Energy*, vol. 307, Feb. 2022, Art. no. 118150.

[18] Z. Xu, S. Chen, M. Sang, Z. Wang, X. Bo, and Q. You, "Air quality improvement through vehicle electrification in Hainan Province, China," *Chemosphere*, vol. 316, Mar. 2023, Art. no. 137814.

[19] A. Eštoková, F. M. Wolfová, and M. Ondová, "Concrete structures and their impacts on climate change and water and raw material resource depletion," *Int. J. Civil Eng.*, vol. 20, no. 6, pp. 735–747, 2022.

[20] Y. Wang, S. Pan, J. Yin, H. Feng, M. Wang, and T. Chen, "Resource potential and global warming potential of fruit and vegetable waste in China based on different treatment strategies," *Waste Manage.*, vol. 140, pp. 225–232, Mar. 2022.

[21] Y. Huang, B. Tao, R. Lal, K. Lorenz, P.-A. Jacinthe, R. K. Shrestha, X. Bai, M. P. Singh, L. E. Lindsey, and W. Ren, "A global synthesis of biochar's sustainability in climate-smart agriculture—Evidence from field and laboratory experiments," *Renew. Sustain. Energy Rev.*, vol. 172, Feb. 2023, Art. no. 113042.

[22] J.-Y. Lee, S.-E. Lee, and D.-W. Lee, "Current status and future prospects of biological routes to bio-based products using raw materials, wastes, and residues as renewable resources," *Crit. Rev. Environ. Sci. Technol.*, vol. 52, no. 14, pp. 2453–2509, Jul. 2022.

[23] A. Peys, V. Isteri, J. Yliniemi, A. S. Yorkshire, P. N. Lemougna, C. Utton, J. L. Provis, R. Snellings, and T. Hanein, "Sustainable iron-rich cements: Raw material sources and binder types," *Cement Concrete Res.*, vol. 157, Jul. 2022, Art. no. 106834.

[24] B. Pavlić, M. Aćimović, A. Sknepnek, D. Miletić, Ž. Mrkonjić, A. C. Kljakić, J. Jerković, A. Mišan, M. Pojić, A. Stupar, Z. Zeković, and N. Teslić, "Sustainable raw materials for efficient valorization and recovery of bioactive compounds," *Ind. Crops Products*, vol. 193, Mar. 2023, Art. no. 116167.

[25] F. Chien, K. Y. Chau, M. Sadiq, and C.-C. Hsu, ''The impact of economic and non-economic determinants on the natural resources commodity prices volatility in China,'' *Resour. Policy*, vol. 78, Sep. 2022, Art. no. 102863.

[26] D. Charlier and F. Fizaine, ''Decoupling gross domestic product and consumption of raw materials: A macro-panel analysis,'' *Sustain. Prod. Consumption*, vol. 36, pp. 194–206, Mar. 2023.

[27] H. Liu, M. Alharthi, A. Atil, M. W. Zafar, and I. Khan, ''A non-linear analysis of the impacts of natural resources and education on environmental quality: Green energy and its role in the future,'' *Resour. Policy*, vol. 79, Dec. 2022, Art. no. 102940.

[28] V. Steinbach, ''F.-W. Wellmer—A life as a raw materials expert at the crossroads of research, industry and politics,'' *Mineral Econ.*, vol. 35, pp. 349–350, Jun. 2022.

[29] M. Bianchi and M. Cordella, ''Does circular economy mitigate the extraction of natural resources? Empirical evidence based on analysis of 28 European economies over the past decade,'' *Ecolog. Econ.*, vol. 203, Jan. 2023, Art. no. 107607.

[30] Z. Zhang, H. Fu, Z. Li, J. Huang, Z. Xu, Y. Lai, X. Qian, and S. Zhang, ''Hydrogel materials for sustainable water resources harvesting & treatment: Synthesis, mechanism and applications,'' *Chem. Eng. J.*, vol. 439, Jul. 2022, Art. no. 135756.

[31] P. Ghosal, B. Gupta, R. S. Ambekar, M. M. Rahman, P. M. Ajayan, N. Aich, A. K. Gupta, and C. S. Tiwary, ''3D printed materials in water treatment applications,'' *Adv. Sustain. Syst.*, vol. 6, no. 3, Mar. 2022, Art. no. 2100282.

[32] J. J. P. Fernández and E. H. S. López, ''Clay, fire, air, and mostly water: Understanding the importance of water resources in pottery workshops in ancient iberia by integrating ethnoarchaeological, experimental, and archaeological research,'' *Ethnoarchaeology*, vol. 13, pp. 33–58, Jul. 2022.

[33] A. Umami, H. Sukmana, E. A. Wikurendra, and E. Paulik, ''A review on water management issues: Potential and challenges in Indonesia,'' *Sustain. Water Resour. Manage.*, vol. 8, no. 3, pp. 1–15, Jun. 2022.

[34] A. Tarpanelli, A. Paris, A. W. Sichangi, F. O'Loughlin, and F. Papa, ''Water resources in Africa: The role of Earth observation data and hydrodynamic modeling to derive river discharge,'' *Surv. Geophys.*, vol. 44, no. 1, pp. 97–122, Feb. 2023.

[35] G. L. Kyriakopoulos, M. G. Zamparas, and V. C. Kapsalis, ''Investigating the human impacts and the environmental consequences of microplastics disposal into water resources,'' *Sustainability*, vol. 14, no. 2, p. 828, Jan. 2022.

[36] J. Sang, B. Hou, H. Wang, and X. Ding, ''Prediction of water resources change trend in the three Gorges reservoir area under future climate change,'' *J. Hydrol.*, vol. 617, Feb. 2023, Art. no. 128881.

[37] Z. Karimidastenaei, T. Avellán, M. Sadegh, B. Kløve, and A. T. Haghighi, ''Unconventional water resources: Global opportunities and challenges,'' *Sci. Total Environ.*, vol. 827, Jun. 2022, Art. no. 154429.

[38] B. C. Almroth, S. E. Cornell, M. L. Diamond, C. A. de Wit, P. Fantke, and Z. Wang, ''Understanding and addressing the planetary crisis of chemicals and plastics,'' *One Earth*, vol. 5, no. 10, pp. 1070–1074, Oct. 2022.

[39] L. Pola, S. Collado, P. Oulego, and M. Díaz, ''Kraft black liquor as a renewable source of value-added chemicals,'' *Chem. Eng. J.*, vol. 448, Nov. 2022, Art. no. 137728.

[40] V. Kumar, V. Bansal, A. Madhavan, M. Kumar, R. Sindhu, M. K. Awasthi, P. Binod, and S. Saran, ''Active pharmaceutical ingredient (API) chemicals: A critical review of current biotechnological approaches,'' *Bioengineered*, vol. 13, no. 2, pp. 4309–4327, Feb. 2022.

[41] M. Martins, P. F. Ávila, M. F. da Silva, A. H. F. de Melo, A. M. M. Lopes, and G. R., ''Lignocellulose bioconversion through chemical methods, platform chemicals, and new chemicals,'' in *Lignocellulose Bioconversion Through White Biotechnology*. New York, NY, USA: Wiley, 2022, pp. 221–247.

[42] J. A. Tickner, K. Geiser, and S. Baima, ''Transitioning the chemical industry: Elements of a roadmap toward sustainable chemicals and materials,'' *Environ., Sci. Policy Sustain. Develop.*, vol. 64, no. 2, pp. 22–36, Mar. 2022.

[43] P. G. A. Gonzalez, J. C. de Jesus Gariboti, J. F. L. Silva, E. S. Lopes, E. R. Abaide, M. S. Lopes, V. O. C. Concha, R. F. Felisbino, E. L. Gomes, and L. P. Tovar, ''Soybean straw as a feedstock for value-added chemicals and materials: Recent trends and emerging prospects,'' *BioEnergy Res.*, pp. 1–24, Sep. 2022.

[44] S. Yüksel and H. Dinçer, ''Identifying the strategic priorities of nuclear energy investments using hesitant 2-tuple interval-valued Pythagorean fuzzy DEMATEL,'' *Prog. Nucl. Energy*, vol. 145, Mar. 2022, Art. no. 104103.

[45] M. A. Bhuiyan, H. Dinçer, S. Yüksel, A. Mikhaylov, M. S. S. Danish, G. Pinter, D. D. Uyeh, and D. Stepanova, ''Economic indicators and bioenergy supply in developed economies: QROF-DEMATEL and random forest models,'' *Energy Rep.*, vol. 8, pp. 561–570, Nov. 2022.

[46] M.-Q. Wu, T.-Y. Chen, and J.-P. Fan, ''Divergence measure of T-spherical fuzzy sets and its applications in pattern recognition,'' *IEEE Access*, vol. 8, pp. 10208–10221, 2020.

[47] F. Özdemirci, S. Yüksel, H. Dinçer, and S. Eti, ''An assessment of alternative social banking systems using T-spherical fuzzy TOP-DEMATEL approach,'' *Decis. Analytics J.*, vol. 6, Mar. 2023, Art. no. 100184.

[48] M. Alimohammadlou and Z. Khoshsepehr, ''The role of society 5.0 in achieving sustainable development: A spherical fuzzy set approach,'' *Environ. Sci. Pollut. Res.*, pp. 1–25, Feb. 2023.

[49] K. Debnath and S. K. Roy, ''Power partitioned neutral aggregation operators for T-spherical fuzzy sets: An application to H2 refuelling site selection,'' *Expert Syst. Appl.*, vol. 216, Apr. 2023, Art. no. 119470.

[50] S. Boral, I. Howard, S. K. Chaturvedi, K. McKee, and V. N. A. Naikan, ''An integrated approach for fuzzy failure modes and effects analysis using fuzzy AHP and fuzzy MAIRCA,'' *Eng. Failure Anal.*, vol. 108, Jan. 2020, Art. no. 104195.

[51] K. Chatterjee, D. Pamucar, and E. K. Zavadskas, ''Evaluating the performance of suppliers based on using the R'AMATEL-MAIRCA method for green supply chain implementation in electronics industry,'' *J. Cleaner Prod.*, vol. 184, pp. 101–129, May 2018.

[52] A. Fetanat and M. Tayebi, ''Industrial filtration technologies selection for contamination control in natural gas processing plants: A sustainability and maintainability-based decision support system under q-rung orthopair fuzzy set,'' *Process Saf. Environ. Protection*, vol. 170, pp. 310–327, Feb. 2023.

[53] J. Yu, Q. Zeng, Y. Yu, S. Wu, H. Ding, W. Ma, H. Gao, and J. Yang, ''Failure mode and effects analysis based on rough cloud model and MULTIMOORA method: Application to single-point mooring system,'' *Appl. Soft Comput.*, vol. 132, Jan. 2023, Art. no. 109841.

[54] R. A. Sheldon, M. L. Bode, and S. G. Akakios, ''Metrics of green chemistry: Waste minimization,'' *Current Opinion Green Sustain. Chem.*, vol. 33, Feb. 2022, Art. no. 100569.

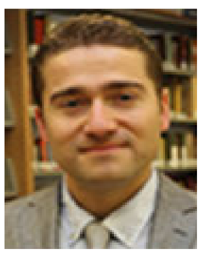
[55] X. Y. Zhao, J. Y. Yang, N. Ning, and Z. S. Yang, ''Chemical stabilization of heavy metals in municipal solid waste incineration fly ash: A review,'' *Environ. Sci. Pollut. Res.*, vol. 29, pp. 40384–40402, Mar. 2022.

[56] R. Varshney, P. Singh, and D. Yadav, ''Hazardous wastes treatment, storage, and disposal facilities,'' in *Hazardous Waste Management*. Amsterdam, The Netherlands: Elsevier, 2022, pp. 33–64.

[57] M. Sajid, A. Raheem, N. Ullah, M. Asim, M. S. Ur Rehman, and N. Ali, ''Gasification of municipal solid waste: Progress, challenges, and prospects,'' *Renew. Sustain. Energy Rev.*, vol. 168, Oct. 2022, Art. no. 112815.

[58] A. I. Hassan and H. M. Saleh, ''Toxicity and hazardous waste regulations,'' in *Hazardous Waste Management*. Amsterdam, The Netherlands: Elsevier, 2022, pp. 165–182.

[59] A. J. Siril, S. N. A. Bakar, and M. O. Fatehah, ''Hazardous waste management, challenges, and risks in handling laboratory waste in universities,'' in *Handbook of Solid Waste Management*. Singapore: Springer, 2022, pp. 1655–1714.



HASAN DİNÇER received the B.A.S. degree in financial markets and investment management from Marmara University, and the Ph.D. degree in finance and banking. His Ph.D. dissertation was titled, ''The Effect of Changes on the Competitive Strategies of New Service Development in the Banking Sector.'' He is currently a Professor in finance with the Faculty of Economics and Administrative Sciences, Istanbul Medipol University, Istanbul, Turkey. He has work experience in the finance industry as a portfolio specialist and his major academic studies focus on financial instruments, performance evaluation, and economics. He is an Executive Editor of the *International Journal of Finance and Banking Studies* (IJFBS) and the Founder Member of the Society for the Study of Business and Finance (SSBF). He has about 200 scientific articles and some of them are indexed in SSCI, SCI-expended, and Scopus. In addition to them, he is also an editor of many different books published by Springer and IGI Global.

SERKAN ETİ received the B.S. degree in mathematics from Yıldız Technical University, and the master's and Ph.D. degrees from Marmara University, in 2016. His master's dissertation was titled "A Research on Comparison of Models Explaining the Profitability Base on Financial Data." He is currently an Assistant Professor with İstanbul Medipol University. His research interests include data mining, fuzzy logic, and multi-criteria decision-making methods.

TAMER AKSOY received the B.A. degree in economics from the Faculty of Political Sciences, Ankara University, the M.A. degree in economics from Hacettepe University, and the Ph.D. degree in international banking from Gazi University. He is currently a Professor in accounting and finance with the School of Business, Ibn Haldun University. He has also a long and extensive work experience spaning over 33 years. He was with Citicorp Investment Bank, Zürich, and Switzerland, for a short time. He was an Internal Auditor, an Inspector (for ten years), and the Chief Audit Executive (CAE) with the Group's Internal Audit Function (for 23 years) for OYAK. He was with OYAK Maritime and Port Management Inc. of the Group as an Advisor to the CEO. Besides, he also acted as a member of the board of directors of various leading commercial companies in different sectors, such as Adana Cement, Bolu Cement, Goodyear Tyres-Turkey, Omsan Logistics, Oysa Cement, and Oyak Bank. Furthermore, including the Global Institute of Internal Auditors (IIA), USA, he undertook many duties on a voluntary basis for local/international professional foundations as a committee member, the head of the committee, and a member of BODs/advisory boards. Moreover, he has also international professional licenses of CPA, CFE, Independent Auditor (BD), and CRMA. His research interests include strategic auditing, internal control, financial accounting, financial management, corporate risk management, and international banking.

SERHAT YÜKSEL received the B.S. degree in business administration (in English) from Yeditepe University, in 2006, with a full scholarship, the master's degree in economics from Boğaziçi University, in 2008, and the Ph.D. degree in banking from Marmara University, in 2015. He is currently an Associate Professor in finance with İstanbul Medipol University. Before this position, he was a Senior Internal Auditor for seven years with Finansbank, Istanbul, Turkey, and an Assistant Professor with Konya Food and Agriculture University, for one year. His research interests include energy economics, banking, finance, and financial crisis. He has more than 200 scientific articles and some of them are indexed in SSCI, SCI, Scopus, and Econlit. Also, he is the editor of some books that will be published by Springer and IGI Global.

ÜMİT HACIOĞLU received the Ph.D. degree in finance and banking from Kadir Has University, in 2005. He is currently a Professor in applied business and finance with Ibn Haldun University, Istanbul, Turkey. His research interests include applied business strategies, blockchain economics, digital business strategies, and financial decision making. He has editorial roles in international journals. He is also serving as the Managing Editor for the *International Journal of Research in Business and Social Science* and *International Journal of Business Ecosystem and Strategy*. He is a Founding Member of the Society for the Study of Business and Finance (SSBF) and the Managing Director of the Bussecon International Academy, Istanbul, Turkey.

ALEXEY MIKHAYLOV received the Ph.D. degree.

He is currently the Head of the Laboratory and an Associate Professor with the Financial markets and Financial Engineering Department, Financial University, under the Government of the Russian Federation, Moscow. He is the author of many scientific publications and conference papers indexed in SCOPUS and Web of Science and the author of eight scientific monographs. He specializes in energy, economics, econometrics and finance, business, management and accounting, environmental science, materials science, mathematics, computer science, psychology, social sciences, and neuroscience. He is a Board Member of the Society of Open Innovation: Technology, Market, and Complexity (SOI), ACI Russia—Financial Markets Association, the council on professional qualifications at the financial market, and the Russian Association of Crypto Industry and Blockchain.

S. M. MUYEEN (Senior Member, IEEE) received the B.Sc.Eng. degree in electrical and electronic engineering from the Rajshahi University of Engineering and Technology (RUET, formerly known as the Rajshahi Institute of Technology), Bangladesh, in 2000, and the M.Eng. and Ph.D. degrees in electrical and electronic engineering from the Kitami Institute of Technology, Japan, in 2005 and 2008, respectively. Currently, he is a Full Professor with Electrical Engineering Department, Qatar University. He has been a keynote speaker and an invited speaker at many international conferences, workshops, and universities. He has published more than 250 articles in different journals and international conferences. He has published seven books as the author or an editor. His research interests include power system stability and control, electrical machine, FACTS, energy storage systems (ESSs), renewable energy, and HVDC systems. He is a fellow of Engineers Australia. He is serving as an Editor/Associate Editor for many prestigious journals from IEEE, IET, and other publishers, including IEEE Transactions on Energy Conversion, IEEE Power Engineering Letters, *IET Renewable Power Generation*, and *IET Generation, Transmission and Distribution*.