This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

# Evaluation of Multidimensional Carbon Neutrality Policies in Transportation Using a Novel Quantum Picture Fuzzy Rough Modelling

**GANG KOU[1], DRAGAN PAMUCAR[2,3,4*], SERHAT YÜKSEL[5,6,7], HASAN DİNÇER[5,7,*], MUHAMMET DEVECİ[8,9,10], MUHAMMAD UMAR[6]**

1 School of Business Administration, Faculty of Business Administration, Southwestern University of Finance and Economics, Chengdu,611130, China; email: kougang@swufe.edu.cn
2 Faculty of Organizational Sciences, University of Belgrade, Belgrade, Serbia, email: dpamucar@gmail.com
3 College of Engineering, Yuan Ze University, Taoyuan City 320315, Taiwan
4 Department of Computer Science and Mathematics, Lebanese American University, Byblos 1102 2801, Lebanon
5 School of Business, Istanbul Medipol University, Istanbul, Turkey, email: hdincer@medipol.edu.tr; serhatyuksel@medipol.edu.tr
6 Adnan Kassar School of Business, Lebanese American University, Beirut, Lebanon; muhammad.umar@lau.edu.lb
7 Clinic of Economics, Azerbaijan State University of Economics (UNEC), Istiqlaliyyat Str. 6, Baku, AZ1141, Azerbaijan
8 Department of Industrial Engineering, Turkish Naval Academy, National Defence University, 34942 Tuzla, Istanbul, Turkey; email: muhammetdeveci@gmail.com
Royal School of Mines, Imperial College London, London SW7 2AZ, UK
10 Department of Electrical and Computer Engineering, Lebanese American University, Byblos, Lebanon

*Corresponding author: Hasan Dinçer (e-mail: dpamucar@gmail.com; hdincer@medipol.edu.tr)

**ABSTRACT** Carbon neutrality policies are of great importance for the transportation sector. Thus, some issues need to be taken into consideration to increase the effectiveness of carbon neutrality policies in this sector. However, the biggest disadvantage of these improvements is that they increase costs. Instead of improving a large number of factors, it is more financially feasible to take action on the ones that are more important. Nevertheless, there are a limited number of studies in which priority analysis is made for the factors affecting this process. Therefore, the main missing part in the literature is that a new study should be made in which the importance weights of these variables are determined. The purpose of this study is to evaluate carbon neutrality policies in transportation industry with a novel decision-making model. First, selected indicators are evaluated by quantum picture fuzzy row sets-based multi-step wise weight assessment ratio analysis (M-SWARA) technique. Secondly, the alternatives for the carbon neutrality policies in this industry are ranked. For this purpose, multi-objective optimization on the basis of ratio analysis (MOORA) methodology is considered with quantum picture fuzzy row sets. The main motivation of making this study is the need for a novel and comprehensive decision-making model. The main reason behind this situation is that most of the existing models could not consider the causal directions among the indicators. Due to this situation, this proposed model is created by using causality relationships between the indicators of carbon neutrality policies in transportation industry. The main contribution of this study is that a new model is proposed by integrating quantum theory and picture fuzzy rough sets. This situation has a positive contribution to make sensitive evaluations. Additionally, a novel approach (M-SWARA) is proposed to weight the criteria so that causality relationship among the determinants can be considered in this process. The findings demonstrate that infrastructure development is the most important factor of effective carbon neutrality policies for transportation industry. Cost is another critical indicator in this respect. On the other hand, according to the ranking results, it is determined that reducing traditional fuels with zero-carbon alternatives is the most essential alternative for the carbon neutrality policies in transportation. It would be appropriate for transportation companies to attach importance to the use of electric vehicles. In this context, government incentives for the use of electric vehicles need to be offered. For example, a tax reduction may increase the use of electric vehicles as it will provide a significant cost advantage.

**INDEX TERMS** Carbon Neutrality; Clean Energy; Transportation Sector; Picture Fuzzy Sets; Rough Sets; M-SWARA



This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

## I. INTRODUCTION

Carbon neutrality policies are practices that aim to reduce the amount of carbon emissions of a country or a business. The problem of climate change has become quite dangerous, especially in recent years. This can lead to an increase in natural disasters and food shortages [1]. Therefore, these policies are of great importance both in minimizing these problems and in ensuring the sustainability of economic development. Moreover, to implement these policies, the use of renewable energy must be increased. This contributes significantly to the development of clean energy technologies. Carbon neutrality policies are vital for positively improving the image of both businesses and countries internationally. The ability of these institutions to make environmentally friendly policies enables cooperation with other countries and companies [2]. This, in turn, contributes significantly to economic development.

Carbon neutrality policies are of great importance for the transportation sector. One of the most important reasons for the carbon emission problem is the energy need in the transportation sector to be supplied from fossil fuels. As a result of the effective and correct implementation of carbon neutrality policies, it is possible to minimize the greenhouse gas emission problem caused by the transportation sector [3]. There are some actions that can be applied in this context. For example, the use of electric vehicles in the transportation sector contributes significantly to reducing air pollution. In addition to these, hydrogen energy can also be taken into consideration in meeting the energy need. This also helps to minimize carbon emissions. Furthermore, ensuring energy efficiency in the applications made allows less energy to be used [4]. Therefore, it is possible to consume fewer natural resources.

Some issues need to be taken into consideration to increase the effectiveness of carbon neutrality policies in the transportation sector. Financial considerations are of great importance in ensuring the effectiveness of carbon neutrality policies in this sector. The provision of adequate financial incentives helps to successfully implement these policies [6]. Ensuring customer satisfaction is also important for the correct implementation of these policies. If customer satisfaction is not ensured, this situation will become very difficult. To increase the effectiveness of carbon neutrality policies in the transportation sector, organizational effectiveness must be ensured. For these policies to be implemented successfully, the departments in the enterprises should work in harmony with each other [7]. To increase the effectiveness of carbon neutrality policies in the transportation sector, technological innovations should also be provided.

These issues need to be improved to correctly implement carbon neutral policies in the transportation sector. However, the biggest disadvantage of these improvements is that they increase costs. Therefore, the increase in costs as a result of numerous improvements leads to a decrease in profitability [8]. Instead of improving a large number of factors, it is more financially feasible to take action on the ones that are more important. Therefore, a priority analysis for these factors needs to be carried out. In the literature, the importance of carbon neutral policies has often been emphasized [9]. However, there are a limited number of studies in which priority analysis is made for the factors affecting this process. Therefore, it is thought that the main missing part in the literature is that a new study should be made in which the importance weights of these variables are determined.

Accordingly, this study aims to evaluate carbon neutrality policies in transportation industry. In this context, the main research question is to understand which indicators are more critical to define appropriate carbon neutrality policies. For this purpose, a new fuzzy decision-making model has been constructed. At the first stage, selected indicators are examined with quantum picture fuzzy row sets-based M-SWARA technique. Moreover, the alternatives for the carbon neutrality policies in this industry are ranked. In this scope, MOORA methodology is considered with quantum picture fuzzy row sets. The main motivation to make this study is that there is a strong need for a novel and comprehensive decision-making model. The main reason is that currently existing decision-making models are criticized due to many different reasons. For instance, AHP, ANP and SWARA techniques cannot consider causal directions among the criteria. Li et al. [10] and Jin [11] focused on the priority evaluations of carbon neutrality policies in China. In this process, AHP methodology was taken into consideration to find the weights of the selected criteria. However, impact relation map of these factors cannot be created. Similarly, Muryani et al. [12] tried to identify prior strategies to minimize carbon emission in Indonesia. In this context, the most significant determinants of this problem are identified with the help of ANP approach. Nonetheless, the causal directions of these items cannot be defined. On the other side, Koska and Erdem [13] and Soni et al. [14] considered SWARA technique to weight the factors with respect to the waste treatment technology selection. Nevertheless, the most influenced and influencing criteria cannot be determined. However, for some subjects, causality analysis should be used to reach more appropriate results. The indicators of carbon neutrality policies in transportation industry can have an influence on each other. For instance, providing financial effectiveness of these policies can have a powerful contribution to improve the research and development activities. In this framework, M-SWARA technique is newly generated in this proposed model. In this process, by making some improvements to the classical SWARA, the causal directions among these criteria can be shown.

The main contributions of this study are given below.

(i) Integration of quantum theory and picture fuzzy rough sets has an increasing impact on the quality of the proposed model. Because quantum theory considers different probabilities, sensitive evaluations can be conducted. This issue provides opportunities to minimize uncertainties in

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

decision-making models. Minimizing uncertainty can increase efficiency in decision-making processes. As the degree of uncertainty decreases, risk management can be carried out more effectively. Minimizing uncertainty often requires collecting more information. Therefore, in this model, it is aimed to reduce uncertainty by integrating picture fuzzy numbers with quantum theory. On the other hand, picture fuzzy rough sets are created by combination of the rough set theory and picture fuzzy sets. Uncertain information can be managed more effectively with the help of these sets. Identification of the most significant alternatives for the carbon neutrality policies in transportation is a very complex process. Due to high uncertainties in this process, more sensitive evaluations should be conducted to reach more appropriate findings. Hence, by integrating the quantum theory and picture fuzzy rough sets in this proposed model, it is aimed to minimize uncertainties.

(ii) A novel approach (M-SWARA) is proposed to weight the criteria so that causality relationship among the determinants can be considered in this process. Priority strategies can be presented for the improvements of the carbon neutrality policies in transportation industry. With the help of these results, companies can implement appropriate policies without having extra costs. Hence, the causal directions between the indicators should be considered in the analysis process. Most of the previous studies mainly focused on the importance of the main indicators of the carbon emission problem, such as cost effectiveness [15,16], customer satisfaction [17,18] and technological development [19,20]. However, these studies did not make a priority evaluation to understand the most critical factors. Hence, the main superiority of this study is that prior strategies can be presented to minimize carbon emission problem.

(iii) Owing to the MOORA method, both positive and negative criteria can be taken into consideration together. There are different criteria that affect the effectiveness of carbon neutral policies in the transportation sector. Some of these criteria are negative and some are positive factors. Therefore, considering only alternatives that have a positive effect may negatively affect the effectiveness of analysis processes. Hence, taking the MOORA technique into consideration in this process allows more accurate analysis to be performed. However, some previous studies could only consider the positive items due to the selected methodology. For instance, Sengupta et al. [21] and Muninathan et al. [22] focused on the main indicators of the carbon emission by the help of TOPSIS technique. Similarly, Paul et al. [23] and Tian et al. [24] used VIKOR approach to make evaluations regarding the carbon neutrality. In these studies, only the positive criteria were taken into consideration.

The next section includes literature review. Proposed methodology is explained in the third part. Analysis results are shown in the following section. Discussion and conclusion are presented in the final parts.

## II. LITERATURE REVIEW

This section consists of three different subsections. Firstly, different factors impacting the effectiveness of carbon neutrality programs are evaluated. Next, factor priority analysis techniques are explained. Finally, the main literature review results are discussed.

### *A. Literature on Different Factors Impacting the Effectiveness of Carbon Neutrality Programs*

Financial issues are of high importance in increasing the effectiveness of carbon neutrality policies in the transportation sector. Lv et al. [25] defined that to achieve carbon neutrality targets in the transportation sector, it is necessary to use up-to-date technology. This situation requires high amounts of investments. Dhir et al. [26] identified that for these investments to be made on time, financial resources must be easily accessible. The most important reason why the transportation sector increases the carbon emission problem is the preference of fossil fuels for energy needs. Therefore, clean energy sources should be preferred instead of fossil fuels in this process. To achieve this goal, it is necessary to invest in high-volume projects [27]. Also, Zhou [28] mentioned that tax reductions and affordable loans provide financial convenience to investors. For carbon neutral policies to be implemented correctly in the transportation sector, environmentally friendly transportation technologies need to be developed [29]. According to Jenn [30], to achieve this, it is important to obtain high amount of funds for research and development studies.

Ensuring customer satisfaction also plays a critical role in the successful implementation of these policies. Cai et al. [31] stated that to increase environmentally friendly solutions for the transportation sector, customers' awareness of these issues must also increase. According to Mittal and Shah [32], to properly meet the expectations of these increasingly conscious customer groups, environmentally friendly practices must be offered. Otherwise, businesses will experience significant customer loss. In other words, environmental sustainability practices in the transportation sector need to be taken into consideration to ensure customer loyalty [33]. To be successful in this process, customers' expectations must be understood correctly. Zahoor et al. [34] identified that it is necessary to provide customer feedback on applications. This is also very necessary to attract the attention of new customers. Lin et al. [35] also defined that customer feedback is vital for transportation companies to properly design their applications. By taking these views into account, businesses can determine the most appropriate and correct policies for environmental issues.

It is extremely important to ensure organizational effectiveness to increase the effectiveness of carbon neutrality policies in the transportation sector. Shang and Lv [36] concluded that to implement these policies correctly, first, the environmental targets of the enterprises must be determined correctly. Yang and Lo [37] underlined that it is

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

essential for businesses to make correct strategies and plans. In this context, businesses need departments that work in harmony with each other to develop a correct action plan. On the other hand, Xiang et al. [38] demonstrated that businesses need to ensure resource efficiency to implement carbon neutrality policies correctly. In this context, both financial and personnel resources must be used correctly. This situation seriously supports the implementation of correct applications. Moreover, Xu et al. [39] underlined that to increase the performance of carbon neutrality policies, businesses should monitor this process. The findings obtained as a result of these monitoring can help detect possible problems early. Pan et al. [40] highlighted that it is possible to increase the performance by taking the necessary actions in a timely manner.

It is essential to increase technological innovations in increasing the effectiveness of carbon neutrality policies in the transportation sector. Du et al. [41] determined technological innovations enable the correct implementation of practices that reduce carbon emissions. In this context, businesses need to have up-to-date technology to develop applications such as electric vehicles. According to Sun and Xia [42], to increase the effectiveness of this process, it is important for businesses to increase investments in the development of technological infrastructure. On the other hand, Rinawati et al. [43] underlined that the use of advanced technology also contributes to energy efficiency. Thus, it is possible to reduce carbon emissions by consuming less energy. In addition to these issues, Proskurina and Mendoza-Martinez [44] identified that thanks to technological innovations, it is possible to follow the processes of businesses live. Ding and Liu [45] underlined that owing to this tracking system, the problems that occur in the process can be resolved quickly. This supports the more successful implementation of carbon neutrality policies.

Different alternatives for the carbon neutrality policies were also discussed in the literature in a detailed way. Some of the scholars underlined the significance of presenting the low-emission targets. Low carbon emission targets enable businesses to effectively contribute to the fight against climate change [46]. Azam et al. [47] and Ahmed et al. [48] denoted that meeting these goals also helps businesses fulfil their environmental responsibilities. Moreover, using less fossil fuel in businesses is another prominent alternative to minimize carbon emissions [49]. Bartowitz et al. [50] and Ibrahim [51] identified that using fewer fossil fuels plays an important role in combating climate change by reducing the carbon footprint. Similarly, turning to renewable energy sources instead of fossil fuels supports more sustainable energy production. Furthermore, ensuring energy efficiency in businesses is another alternative that can be taken into consideration in this process [52]. Hong et al. [53] also mentioned that when energy efficiency is achieved in a business, less energy can be consumed to meet the same energy need. Issa et al. [54] defined that this situation allows natural resources to be consumed less. On the other hand, ensuring energy efficiency also reduces air pollution caused by energy production. This condition makes it possible to combat the carbon emission problem more effectively.

### *B. Literature on Factor Priority Analysis Techniques*

Multi-criteria decision-making models were considered by many different scholars in the literature with respect to the energy economics subject. In this process, factor priority evaluations are performed for the improvements of the clean energy projects, carbon emission reduction policies and effective waste management. In some of these studies, models were proposed by using Pythagorean fuzzy sets. For example, Ding et al. [55] focused on sustainable energy pricing with the help of Pythagorean fuzzy DEMATEL. Moreover, Kamali Saraji et al. [56] and Al-Barakati et al. [57] integrated SWARA, TOPSIS and WASPAS approaches with these sets for the purpose of evaluating clean energy projects. Similarly, Yüksel and Dinçer [58] tried to identify strategic priorities of nuclear energy investments using Pythagorean fuzzy DEMATEL. On the other side, some other scholars integrated different decision-making techniques with spherical fuzzy sets to make factor priority analysis regarding renewable energy improvements [59-61]. In addition to them, some other studies considered trapezoidal fuzzy sets in the models to minimize uncertainties in the analysis process. Within this framework, Priyan et al. [62], Wu et al. [63] and Sharma et al. [64] used these fuzzy sets to identify key determinants of energy efficiency and energy storage effectiveness.

### *C. Literature Review Results*

The main results of the literature review are indicated below. Carbon neutrality policies play a critical role for transportation industry. Due to this situation, this subject was evaluated in many different studies. The scholars mainly examined how to improve this situation. Within this framework, the indicators were highlighted for this condition. However, the biggest disadvantage of these improvements is that they increase costs. Because of this issue, trying to make lots of improvements at the same time is not financially optimal. For providing effectiveness in this process, there is a strong need for a priority analysis. With the help of this situation, it can be possible for the companies to implement prior strategies firstly. Nonetheless, there are limited studies in the literature with respect to this issue. This situation can be accepted as the main missing part in the literature regarding this subject. To fill this missing part, a new model is generated in this study to find more critical determinants of carbon neutrality policies in transportation industry.

## III. METHODOLOGY

The techniques considered in the proposed model are explained in this section. The equations are presented in the appendix part.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

### *A. Modelling Uncertainty with Quantum picture fuzzy rough sets with golden cuts*

Quantum theory is mainly used in the science of physics. While considering different probabilities, this theory can make sensitive assessments. Owing to this benefit, it is integrated with fuzzy decision-making logic with the purpose of handling uncertainties in a more effective manner. The details are identified in Equations (1)-(3) where $\theta$ refers to the phase angle, u gives information about the event and $\varphi^2$ indicates amplitude [65].

Picture fuzzy sets are generated as an extension of the classical sets. Positive, netural, negative, refusal membership degrees are considered by these numbers [66]. While using them, it is mainly aimed to manage vagueness in the evaluation process more successfully. Equation (4) demonstrates the classical fuzzy sets and intuitionistic fuzzy sets are given in Equation (5). Within this context, $\mu_A$ and $v_A$ define membership and non-membership functions. By considering this information, picture fuzzy sets are shown in Equation (6) in which $n_A$ and $h_A$ indicate neutral and refusal degrees [67]. General operations are explained in Equations (7)-(11). Rough numbers are also created to minimize subjective and uncertain evaluations in the analysis process. Lower ($\underline{Apr}(C_i)$), upper ($\overline{Apr}(C_i)$) approximation, and boundary region ($Bnd(C_i)$) are identified in Equations (12)-(14) [68]. Moreover, lower ($\underline{Lim}(C_i)$), upper ($\overline{Lim}(C_i)$) limits and the rough number ($RN(C_i)$) are explained in Equations (15)-(17) where $N_L$ and $N_U$ are the number of objects [69]. Equations (18)-(26) demonstrate the quantum picture fuzzy rough sets in which $C_{i\mu_A}$ refers to the membership, $C_{in_A}$ denotes the neutral degree, $C_{iv_A}$ shows the non-membership, and $C_{ih_A}$ means the refusal degrees. Also, $N_{L\mu_A}, N_{Ln_A}, N_{Lv_A}, N_{Lh_A}$ define the number of elements in $\underline{Apr}(C_{i\mu_A})$, $\underline{Apr}(C_{in_A})$, $\underline{Apr}(C_{iv_A})$, $\underline{Apr}(C_{ih_A})$ whereas $N_{U\mu_A}, N_{Un_A}, N_{Uv_A}, N_{Uh_A}$ are identified for $\overline{Apr}(C_{i\mu_A})$, $\overline{Apr}(C_{in_A})$, $\overline{Apr}(C_{iv_A})$, $\overline{Apr}(C_{ih_A})$. Equations (27)-(34) show the details of these items. In Equations (35) and (36), general formulation of the quantum picture fuzzy sets is explained. The degrees are computed with golden ratio (G) to increase the appropriateness of the findings [70]. Equations (37) and (38) explain this situation [71]. The phase angles of the degrees are formulated as in Equations (39)-(41). Equations (42)-(45) explain the operations of quantum picture fuzzy rough numbers.

The integration of Quantum Picture Fuzzy Rough Sets in decision-making models stems from the inherent limitations of classical methodologies in addressing the formidable challenges posed by uncertainties. Classical decision-making techniques often falter when confronted with intricate scenarios characterized by dynamic variables and nuanced states of membership. The conventional probabilistic frameworks, governed by classical logic, exhibit shortcomings in encapsulating the intricacies inherent in real-world problems. For instance, the complex decision problems could include several dynamic elements together such as positive, negative, and neutral degrees. So, use of quantum picture fuzzy rough sets could provide more sensitive results by using both amplitudes and phase angles of the related degrees at the same time.

### *B. M-SWARA with Quantum picture fuzzy rough sets*

SWARA aims to compute the weights of different indicators. In this process, hierarchical priorities of the experts are considered. However, this technique cannot create impact relation map of these factors. For this purpose, this method is extended with some improvements.

M-SWARA (Multi-SWARA) with Quantum Picture Fuzzy Rough Sets is an extended methodology derived from SWARA (Step-wise Weight Assessment Ratio Analysis) to address the limitation of neglecting causal directions between indicators. This extension incorporates quantum picture fuzzy rough sets to identify causality relationships among different items. The motivation for introducing M-SWARA with Quantum Picture Fuzzy Rough Sets stems from the limitations of the original SWARA methodology. While SWARA effectively weighs different indicators using hierarchical priorities, it falls short in considering causal directions between these indicators. This gap prompted the development of M-SWARA to enhance the methodology by incorporating quantum picture fuzzy rough sets. In this approach, the stable values of relation matrix with the values of $w_j$ are defined by transposing and limiting the matrix to the power of 2t+1. t is an arbitrarily large number. Additionally, the impact-relation degrees of the criteria are constructed from the relation matrix by using the threshold value $\alpha$. So, it is aimed to introduce a new extension of the SWARA to provide more accurate results along with the impact-relation degrees than the conventional SWARA methodology.

As a result, a new model is proposed with the name of M-SWARA. Hence, it is possible to make causality evaluation with the help of this new approach. Evaluations are obtained in the first step. Next, decision matrix is identified by Equation (46) [72]. The aggregated values are computed with Equation (47). Equation (48) is considered to obtain defuzzified values. Equations (49)-(51) are used to generate $s_j$ (importance), $k_j$ (coefficient), $q_j$ (recomputed weight), and $w_j$ (weight) values. This matrix is transposed and limited to the power of "2t+1" so that stable values can be identified. Finally, the causal directions can be obtained with the help of threshold value.

### *C. MOORA with Quantum picture fuzzy rough sets*

MOORA is used for ranking alternatives. The main superiority of this technique is that both positive and negative indicators can be taken into consideration. This methodology is extended with quantum picture fuzzy rough sets in this study. After the collection of the evaluations, decision matrix is constructed by Equation (52) [73]. With the help of Equation (48), defuzzified values can be

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

computed. Equation (53) is considered for the calculation of the normalized values. Positive and negative impacts are examined in the next process. Within this context, Equation (54) is used. Equation (55) is taken into consideration to identify the weighted results. These values are used to rank the alternatives.

## IV. ANALYSIS RESULTS

For the purpose of examining carbon neutrality policies in transportation industry, a two-stage model is created. The details of the proposed model are shown in Figure 1.

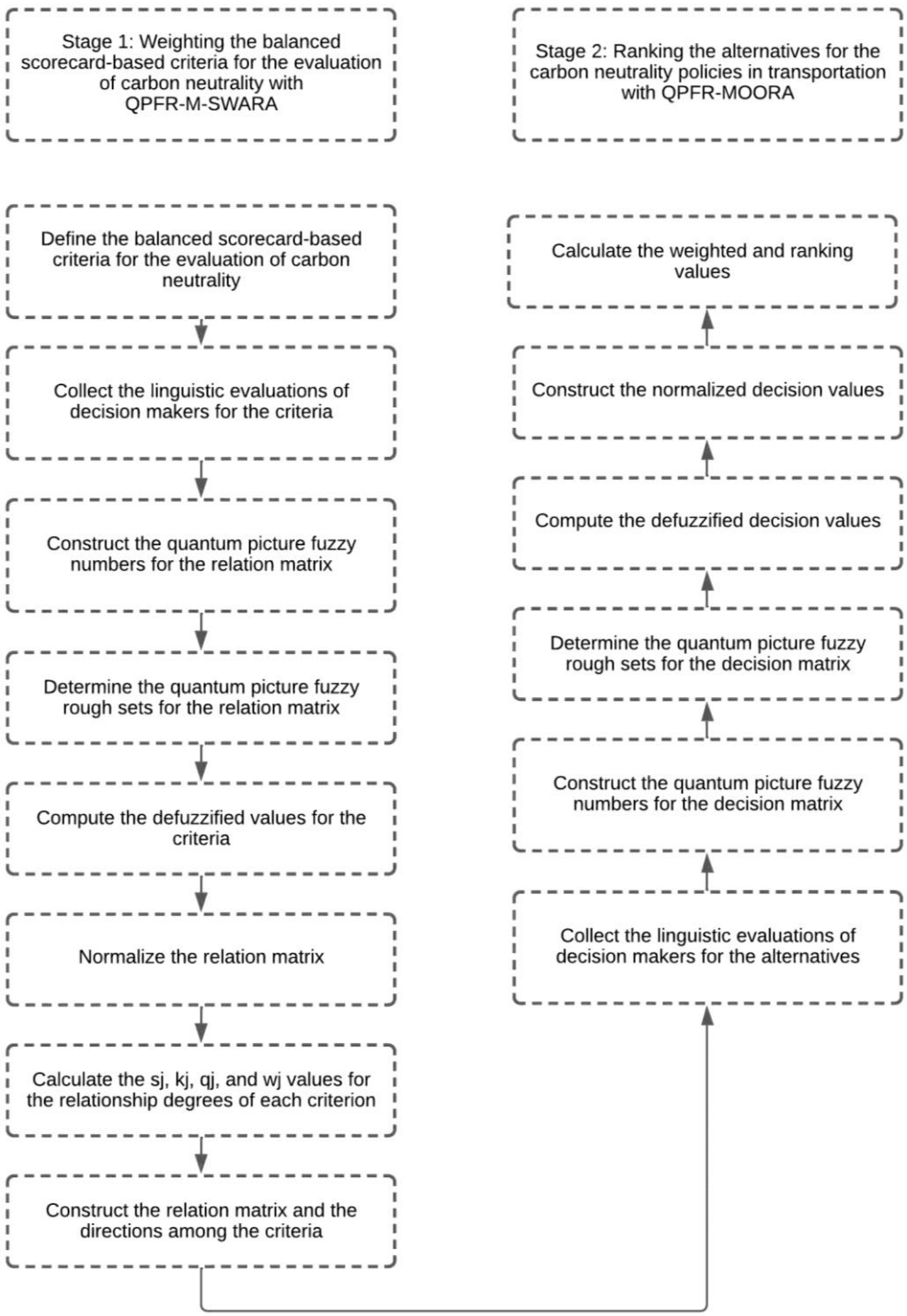



**FIGURE 1. The algorithm of hybrid model**

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

In the first stage of the model, selected determinants are evaluated with quantum picture fuzzy row sets-based M-SWARA technique. There are lots of decision-making models for weighting the criteria, such as AHP and ANP. However, these methods cannot consider casual directions while weighting the factors. Nonetheless, the indicators of carbon neutrality policies in transportation industry can have an impact on each other. Due to this issue, the causality relationship between these items should be taken into consideration to reach more effective results. As a result, it is seen that M-SWARA methodology is more optimal for this evaluation. On the other side, uncertainty is one of the most critical problems in the decision-making process. Hence, a comprehensive evaluation is needed to solve the complex problems. Owing to this situation, in this proposed model, quantum theory is integrated with the picture fuzzy rough sets. The main reason for this situation is that quantum theory provides very successful solutions for future predictions. Thus, with the help of this integration, it becomes possible to minimize uncertainties in this process. Furthermore, the alternatives for the carbon neutrality policies in this industry are ranked. Within this framework, MOORA technique is used with quantum picture fuzzy row sets. MOORA technique can handle many objective functions simultaneously. In this way, d can determine the most appropriate solutions by evaluating the relationships of variables with each other. In contrast, other methods such as VIKOR mostly use the weighted sum approach. Therefore, it may be more limited than MOORA in adapting to multi-objective targets. The results of this model are explained in the following subsections.

### *A. Weighting the criteria for the evaluation of carbon neutrality*

The indicators are identified with respect to the evaluation of carbon neutrality in transportation industry. In this context, these criteria are selected based on balanced scorecard technique. This approach mainly focused on four different perspectives that are financial, customer, internal process, and learning and growth. The main superiority of this approach is that both financial and nonfinancial issues can be considered together in the analysis process. With the help of this condition, more effective findings can be obtained. Selected indicators are explained in Table 1.

**TABLE 1. Criteria for the evaluation of carbon neutrality**

| Balanced scorecard-perspectives | Criteria | References |
|---|---|---|
| Financial | Costs | [4]; [9]; [14]; [26] |
| Customer | Customer Satisfaction | [11]; [18]; [33]; [35] |
| Internal Process | Infrastructure Development | [9]; [10]; [17]; [42] |
| Learning and Growth | Innovation and Technology Adoption | [16]; [20]; [24]; [29] |

Cost effectiveness in the process must be ensured to effectively implement carbon neutral policies in the transportation sector. Otherwise, the financial sustainability of the projects will not be possible. Meeting customers' expectations correctly also contributes to the proper implementation of these policies. This helps increase the preference of the projects. On the other hand, businesses with organizational effectiveness can also carry out these policies more effectively. Finally, businesses with a strong technological infrastructure can gain a significant competitive advantage. In this way, carbon neutral policies can be implemented effectively. In the following step, the evaluations are obtained from three different decision makers. These people have minimum 25 years of working experience. Two of these people work as general managers in international carbon emission companies. The third expert is the professor of energy economics and finance. He has lots of significant publications with respect to the renewable energy projects, carbon emission reduction strategies and effective waste management. In this process, these people consider the scales in Table A1. Table A2 gives information about the evaluations. In the following step, quantum picture fuzzy numbers for the relation matrix are generated. Table A3 indicates these numbers. Quantum picture fuzzy rough sets for the relation matrix are presented in Table A4. Defuzzified values are computed in Table A5. These values are normalized in Table A6. Moreover, sj, kj, qj, and wj values are computed in Table A7. Relation matrix is constructed in the next step. The directions among the factors are computed based on these values. Table 2 gives information about these details.

**TABLE 2. Relation matrix and impact directions**

| | Cost | Customer | Infrastructure | Innovation | Impact directions |
|---|---|---|---|---|---|
| **Cost** | | 0.246 | 0.322 | 0.432 | Cost → Innovation |
| **Customer** | 0.324 | | 0.430 | 0.247 | Customer → Infrastructure |
| **Infrastructure** | 0.432 | 0.322 | | 0.247 | Infrastructure → Cost |
| **Innovation** | 0.300 | 0.300 | 0.399 | | Innovation → Infrastructure |

Table 2 denotes that infrastructure development is the most influenced item because both customer satisfaction and innovation and technology adoption have an influence on this factor. Creating this impact relation map can be the main contribution of this proposed model in comparison with some of the previously generated models in the literature.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

The decision-making models used AHP and ANP cannot identify the causal relationship between these indicators. Considering this relationship provides an opportunity to generate more effective investment strategies. For example, technological improvements have a strong impact on the financial issues. By considering these conditions, it is understood that these improvements play a crucial role for the cost effectiveness. Stable matrix is generated after this calculation. The details of this new matrix are demonstrated in Table 3.

**TABLE 3.** Stable matrix

| | Cost | Customer | Infrastructure | Innovation |
|---|---|---|---|---|
| **Cost** | 0.263 | 0.263 | 0.263 | 0.263 |
| **Customer** | 0.224 | 0.224 | 0.225 | 0.224 |
| **Infrastructure** | 0.276 | 0.276 | 0.276 | 0.276 |
| **Innovation** | 0.237 | 0.237 | 0.237 | 0.237 |

The values in stable matrix demonstrate the weights of the criteria. It is seen that infrastructure development is the most important factor of effective carbon neutrality policies for transportation industry with the highest weight (0.276). Cost is another critical indicator in this respect since it has the weight of 0.163. It is possible to offer policy recommendations that support the development of technological infrastructure to ensure the effectiveness of carbon neutrality policies in the transportation sector. In this context, incentives can be provided primarily for green transportation technologies. In this context, tax reductions should be offered to increase the use of electric vehicles. On the other hand, some measures should be taken to improve the network infrastructure. Increasing the number of charging stations for electric vehicles has a very important role in this process. Moreover, the development of smart transportation systems is also necessary to ensure the effectiveness of carbon neutrality policies in the transportation sector. This allows energy efficiency to be increased. Using less energy also contributes significantly to reducing carbon emissions.

### *B. Ranking the alternatives for the carbon neutrality policies in transportation*

The second stage includes the evaluation of the alternatives for the carbon neutrality policies for transportation industry. For this purpose, five different alternatives are selected according to literature review results. Table 4 explains the details of these alternatives.

**TABLE 4.** Alternatives for the carbon neutrality policies in transportation

| Alternatives | References |
|---|---|
| Encouraging the transportation modes with sustainable alternatives (ETMWS) | [17] |
| Presenting the low-emission targets per passenger (PTLET) | [4] |
| Reducing traditional fuels with zero-carbon alternatives (RTFZC) | [22] |
| Selecting the optimized vehicle fleet with less-energy consumption (SOVFW) | [27] |
| Optimizing the energy consumption and the targeted time (OECTG) | [11] |

The evaluations regarding the alternatives are indicated in Table A8. Quantum picture fuzzy numbers for the decision matrix are computed in Table A9. Quantum picture fuzzy rough sets for the decision matrix are identified in Table A10. Defuzzified values are computed in the next process, and new matrix is generated in Table A11. Normalized values are calculated in the following step. Table A12 explains the details of normalized matrix. After that, the weighted values are calculated. These results are considered to rank the alternatives. Table 5 demonstrates the ranking results.

**TABLE 5.** The weighted values and ranking values

| Alternatives | Benefit Values | Cost Values | Weighted Scores | Ranking Results |
|---|---|---|---|---|
| ETMWS | 0.338 | 0.121 | 0.218 | 3 |
| PTLET | 0.324 | 0.105 | 0.219 | 2 |
| RTFZC | 0.351 | 0.121 | 0.230 | 1 |
| SOVFW | 0.313 | 0.125 | 0.188 | 5 |
| OECTG | 0.318 | 0.115 | 0.203 | 4 |

Table 5 indicates that reducing traditional fuels with zero-carbon alternatives is the most essential alternative for the carbon neutrality policies in transportation. Presenting the low-emission targets per passenger and encouraging the

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

transportation modes with sustainable alternatives are also important issues for this situation. However, optimizing the energy consumption and the targeted time and selecting the optimized vehicle fleet with less-energy consumption are on the last ranks. In this proposed model, MOORA methodology is integrated with the quantum picture fuzzy rough sets. This integration plays a key role for the minimization of the uncertainties in the evaluation process. With the help of this condition, more effective results can be identified. Because of this issue, it is thought that this integration paves the ways for the future decision-making models.

At the last stage, the extended TOPSIS is also applied for providing the comparative ranking results and the robustness check of the proposed methodology. Additionally, the sensitivity analysis is considered to understand the possible effects of the changing weighting results into the ranking performances by the cases. For that, 4 cases are defined by changing the weights of the criteria consecutively into the criteria set. The comparative ranking results by the cases are given in Table 6.

**TABLE 6. The comparative ranking results with sensitivity analysis**

| Alternatives | Case 1 | | Case 2 | | Case 3 | | Case 4 | |
|---|---|---|---|---|---|---|---|---|
| | Extended MOORA | Extended TOPSIS | Extended MOORA | Extended TOPSIS | Extended MOORA | Extended TOPSIS | Extended MOORA | Extended TOPSIS |
| ETMWS | 3 | 3 | 2 | 3 | 2 | 3 | 3 | 3 |
| PTLET | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 2 |
| RTFZC | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| SOVFW | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| OECTG | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |

According to Table 6, PTLET has the best ranking result among the alternatives. However, the comparative results illustrate that the rankings of both methodologies are similar by the cases. This is clear evidence for the coherency of our proposed methodology in case of the comparative results and the sensitivity analysis.

## V. DISCUSSION

Infrastructure development of businesses is of great importance in increasing the effectiveness of carbon neutrality policies in the transportation sector. In this context, first, energy efficiency must be ensured. To achieve this goal, transportation companies must create an infrastructure that consumes much less energy in their business processes. In this way, it is possible to consume much smaller amounts of natural resources. Wu et al. [74] defined that this contributes to significantly reducing the carbon emission problem. On the other hand, Li et al. [75] discussed that effective data collection processes also play an important role in the process of transportation companies creating a good infrastructure. Thanks to the accuracy of the data collected through business processes, it is possible to test the effectiveness of these processes much more successfully. Similarly, Akimoto et al. [76] and Wen and Wang [77] underlined that this situation allows malfunctions in the processes to be detected more easily and these problems to be resolved in a short time. Thus, it will be easier to implement carbon neutrality policies more successfully.

In addition, it is also important that the buildings and facilities of transportation companies are environmentally friendly. Designing these facilities in accordance with the green building concept allows for less carbon emissions in the production process. In this context, Arriet et al. [78] mentioned that providing the electricity needs in the production process from environmentally friendly energy sources such as solar panels instead of fossil fuels ensures less carbon emissions. On the other hand, Yu et al. [79] identified that it would be appropriate for transportation companies to attach importance to the use of electric vehicles. According to Tong et al. [80], owing to these vehicles, it is possible to seriously reduce the carbon emissions caused by this sector. In this context, government incentives for the use of electric vehicles need to be offered. For example, a tax reduction may increase the use of electric vehicles as it will provide a significant cost advantage. On the other hand, Zhang and Hanaoka [81] and Dong et al. [81] denoted that for these vehicles to be used effectively, it is necessary to create a wide range of charging stations throughout the country. In this way, transportation businesses will cause less carbon emissions while continuing their activities.

## VI. POLICY IMPLICATIONS

The most important issue in increasing the effectiveness of carbon neutrality policies in the transportation sector is determined as infrastructure development. Therefore, it is important to implement some policies to ensure infrastructure development in this context. First, some infrastructure strengthening works should be carried out to develop electric transportation. In this context, the infrastructure of charging stations should be developed to encourage the use of electric vehicles. This situation contributes to people and businesses choosing electric

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

vehicles. In addition, some practices should be implemented to reduce dependence on fossil fuels. In this context, alternative fuels based on renewable energy sources should be encouraged. In this process, incentives such as tax deductions provided by the government offer significant cost advantages to users. In this way, it is possible for the use of renewable energy to become more widespread.

## VII. CONCLUSION

This study examines carbon neutrality policies in transportation industry with a novel decision-making model. In the first stage, determinants are evaluated by quantum picture fuzzy row sets-based M-SWARA technique. Secondly, the alternatives for the carbon neutrality policies in this industry are ranked. For this purpose, MOORA methodology is considered with quantum picture fuzzy row sets. It is found that infrastructure development is the most influenced item because both customer satisfaction and innovation and technology adoption have an influence on this factor. Moreover, according to the weighting results, it is identified that infrastructure development is the most important factor of effective carbon neutrality policies for transportation industry with the highest weight (0.276). Cost is another critical indicator in this respect because it has the weight of 0.163. On the other hand, the ranking results demonstrate that reducing traditional fuels with zero-carbon alternatives is the most essential alternative for the carbon neutrality policies in transportation. Presenting the low-emission targets per passenger and encouraging the transportation modes with sustainable alternatives are also important issues for this situation. However, optimizing the energy consumption and the targeted time and selecting the optimized vehicle fleet with less-energy consumption are on the last ranks.

The main contribution of this study is that a new model is proposed by integrating quantum theory and picture fuzzy rough sets. This situation has a positive contribution to make sensitive evaluations. With the help of this issue, uncertainties in decision-making models can be handled more appropriately. Also, priority strategies can be presented for the improvements of the carbon neutrality policies in transportation industry. Owing to these results, companies can implement effective policies without having extra costs. The evaluation in this study is made only for transportation industry that can be accepted as the main limitation. Carbon neutrality policies also play a critical role for other industries, such as textile. Thus, in the following studies, these industries can be examined in this context. In this way, it is possible to determine specific sector-based strategies and policies to minimize carbon emissions. Additionally, the proposed model can be improved in the future studies. Existing ranking models in the literature are criticized by the scholars. Therefore, a novel ranking technique can be developed to overcome these criticisms. On the other side, another significant limitation is that the evaluations of all experts are considered as equal. However, the quality of the experts can differ based on some conditions, such as education level, work experience and position in the company. Hence, regarding the future research direction, a new model can be created in which the significance weights of the experts are defined.

**ACKNOWLEDGEMENT:** This paper was partially supported by grants from the National Natural Science Foundation of China (#71910107002).

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

## References


[1] Liu, L., Wang, X., & Wang, Z. (). "Recent progress and emerging strategies for carbon peak and carbon neutrality in China". *Greenhouse Gases: Science and Technology*, 2023.

[2] Wang, C., Raza, S. A., Adebayo, T. S., Yi, S., & Shah, M. I. (). "The roles of hydro, nuclear and biomass energy towards carbon neutrality target in China: a policy-based analysis" *Energy*, *262*, 125303, 2023.

[3] Antimiani, A., Costantini, V., & Paglialunga, E. (). "Fossil fuels subsidy removal and the EU carbon neutrality policy" *Energy Economics*, *119*, 106524, 2023.

[4] Dong, S., Zhao, H., Zheng, Y., & Ni, L. (). "Carbon reduction analysis of electric heat pumps in carbon neutrality in China" *Sustainable Cities and Society*, *97*, 104758, 2023.

[5] Chen, P., Zhang, S., Meng, J., Lei, T., Li, B., & Coffman, D. M. (). "Technological solutions to China's carbon neutrality in the steel and cement sectors" *Earth's Future*, *11*(9), e2022EF003255, 2023.

[6] Zahoor, A., Mehr, F., Mao, G., Yu, Y., & Sápi, A. (). "The carbon neutrality feasibility of worldwide and in China's transportation sector by E-car and renewable energy sources before 2060" *Journal of Energy Storage*, *61*, 106696, 2023.

[7] Zhang, R., & Hanaoka, T. (). "Opportunities and challenges of post-pandemic's new normal: Rethinking the contribution of the transport sector to China's carbon neutrality by 2060". *Science of The Total Environment*, 164976, 2023.

[8] Khurshid, A., Khan, K., & Cifuentes-Faura, J. (). "2030 Agenda of sustainable transport: Can current progress lead towards carbon neutrality?" *Transportation Research Part D: Transport and Environment*, *122*, 103869, 2023.

[9] Hossain, M. S., Fang, Y. R., Ma, T., Huang, C., Peng, W., Urpelainen, J., ... & Dai, H. (). "Narrowing fossil fuel consumption in the Indian road transport sector towards reaching carbon neutrality" *Energy Policy*, *172*, 113330, 2023.

[10] Li, C., Solangi, Y. A., & Ali, S. (). "Evaluating the factors of green finance to achieve carbon peak and carbon neutrality targets in China: A delphi and fuzzy AHP approach" Sustainability, vol. 15, no. 3, 2721, 2023.

[11] Jin, H. (). "Analyzing factors and resource policymaking options for sustainable resource management and carbon neutrality in mining industry: Empirical study in China" Resources Policy, vol. 86, 104185, 2023.

[12] Muryani, M., Nisa', K., Esquivias, M. A., & Zulkarnain, S. H. (). "Strategies to Control Industrial Emissions: An Analytical Network Process Approach in East Java, Indonesia". Sustainability, vol. 15, no. 10, 7761, 2023.

[13] Koska, A., & Erdem, M. B. (). "Performance Analysis of Manufacturing Waste Using SWARA and VIKOR Methods: Evaluation of Turkey within the Scope of the Circular Economy". Sustainability, vol. 15, no. 16, 12110, 2023.

[14] Soni, A., Das, P. K., & Kumar, S. (). "Application of q-rung orthopair fuzzy based SWARA-COPRAS model for municipal waste treatment technology selection" Environmental Science and Pollution Research, vol. 30, no. 37, pp. 88111-88131, 2023.

[15] Guo, X., Sun, Y., & Ren, D. (). "Life cycle carbon emission and cost-effectiveness analysis of electric vehicles in China" Energy for Sustainable Development, vol. 72, pp. 1-10, 2023.

[16] Davis, M., Okunlola, A., Di Lullo, G., Giwa, T., & Kumar, A. (). "Greenhouse gas reduction potential and cost-effectiveness of economy-wide hydrogen-natural gas blending for energy end uses" Renewable and Sustainable Energy Reviews, vol. 171, 112962, 2023.

[17] Han, L., Wu, P., & Chu, C. (). "A distributionally robust production planning model for maximizing customer satisfaction with budget and carbon emissions constraints" Computers & Industrial Engineering, 182, 109412, 2023.

[18] Du, J., Wang, X., Wu, X., Zhou, F., & Zhou, L. (). "Multi-objective optimization for two-echelon joint delivery location routing problem considering carbon emission under online shopping" Transportation Letters, vol. 15, no. 8, pp. 907-925, 2023.

[19] Xiong, Y., & Lin, H. (). "Research on Impact of Carbon Emission Reduction on Enterprise Value Based on Multiple Linear Regression Model" In 2023 IEEE 3rd International Conference on Electronic Communications, Internet of Things and Big Data (ICEIB) (pp. 387-391). IEEE, 2023.

[20] Sun, C., Tie, Y., & Yu, L. (). "How to achieve both environmental protection and firm performance improvement: Based on China's carbon emissions trading (CET) policy" Energy Economics, 107282, 2024.

[21] Sengupta, D., Das, A., Bera, U. K., & Chen, L. (). "A sustainable green reverse logistics plan for plastic solid waste management using TOPSIS


This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

method" Environmental Science and Pollution Research, vol. 30, no. 43, pp. 97734-97753, 2023.

[22] Muninathan, K., Ramanan, M. V., Monish, N., & Baskar, G. (). "Economic analysis and TOPSIS approach to optimize the CI engine characteristics using span 80 mixed carbon nanotubes emulsified Sapindus trifoliatus (soapnut) biodiesel by artificial neural network prediction model" Applied Energy, 355, 122309, 2024.

[23] Paul, T. K., Jana, C., Pal, M., & Simic, V. (). "Sustainable carbon-dioxide storage assessment in geological media using modified Pythagorean fuzzy VIKOR and DEMATEL approach". International Journal of Hydrogen Energy, vol. 48, no. 25, pp. 9474-9497, 2023.

[24] Tian, S., Zhou, Y., Fu, Y., Ji, L., & Li, Z. (). "Comprehensive Cost-Benefit Assessment of Offshore Wind Power Based on Improved VIKOR Method" In 2023 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia) (pp. 1268-1273). IEEE, 2023.

[25] Lv, Z., Wang, N., Lou, R., Tian, Y., & Guizani, M. (). "Towards carbon Neutrality: Prediction of wave energy based on improved GRU in Maritime transportation". *Applied Energy*, *331*, 120394, 2023.

[26] Dhir, A., Luqman, A., Gupta, J., & Gugnani, R. (). "Charting a path toward a greener world: A review of facilitating and inhibiting factors for carbon neutrality" *Journal of Cleaner Production*, 138423, 2023.

[27] Li, X. W., & Miao, H. Z. (). "How to Incorporate Autonomous Vehicles into the Carbon Neutrality Framework of China: Legal and Policy Perspectives" *Sustainability*, vol. 15, no. 7, 5671, 2023.

[28] Zhou, Y. (). "Worldwide carbon neutrality transition? Energy efficiency, renewable, carbon trading and advanced energy policies" *Energy Reviews*, 100026, 2023.

[29] Kii, M., Isikawa, R., & Kometani, Y. (). "Toward a carbon neutral urban transportation system in Japan" *IATSS Research*, 2023.

[30] Jenn, A. (). "Emissions of electric vehicles in California's transition to carbon neutrality" *Applied Energy*, *339*, 120974, 2023.

[31] Cai, L., Luo, J., Wang, M., Guo, J., Duan, J., Li, J., ... & Ren, D. (). "Pathways for municipalities to achieve carbon emission peak and carbon neutrality: A study based on the leap model" *Energy*, *262*, 125435, 2023.

[32] Mittal, V., & Shah, R. (). "Modeling the Global Annual Carbon Footprint for the Transportation Sector and a Path to Sustainability" *Modelling*, vol. 4, no. 2, pp. 264-282, 2023.

[33] Khanna, N. Z., Zhang, J., Lu, H., Feng, W., Johnson-Wang, M., & Zhou, N. (). "Conceptualizing demand-side technological and social innovations in modeling pathways to carbon neutrality" *Energy Research & Social Science*, *100*, 103115, 2023.

[34] Zahoor, A., Yu, Y., Zhang, H., Nihed, B., Afrane, S., Peng, S., ... & Mao, G. (). "Can the new energy vehicles (NEVs) and power battery industry help China to meet the carbon neutrality goal before 2060?" *Journal of Environmental Management*, *336*, 117663, 2023.

[35] Lin, Z., Wang, P., Ren, S., & Zhao, D. (). "Economic and environmental impacts of EVs promotion under the 2060 carbon neutrality target—A CGE based study in Shaanxi Province of China" *Applied Energy*, *332*, 120501, 2023.

[36] Shang, W. L., & Lv, Z. (). "Low carbon technology for carbon neutrality in sustainable cities: A survey" *Sustainable Cities and Society*, *92*, 104489, 2023.

[37] Yang, Y., & Lo, K. (). "China's renewable energy and energy efficiency policies toward carbon neutrality: A systematic cross-sectoral review" *Energy & Environment*, 0958305X231167472, 2023.

[38] Xiang, P. P., He, C. M., Chen, S., Jiang, W. Y., Liu, J., & Jiang, K. J. (). "Role of hydrogen in China's energy transition towards carbon neutrality target: IPAC analysis" *Advances in Climate Change Research*, vol. 14, no. 1, pp. 43-48, 2023.

[39] Xu, S., Zhai, Y., Feng, J., & Liu, G. (). "A framework of carbon-neutral waste transportation: Modeling and sensitive analysis" *Circular Economy*, vol. 2, no. 1, 100024, 2023.

[40] Pan, H., Page, J., Shi, R., Cong, C., Cai, Z., Barthel, S., ... & Kalantari, Z. (). "Contribution of prioritized urban nature-based solutions allocation to carbon neutrality" *Nature Climate Change*, pp. 1-9, 2023.

[41] Du, J., Cheng, J., & Ali, K. (). "Modelling the green logistics and financial innovation on carbon neutrality goal, a fresh insight for BRICS-T". *Geological Journal*, vol. 58, no. 7, pp. 2742-2756, 2023.

[42] Sun, D., & Xia, J. (). "Research on road transport planning aiming at near zero carbon emissions: Taking Ruicheng County as an example" *Energy*, 263, 125834, 2023.

[43] Rinawati, D. I., Keeley, A. R., Takeda, S., Itsubo, N., & Managi, S. (). "Potential for reducing CO2

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

emissions from passenger cars in Japan by 2030 to achieve carbon neutrality" *IATSS Research*, 2023.

[44] Proskurina, S., & Mendoza-Martinez, C. (). "Expectations for Bioenergy Considering Carbon Neutrality Targets in the EU" *Energies*, vol. 16, no. 14, 5314, 2023.

[45] Ding, X., & Liu, X. (). "Renewable energy development and transportation infrastructure matters for green economic growth? Empirical evidence from China" *Economic Analysis and Policy*, vol. 79, pp. 634-646, 2023.

[46] Xu, F., Lu, Y., Huo, Q., Yin, J., Qiu, P., & Ding, C. (). "Flexible Low-Carbon Optimal Dispatch of Honeycombed Active Distribution Network" *Energies*, vol. 15, no. 19, 7107, 2022.

[47] Azam, M., Younes, B. Z., Hunjra, A. I., & Hussain, N. (). "Integrated Spatial-Temporal decomposition analysis for life cycle assessment of carbon emission intensity change in various regions of China" *Resources Policy*, *79*, 103062, 2022.

[48] Ahmed, M., Jones, T. D., & Abdolvand, A. (). "Ink formulation and printing of electrolyte for a doped ceria solid oxide fuel cell" *Materials Letters*, *327*, 132999, 2022.

[49] Rehman, A., Ma, H., Ozturk, I., & Radulescu, M. (). "Revealing the dynamic effects of fossil fuel energy, nuclear energy, renewable energy, and carbon emissions on Pakistan's economic growth" *Environmental Science and Pollution Research*, vol. 29, no. 32, pp. 48784-48794, 2022.

[50] Bartowitz, K. J., Walsh, E. S., Stenzel, J. E., Kolden, C. A., & Hudiburg, T. W. (). "Forest carbon emission sources are not equal: Putting fire, harvest, and fossil fuel emissions in context" *Frontiers in Forests and Global Change*, *5*, 2022.

[51] Ibrahim, R. L. (). "Beyond COP26: can income level moderate fossil fuels, carbon emissions, and human capital for healthy life expectancy in Africa?" *Environmental Science and Pollution Research*, vol. 29, no. 58, pp. 87568-87582, 2022.

[52] Zhang, L., Mu, R., Zhan, Y., Yu, J., Liu, L., Yu, Y., & Zhang, J. (). "Digital economy, energy efficiency, and carbon emissions: Evidence from provincial panel data in China" *Science of The Total Environment*, *852*, 158403, 2022.

[53] Hong, Q., Cui, L., & Hong, P. (). "The impact of carbon emissions trading on energy efficiency: Evidence from quasi-experiment in China's carbon emissions trading pilot" *Energy Economics*, *110*, 106025, 2022.

[54] Issa, M., Ilinca, A., & Martini, F. (). "Ship energy efficiency and maritime sector initiatives to reduce carbon emissions" *Energies*, vol. 15, no. 21, 7910, 2022.

[55] Ding, Z., Yüksel, S., & Dincer, H. (). "An Integrated Pythagorean fuzzy soft computing approach to environmental management systems for sustainable energy pricing." Energy Reports, vol. 7, pp. 5575-5588, 2021.

[56] Kamali Saraji, M., Streimikiene, D., & Ciegis, R. (). "A novel Pythagorean fuzzy-SWARA-TOPSIS framework for evaluating the EU progress towards sustainable energy development" Environmental monitoring and assessment, vol. 194, no. 1, 42, 2022.

[57] Al-Barakati, A., Mishra, A. R., Mardani, A., & Rani, P. (). "An extended interval-valued Pythagorean fuzzy WASPAS method based on new similarity measures to evaluate the renewable energy sources" Applied Soft Computing, vol. 120, 108689, 2022.

[58] Yüksel, S., & Dinçer, H. (). "Identifying the strategic priorities of nuclear energy investments using hesitant 2-tuple interval-valued Pythagorean fuzzy DEMATEL" Progress in Nuclear Energy, vol. 145, 104103, 2022.

[59] Kutlu Gündoğdu, F., & Kahraman, C. (). "A novel spherical fuzzy analytic hierarchy process and its renewable energy application" Soft Computing, vol. 24, pp. 4607-4621, 2020.

[60] Akram, M., Ullah, K., & Pamucar, D. (). "Performance evaluation of solar energy cells using the interval-valued T-spherical fuzzy Bonferroni mean operators" Energies, vol. 15, no. 1, 292, 2022.

[61] Yuan, G., Xie, F., Dinçer, H., & Yüksel, S. (). "The theory of inventive problem solving (TRIZ)-based strategic mapping of green nuclear energy investments with spherical fuzzy group decision-making approach" International Journal of Energy Research, vol. 45, no. 8, pp. 12284-12300, 2021.

[62] Priyan, S., Udayakumar, R., Mala, P., Prabha, M., & Ghosh, A. (). "A sustainable dual-channel inventory model with trapezoidal fuzzy demand and energy consumption" Cleaner Engineering and Technology, vol. 6, 100400, 2022.

[63] Wu, Y., Zhang, T., & Yi, L. (). "An internal type-2 trapezoidal fuzzy sets-PROMETHEE-II based investment decision framework of compressed air energy storage project in China under the perspective of different investors" Journal of Energy Storage, vol. 30, 101548, 2020.

[64] Sharma, A., Kumar, R., & Bajaj, R. K. (). "On Energy-constrained quickest path problem in green communication using intuitionistic trapezoidal fuzzy numbers" Recent Advances in Computer

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

Science and Communications (Formerly: Recent Patents on Computer Science), vol. 14, no. 1, pp. 192-200, 2021.

[65] Kayacık, M., Dinçer, H., & Yüksel, S. (). "Using quantum spherical fuzzy decision support system as a novel sustainability index approach for analyzing industries listed in the stock exchange" *Borsa Istanbul Review*, vol. 22, no. 6, pp. 1145-1157, 2022.

[66] He, S., & Wang, Y. (). "Evaluating new energy vehicles by picture fuzzy sets based on sentiment analysis from online reviews" *Artificial Intelligence Review*, vol. 56, no. 3, pp. 2171-2192, 2023.

[67] Güneri, B., & Deveci, M. (). "Evaluation of supplier selection in the defense industry using q-rung orthopair fuzzy set based EDAS approach" *Expert Systems with Applications*, vol. *222*, 119846, 2023.

[68] Deveci, M., Pamucar, D., & Oguz, E. (). "Floating photovoltaic site selection using fuzzy rough numbers based LAAW and RAFSI model" *Applied Energy*, vol. 324, 119597, 2022.

[69] Gokasar, I., Pamucar, D., Deveci, M., & Ding, W. (). "A novel rough numbers based extended MACBETH method for the prioritization of the connected autonomous vehicles in real-time traffic management" *Expert Systems with Applications*, vol. 211, 118445, 2023.

[70] Xu, X., Yüksel, S., & Dinçer, H. (). "An integrated decision-making approach with golden cut and bipolar q-ROFSs to renewable energy storage investments" *International Journal of Fuzzy Systems*, vol. *25*, no. 1, pp. 168-181, 2023.

[71] Yüksel, S., & Dinçer, H. (). "Sustainability analysis of digital transformation and circular industrialization with quantum spherical fuzzy modeling and golden cuts" *Applied Soft Computing*, vol. 138, 110192, 2023.

[72] Mikhaylov, A., Dinçer, H., Yüksel, S., Pinter, G., & Shaikh, Z. A. (). "Bitcoin mempool growth and trading volumes: Integrated approach based on QROF Multi-SWARA and aggregation operators" *Journal of Innovation & Knowledge*, vol. 8, no. 3, 100378, 2023.

[73] Tian, C., Peng, J. J., Long, Q. Q., Wang, J. Q., & Goh, M. (). "Extended picture fuzzy MULTIMOORA method based on prospect theory for medical institution selection" *Cognitive Computation*, vol. 14, no. 4, pp. 1446-1463, 2022.

[74] Wu, X., Tian, Z., & Guo, J. (). "A review of the theoretical research and practical progress of carbon neutrality" *Sustainable Operations and Computers*, vol. 3, pp. 54-66, 2022.

[75] Li, H., Hao, Y., Xie, C., Han, Y., & Wang, Z. R. (). "Emerging technologies and policies for carbon-neutral transportation" *International Journal of Transportation Science and Technology*, 2022.

[76] Akimoto, K., Sano, F., & Nakano, Y. (). "Assessment of comprehensive energy systems for achieving carbon neutrality in road transport" *Transportation Research Part D: Transport and Environment*, vol. 112, 103487, 2022.

[77] Wen, L., & Wang, A. (). "System dynamics model of Beijing urban public transport carbon emissions based on carbon neutrality target" *Environment, Development and Sustainability*, pp. 1-26, 2022.

[78] Arriet, A., Flores, F., Matamala, Y., & Feijoo, F. (). "Chilean pathways for mid-century carbon neutrality under high renewable potential" *Journal of Cleaner Production*, vol. 379, 134483, 2022.

[79] Yu, Y., Xu, H., Cheng, J., Wan, F., Ju, L., Liu, Q., & Liu, J. (). "Which type of electric vehicle is worth promoting mostly in the context of carbon peaking and carbon neutrality? A case study for a metropolis in China" *Science of The Total Environment*, vol. 837, 155626, 2022.

[80] Tong, X., Dai, H., Lu, P., Zhang, A., & Ma, T. (). "Saving global platinum demand while achieving carbon neutrality in the passenger transport sector: linking material flow analysis with integrated assessment model" *Resources, Conservation and Recycling*, vol. 179, 106110, 2022.

[81] Zhang, R., & Hanaoka, T. (). "Cross-cutting scenarios and strategies for designing decarbonization pathways in the transport sector toward carbon neutrality" *Nature communications*, vol. 13, no. 1, 3629, 2022.

[82] Dong, J., Li, Y., Li, W., & Liu, S. (). "CO2 Emission Reduction Potential of Road Transport to Achieve Carbon Neutrality in China" *Sustainability*, vol. 14, no. 9, 5454, 2022.

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

## Appendix

## Appendix A -Equations

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

$$|C> = \{|u_1>, |u_2>, \dots, |u_n>\} \tag{2}$$

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

$$A = \{\langle x, \mu_A(x)\rangle | x \in X\} \tag{4}$$

$$A = \{\langle x, \mu_A(x), v_A(x)\rangle | x \in X\} \tag{5}$$

$$A = \{\langle x, \mu_A(x), n_A(x), v_A(x), h_A(x)\rangle | x \in X\} \tag{6}$$

$$A \subseteq B \text{ if } \mu_A(x) \le \mu_B(x) \text{ and } n_A(x) \le n_B(x) \text{ and } v_A(x) \ge v_B(x), \forall x \in X \tag{7}$$

$$A = B \text{ if } A \subseteq B \text{ and } B \subseteq A \tag{8}$$

$$A \cup B = \left\{\left(x, max\left(\mu_A(x), \mu_B(x)\right), min\left(n_A(x), n_B(x)\right), min\left(v_A(x), v_B(x)\right)\right) | x \in X\right\} \tag{9}$$

$$A \cap B = \left\{\left(x, min\left(\mu_A(x), \mu_B(x)\right), min\left(n_A(x), n_B(x)\right), max\left(v_A(x), v_B(x)\right)\right) | x \in X\right\} \tag{10}$$

$$coA = \bar{A} = \left\{\left(x, v_A(x), n_A(x), \mu_A(x)\right) | x \in X\right\} \tag{11}$$

$$\underline{Apr}(C_i) = \cup \{Y \in X / R(Y) \le C_i\} \tag{12}$$

$$\overline{Apr}(C_i) = \cup \{Y \in X / R(Y) \ge C_i\} \tag{13}$$

$$Bnd(C_i) = \cup \{Y \in X / R(Y) \ne C_i\} \tag{14}$$

$$\underline{Lim}(C_i) = \sqrt[N_L]{\prod_{i=1}^{N_L} Y \in \underline{Apr}(C_i)} \tag{15}$$

$$\overline{Lim}(C_i) = \sqrt[N_U]{\prod_{i=1}^{N_U} Y \in \overline{Apr}(C_i)} \tag{16}$$

$$RN(C_i) = \left\lceil \underline{Lim}(C_i), \overline{Lim}(C_i) \right\rceil \tag{17}$$

$$|C_A> = \left\{ \begin{matrix} \langle u, (\left\lceil \underline{Lim}(C_{i\mu_A}), \overline{Lim}(C_{i\mu_A}) \right\rceil (u), \left\lceil \underline{Lim}(C_{in_A}), \overline{Lim}(C_{in_A}) \right\rceil (u), \\ \left\lceil \underline{Lim}(C_{iv_A}), \overline{Lim}(C_{iv_A}) \right\rceil (u), \left\lceil \underline{Lim}(C_{ih_A}), \overline{Lim}(C_{ih_A}) \right\rceil (u)) | u \in 2^{|C_A>} \end{matrix} \right\} \tag{18}$$

$$\underline{Lim}\left(C_{i\mu_A}\right) = \frac{1}{N_{L\mu_A}} \sum_{i=1}^{N_{L\mu_A}} Y \in \underline{Apr}\left(C_{i\mu_A}\right) \tag{19}$$

$$\underline{Lim}\left(C_{in_A}\right) = \frac{1}{N_{Ln_A}} \sum_{i=1}^{N_{Ln_A}} Y \in \underline{Apr}\left(C_{in_A}\right) \tag{20}$$

$$\underline{Lim}\left(C_{iv_A}\right) = \frac{1}{N_{Lv_A}} \sum_{i=1}^{N_{Lv_A}} Y \in \underline{Apr}\left(C_{iv_A}\right) \tag{21}$$

$$\underline{Lim}\left(C_{ih_A}\right) = \frac{1}{N_{L\pi_A}} \sum_{i=1}^{N_{L\pi_A}} Y \in \underline{Apr}\left(C_{ih_A}\right) \tag{22}$$

$$\overline{Lim}\left(C_{i\mu_A}\right) = \frac{1}{N_{U\mu_A}} \sum_{i=1}^{N_{U\mu_A}} Y \in \overline{Apr}\left(C_{i\mu_A}\right) \tag{23}$$

$$\overline{Lim}\left(C_{in_A}\right) = \frac{1}{N_{Un_A}} \sum_{i=1}^{N_{Un_A}} Y \in \overline{Apr}\left(C_{in_A}\right) \tag{24}$$

$$\overline{Lim}\left(C_{iv_A}\right) = \frac{1}{N_{Uv_A}} \sum_{i=1}^{N_{Uv_A}} Y \in \overline{Apr}\left(C_{iv_A}\right) \tag{25}$$

$$\overline{Lim}\left(C_{ih_A}\right) = \frac{1}{N_{U\pi_A}} \sum_{i=1}^{N_{U\pi_A}} Y \in \overline{Apr}\left(C_{ih_A}\right) \tag{26}$$

$$\underline{Apr}\left(C_{i\mu_A}\right) = \cup \left\{Y \in X / \tilde{R}(Y) \le C_{i\mu_A}\right\} \tag{27}$$

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

$$\underline{Apr}\left(C_{in_A}\right) = \cup\left\{Y \in X/\tilde{R}(Y) \leq C_{in_A}\right\} \tag{28}$$

$$\underline{Apr}\left(C_{iv_A}\right) = \cup\left\{Y \in X/\tilde{R}(Y) \leq C_{iv_A}\right\} \tag{29}$$

$$\underline{Apr}\left(C_{ih_A}\right) = \cup\left\{Y \in X/\tilde{R}(Y) \leq C_{ih_A}\right\} \tag{30}$$

$$\overline{Apr}\left(C_{i\mu_A}\right) = \cup\left\{Y \in X/\tilde{R}(Y) \leq C_{i\mu_A}\right\} \tag{31}$$

$$\overline{Apr}\left(C_{in_A}\right) = \cup\left\{Y \in X/\tilde{R}(Y) \leq C_{in_A}\right\} \tag{32}$$

$$\overline{Apr}\left(C_{iv_A}\right) = \cup\left\{Y \in X/\tilde{R}(Y) \leq C_{iv_A}\right\} \tag{33}$$

$$\overline{Apr}\left(C_{ih_A}\right) = \cup\left\{Y \in X/\tilde{R}(Y) \leq C_{ih_A}\right\} \tag{34}$$

$$C = \left[C_{\mu}.e^{j2\pi.\alpha}, C_n.e^{j2\pi.\gamma}, C_v.e^{j2\pi.\beta}, C_h.e^{j2\pi.T}\right] \tag{35}$$

$$\varphi^2 = \left|C_{\mu}(|u_i>)\right| \tag{36}$$

$$C_n = \frac{C_{\mu}}{G} \tag{37}$$

$$C_h = \frac{C_v}{G} \tag{38}$$

$$\alpha = \left|C_{\mu}(|u_i>)\right| \tag{39}$$

$$\gamma = \frac{\alpha}{G} \tag{40}$$

$$T = \frac{\beta}{G} \tag{41}$$

$$\lambda * \tilde{A}_c = \left\{\begin{matrix}\left[\underline{Lim}\left(C_{\mu_{\tilde{A}}}\right)\lambda, \overline{Lim}\left(C_{\mu_{\tilde{A}}}\right)\lambda\right] e^{j2\pi.\left[\left(\frac{\underline{\alpha}_{\tilde{A}}}{2\pi}\right)\lambda, \left(\frac{\overline{\alpha}_{\tilde{A}}}{2\pi}\right)\lambda\right]}, \left[\underline{Lim}\left(C_{n_{\tilde{A}}}\right)\lambda, \overline{Lim}\left(C_{n_{\tilde{A}}}\right)\lambda\right] e^{j2\pi.\left[\left(\frac{\underline{\gamma}_{\tilde{A}}}{2\pi}\right)\lambda, \left(\frac{\overline{\gamma}_{\tilde{A}}}{2\pi}\right)\lambda\right]}, \\ \left[\underline{Lim}\left(C_{v_{\tilde{A}}}\right)\lambda, \overline{Lim}\left(C_{v_{\tilde{A}}}\right)\lambda\right] e^{j2\pi.\left[\left(\frac{\underline{\beta}_{\tilde{A}}}{2\pi}\right)\lambda, \left(\frac{\overline{\beta}_{\tilde{A}}}{2\pi}\right)\lambda\right]}, \left[\underline{Lim}\left(C_{h_{\tilde{A}}}\right)\lambda, \overline{Lim}\left(C_{h_{\tilde{A}}}\right)\lambda\right] e^{j2\pi.\left[\left(\frac{\underline{T}_{\tilde{A}}}{2\pi}\right)\lambda, \left(\frac{\overline{T}_{\tilde{A}}}{2\pi}\right)\lambda\right]}\end{matrix}\right\},$$

$$\lambda > 0 \tag{42}$$

$$\tilde{A}_c{}^{\lambda} = \left\{\begin{matrix}\left[\underline{Lim}\left(C_{\mu_{\tilde{A}}}\right)^{\lambda}, \overline{Lim}\left(C_{\mu_{\tilde{A}}}\right)^{\lambda}\right] e^{j2\pi.\left[\left(\frac{\underline{\alpha}_{\tilde{A}}}{2\pi}\right)^{\lambda}, \left(\frac{\overline{\alpha}_{\tilde{A}}}{2\pi}\right)^{\lambda}\right]}, \left[\underline{Lim}\left(C_{n_{\tilde{A}}}\right)^{\lambda}, \overline{Lim}\left(C_{n_{\tilde{A}}}\right)^{\lambda}\right] e^{j2\pi.\left[\left(\frac{\underline{\gamma}_{\tilde{A}}}{2\pi}\right)^{\lambda}, \left(\frac{\overline{\gamma}_{\tilde{A}}}{2\pi}\right)^{\lambda}\right]}, \\ \left[\underline{Lim}\left(C_{v_{\tilde{A}}}\right)^{\lambda}, \overline{Lim}\left(C_{v_{\tilde{A}}}\right)^{\lambda}\right] e^{j2\pi.\left[\left(\frac{\underline{\beta}_{\tilde{A}}}{2\pi}\right)^{\lambda}, \left(\frac{\overline{\beta}_{\tilde{A}}}{2\pi}\right)^{\lambda}\right]}, \left[\underline{Lim}\left(C_{h_{\tilde{A}}}\right)^{\lambda}, \overline{Lim}\left(C_{h_{\tilde{A}}}\right)^{\lambda}\right] e^{j2\pi.\left[\left(\frac{\underline{T}_{\tilde{A}}}{2\pi}\right)^{\lambda}, \left(\frac{\overline{T}_{\tilde{A}}}{2\pi}\right)^{\lambda}\right]},\end{matrix}\right\},$$

$$\lambda > 0 \tag{43}$$

$$\tilde{A}_c \cup \tilde{B}_c = \left\{\begin{matrix}\left[min\left(\underline{Lim}\left(C_{\mu_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\underline{\alpha}_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}\left(C_{\mu_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\underline{\alpha}_{\tilde{B}}}{2\pi}\right)}\right), max\left(\overline{Lim}\left(C_{\mu_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\overline{\alpha}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}\left(C_{\mu_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\overline{\alpha}_{\tilde{B}}}{2\pi}\right)}\right)\right], \\ \left[min\left(\underline{Lim}\left(C_{n_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\underline{\gamma}_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}\left(C_{n_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\underline{\gamma}_{\tilde{B}}}{2\pi}\right)}\right), max\left(\overline{Lim}\left(C_{n_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\overline{\gamma}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}\left(C_{n_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\overline{\gamma}_{\tilde{B}}}{2\pi}\right)}\right)\right], \\ \left[min\left(\underline{Lim}\left(C_{v_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\underline{\beta}_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}\left(C_{v_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\underline{\beta}_{\tilde{B}}}{2\pi}\right)}\right), max\left(\overline{Lim}\left(C_{v_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\overline{\beta}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}\left(C_{v_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\overline{\beta}_{\tilde{B}}}{2\pi}\right)}\right)\right], \\ \left[min\left(\underline{Lim}\left(C_{h_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\underline{T}_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}\left(C_{h_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\underline{T}_{\tilde{B}}}{2\pi}\right)}\right), max\left(\overline{Lim}\left(C_{h_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\overline{T}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}\left(C_{h_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\overline{T}_{\tilde{B}}}{2\pi}\right)}\right)\right]\end{matrix}\right\} \tag{44}$$

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

$$\tilde{A}_c \cap \tilde{B}_c = \left\{ \begin{array}{l} \left[ max\left( \underline{Lim}\left(C_{\mu_{\tilde{A}}}\right) e^{j2\pi.\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}\left(C_{\mu_{\tilde{B}}}\right) e^{j2\pi.\left(\frac{\alpha_{\tilde{B}}}{2\pi}\right)} \right), min\left( \overline{Lim}\left(C_{\mu_{\tilde{A}}}\right) e^{j2\pi.\left(\frac{\overline{\alpha}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}\left(C_{\mu_{\tilde{B}}}\right) e^{j2\pi.\left(\frac{\overline{\alpha}_{\tilde{B}}}{2\pi}\right)} \right) \right], \\ \left[ max\left( \underline{Lim}\left(C_{n_{\tilde{A}}}\right) e^{j2\pi.\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}\left(C_{n_{\tilde{B}}}\right) e^{j2\pi.\left(\frac{\gamma_{\tilde{B}}}{2\pi}\right)} \right), min\left( \overline{Lim}\left(C_{n_{\tilde{A}}}\right) e^{j2\pi.\left(\frac{\overline{\gamma}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}\left(C_{n_{\tilde{B}}}\right) e^{j2\pi.\left(\frac{\overline{\gamma}_{\tilde{B}}}{2\pi}\right)} \right) \right], \\ \left[ max\left( \underline{Lim}\left(C_{v_{\tilde{A}}}\right) e^{j2\pi.\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}\left(C_{v_{\tilde{B}}}\right) e^{j2\pi.\left(\frac{\beta_{\tilde{B}}}{2\pi}\right)} \right), min\left( \overline{Lim}\left(C_{v_{\tilde{A}}}\right) e^{j2\pi.\left(\frac{\overline{\beta}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}\left(C_{v_{\tilde{B}}}\right) e^{j2\pi.\left(\frac{\overline{\beta}_{\tilde{B}}}{2\pi}\right)} \right) \right], \\ \left[ max\left( \underline{Lim}\left(C_{h_{\tilde{A}}}\right) e^{j2\pi.\left(\frac{T_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}\left(C_{h_{\tilde{B}}}\right) e^{j2\pi.\left(\frac{T_{\tilde{B}}}{2\pi}\right)} \right), min\left( \overline{Lim}\left(C_{h_{\tilde{A}}}\right) e^{j2\pi.\left(\frac{\overline{T}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}\left(C_{h_{\tilde{B}}}\right) e^{j2\pi.\left(\frac{\overline{T}_{\tilde{B}}}{2\pi}\right)} \right) \right] \end{array} \right\} \quad (45)$$

$$C_k = \begin{bmatrix} 0 & C_{12} & \cdots & \cdots & C_{1n} \\ C_{21} & 0 & \cdots & \cdots & C_{2n} \\ \vdots & \vdots & \ddots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_{n1} & C_{n2} & \cdots & \cdots & 0 \end{bmatrix} \quad (46)$$

$$\mathrm{C} = \begin{pmatrix} \left[ min_{i=1}^{k}\left(\underline{Lim}\left(C_{\mu_{ij}}\right)\right), max_{i=1}^{k}\left(\overline{Lim}\left(C_{\mu_{ij}}\right)\right) \right] e^{j2\pi.\left[ min_{i=1}^{k}\left(\frac{\alpha_{ij}}{2\pi}\right), max_{i=1}^{k}\left(\frac{\overline{\alpha}_{ij}}{2\pi}\right) \right]}, \\ \left[ min_{i=1}^{k}\left(\underline{Lim}\left(C_{n_{ij}}\right)\right), max_{i=1}^{k}\left(\overline{Lim}\left(C_{n_{ij}}\right)\right) \right] e^{j2\pi.\left[ min_{i=1}^{k}\left(\frac{\gamma_{ij}}{2\pi}\right), max_{i=1}^{k}\left(\frac{\overline{\gamma}_{ij}}{2\pi}\right) \right]}, \\ \left[ min_{i=1}^{k}\left(\underline{Lim}\left(C_{v_{ij}}\right)\right), max_{i=1}^{k}\left(\overline{Lim}\left(C_{v_{ij}}\right)\right) \right] e^{j2\pi.\left[ min_{i=1}^{k}\left(\frac{\beta_{ij}}{2\pi}\right), max_{i=1}^{k}\left(\frac{\overline{\beta}_{ij}}{2\pi}\right) \right]}, \\ \left[ min_{i=1}^{k}\left(\underline{Lim}\left(C_{h_{ij}}\right)\right), max_{i=1}^{k}\left(\overline{Lim}\left(C_{h_{ij}}\right)\right) \right] e^{j2\pi.\left[ min_{i=1}^{k}\left(\frac{T_{ij}}{2\pi}\right), max_{i=1}^{k}\left(\frac{\overline{T}_{ij}}{2\pi}\right) \right]} \end{pmatrix} \quad (47)$$

$$Defc_i = \frac{\begin{pmatrix} \underline{Lim}\left(C_{\mu_i}\right) - \underline{Lim}\left(C_{n_i}\right) + \underline{Lim}\left(C_{\mu_i}\right).\left(\underline{Lim}\left(C_{v_i}\right) - \underline{Lim}\left(C_{h_i}\right)\right) + \left(\frac{\alpha_{ij}}{2\pi}\right) - \left(\frac{\gamma_{ij}}{2\pi}\right) + \left(\frac{\alpha_{ij}}{2\pi}\right).\left(\left(\frac{\beta_{ij}}{2\pi}\right) - \left(\frac{T_{ij}}{2\pi}\right)\right) + \\ \overline{Lim}\left(C_{\mu_i}\right) - \overline{Lim}\left(C_{n_i}\right) + \overline{Lim}\left(C_{\mu_i}\right).\left(\overline{Lim}\left(C_{v_i}\right) - \overline{Lim}\left(C_{h_i}\right)\right) + \left(\frac{\overline{\alpha}_{ij}}{2\pi}\right) - \left(\frac{\overline{\gamma}_{ij}}{2\pi}\right) + \left(\frac{\overline{\alpha}_{ij}}{2\pi}\right).\left(\left(\frac{\overline{\beta}_{ij}}{2\pi}\right) - \left(\frac{\overline{T}_{ij}}{2\pi}\right)\right) \end{pmatrix}}{2} \quad (48)$$

$$k_j = \begin{cases} 1 & j = 1 \\ s_j + 1 & j > 1 \end{cases} \quad (49)$$

$$q_j = \begin{cases} 1 & j = 1 \\ \frac{q_{j-1}}{k_j} & j > 1 \end{cases} \quad (50)$$

$If\ s_{j-1} = s_j,\ q_{j-1} = q_j; If\ s_j = 0,\ k_{j-1} = k_j$

$$w_j = \frac{q_j}{\sum_{k=1}^{n} q_k} \quad (51)$$

$$X_k = \begin{bmatrix} 0 & X_{12} & \cdots & \cdots & X_{1m} \\ X_{21} & 0 & \cdots & \cdots & X_{2m} \\ \vdots & \vdots & \ddots & \cdots & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ X_{n1} & X_{n2} & \cdots & \cdots & 0 \end{bmatrix} \quad (52)$$

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}}. \quad (53)$$

$$Y_i = \sum_{j=1}^{h} X_{ij}^* - \sum_{j=h+1}^{n} X_{ij}^* \quad (54)$$

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

$$Y_i^* = \sum_{j=1}^{h} W_j X_{ij}^* - \sum_{j=h+1}^{n} W_j X_{ij}^* \tag{55}$$

## Appendix B -Tables

**TABLE A1.** Scales and fuzzy numbers

| Scales for Criteria | Scales for Alternatives | Degrees | Fuzzy Numbers |
|---|---|---|---|
| No (n) | Weakest (w) | 0.40 | $\begin{bmatrix}\sqrt{0.16}e^{j2\pi.0.4},\\ \sqrt{0.10}e^{j2\pi.0.25},\\ \sqrt{0.46}e^{j2\pi.0.22},\\ \sqrt{0.28}e^{j2\pi.0.13}\end{bmatrix}$ |
| some (s) | low (p) | 0.45 | $\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$ |
| normal (m) | normal (f) | 0.50 | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ |
| significant (h) | successful (g) | 0.55 | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ |
| perfect (vh) | wonderful (b) | 0.60 | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ |

**TABLE A2.** Evaluations for the criteria

| **Expert 1** | | | | |
|---|---|---|---|---|
| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
| **Cost** | | M | M | M |
| **Customer** | M | | H | M |
| **Infrastructure** | VH | H | | M |
| **Innovation** | M | M | M | |
| **Expert 2** | | | | |
| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
| **Cost** | | M | H | VH |
| **Customer** | M | | H | M |
| **Infrastructure** | VH | VH | | H |
| **Innovation** | M | M | M | |
| **Expert 3** | | | | |
| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
| **Cost** | | S | M | S |
| **Customer** | M | | H | S |
| **Infrastructure** | VH | H | | S |
| **Innovation** | H | H | VH | |

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

**TABLE A3.** Quantum picture fuzzy numbers for the relation matrix

| Expert 1 | | | | |
|---|---|---|---|---|
| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
| **Cost** | | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ |
| **Customer** | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ |
| **Infrastructure** | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ |
| **Innovation** | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | |
| **Expert 2** | | | | |
| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
| **Cost** | | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ |
| **Customer** | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ |
| **Infrastructure** | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ |
| **Innovation** | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | |
| **Expert 3** | | | | |
| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
| **Cost** | | $\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$ |
| **Customer** | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$ |

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

| | | | | |
|---|---|---|---|---|
| **Infrastructure** | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | | $\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$ |
| **Innovation** | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | |

**TABLE A4.** Quantum picture fuzzy rough sets for the direct relation matrix

| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
|---|---|---|---|---|
| **Cost** | | $\left[\sqrt{0.20},\sqrt{0.25}\right]e^{j2\pi.[0.45,0.50]}$,<br>$\left[\sqrt{0.13},\sqrt{0.15}\right]e^{j2\pi.[0.28,0.31]}$,<br>$\left[\sqrt{0.37},\sqrt{0.42}\right]e^{j2\pi.[0.12,0.17]}$,<br>$\left[\sqrt{0.23},\sqrt{0.25}\right]e^{j2\pi.[0.07,0.10]}$ | $\left[\sqrt{0.25},\sqrt{0.30}\right]e^{j2\pi.[0.50,0.55]}$,<br>$\left[\sqrt{0.15},\sqrt{0.19}\right]e^{j2\pi.[0.31,0.34]}$,<br>$\left[\sqrt{0.32},\sqrt{0.37}\right]e^{j2\pi.[0.07,0.12]}$,<br>$\left[\sqrt{0.19},\sqrt{0.23}\right]e^{j2\pi.[0.04,0.07]}$ | $\left[\sqrt{0.20},\sqrt{0.36}\right]e^{j2\pi.[0.55,0.60]}$,<br>$\left[\sqrt{0.13},\sqrt{0.22}\right]e^{j2\pi.[0.34,0.37]}$,<br>$\left[\sqrt{0.32},\sqrt{0.42}\right]e^{j2\pi.[0.07,0.17]}$,<br>$\left[\sqrt{0.19},\sqrt{0.25}\right]e^{j2\pi.[0.04,0.10]}$ |
| **Customer** | $\left[\sqrt{0.25},\sqrt{0.25}\right]e^{j2\pi.[0.50,0.50]}$,<br>$\left[\sqrt{0.15},\sqrt{0.15}\right]e^{j2\pi.[0.31,0.31]}$,<br>$\left[\sqrt{0.37},\sqrt{0.37}\right]e^{j2\pi.[0.12,0.12]}$,<br>$\left[\sqrt{0.23},\sqrt{0.23}\right]e^{j2\pi.[0.07,0.07]}$ | | $\left[\sqrt{0.30},\sqrt{0.36}\right]e^{j2\pi.[0.55,0.60]}$,<br>$\left[\sqrt{0.19},\sqrt{0.22}\right]e^{j2\pi.[0.34,0.37]}$,<br>$\left[\sqrt{0.26},\sqrt{0.32}\right]e^{j2\pi.[0.02,0.07]}$,<br>$\left[\sqrt{0.16},\sqrt{0.19}\right]e^{j2\pi.[0.01,0.04]}$ | $\left[\sqrt{0.20},\sqrt{0.25}\right]e^{j2\pi.[0.45,0.50]}$,<br>$\left[\sqrt{0.13},\sqrt{0.15}\right]e^{j2\pi.[0.28,0.31]}$,<br>$\left[\sqrt{0.37},\sqrt{0.42}\right]e^{j2\pi.[0.12,0.17]}$,<br>$\left[\sqrt{0.23},\sqrt{0.25}\right]e^{j2\pi.[0.07,0.10]}$ |
| **Infrastructure** | $\left[\sqrt{0.36},\sqrt{0.36}\right]e^{j2\pi.[0.60,0.60]}$,<br>$\left[\sqrt{0.22},\sqrt{0.22}\right]e^{j2\pi.[0.37,0.37]}$,<br>$\left[\sqrt{0.26},\sqrt{0.26}\right]e^{j2\pi.[0.02,0.02]}$,<br>$\left[\sqrt{0.16},\sqrt{0.16}\right]e^{j2\pi.[0.01,0.01]}$ | $\left[\sqrt{0.30},\sqrt{0.36}\right]e^{j2\pi.[0.55,0.60]}$,<br>$\left[\sqrt{0.19},\sqrt{0.22}\right]e^{j2\pi.[0.34,0.37]}$,<br>$\left[\sqrt{0.26},\sqrt{0.32}\right]e^{j2\pi.[0.02,0.07]}$,<br>$\left[\sqrt{0.16},\sqrt{0.19}\right]e^{j2\pi.[0.01,0.04]}$ | | $\left[\sqrt{0.20},\sqrt{0.30}\right]e^{j2\pi.[0.45,0.55]}$,<br>$\left[\sqrt{0.13},\sqrt{0.19}\right]e^{j2\pi.[0.28,0.34]}$,<br>$\left[\sqrt{0.37},\sqrt{0.42}\right]e^{j2\pi.[0.12,0.17]}$,<br>$\left[\sqrt{0.23},\sqrt{0.25}\right]e^{j2\pi.[0.07,0.10]}$ |
| **Innovation** | $\left[\sqrt{0.25},\sqrt{0.30}\right]e^{j2\pi.[0.50,0.55]}$,<br>$\left[\sqrt{0.15},\sqrt{0.19}\right]e^{j2\pi.[0.31,0.34]}$,<br>$\left[\sqrt{0.32},\sqrt{0.37}\right]e^{j2\pi.[0.07,0.12]}$,<br>$\left[\sqrt{0.19},\sqrt{0.23}\right]e^{j2\pi.[0.04,0.07]}$ | $\left[\sqrt{0.25},\sqrt{0.30}\right]e^{j2\pi.[0.50,0.55]}$,<br>$\left[\sqrt{0.15},\sqrt{0.19}\right]e^{j2\pi.[0.31,0.34]}$,<br>$\left[\sqrt{0.32},\sqrt{0.37}\right]e^{j2\pi.[0.07,0.12]}$,<br>$\left[\sqrt{0.19},\sqrt{0.23}\right]e^{j2\pi.[0.04,0.07]}$ | $\left[\sqrt{0.25},\sqrt{0.36}\right]e^{j2\pi.[0.50,0.60]}$,<br>$\left[\sqrt{0.15},\sqrt{0.22}\right]e^{j2\pi.[0.31,0.37]}$,<br>$\left[\sqrt{0.32},\sqrt{0.37}\right]e^{j2\pi.[0.07,0.12]}$,<br>$\left[\sqrt{0.19},\sqrt{0.23}\right]e^{j2\pi.[0.04,0.07]}$ | |

**TABLE A5.** Defuzzified values

| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
|---|---|---|---|---|
| **Cost** | 0.000 | 0.332 | 0.365 | 0.372 |
| **Customer** | 0.346 | 0.000 | 0.381 | 0.332 |
| **Infrastructure** | 0.409 | 0.396 | 0.000 | 0.352 |
| **Innovation** | 0.365 | 0.365 | 0.382 | 0.000 |

**TABLE A6.** Normalized matrix

| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
|---|---|---|---|---|
| **Cost** | 0.000 | 0.311 | 0.341 | 0.348 |
| **Customer** | 0.327 | 0.000 | 0.360 | 0.313 |
| **Infrastructure** | 0.353 | 0.343 | 0.000 | 0.304 |
| **Innovation** | 0.328 | 0.328 | 0.344 | 0.000 |

**TABLE A7.** Sj, kj, qj, and wj values

| **Cost** | **sj** | **Kj** | **qj** | **wj** | **Customer** | **sj** | **kj** | **qj** | **wj** |
|---|---|---|---|---|---|---|---|---|---|
| Innovation | 0.348 | 1.000 | 1.000 | 0.432 | Infrastructure | 0.360 | 1.000 | 1.000 | 0.430 |
| Infrastructure | 0.341 | 1.341 | 0.746 | 0.322 | Cost | 0.327 | 1.327 | 0.754 | 0.324 |
| Customer | 0.311 | 1.311 | 0.569 | 0.246 | Innovation | 0.313 | 1.313 | 0.574 | 0.247 |
| **Infrastructure** | **sj** | **Kj** | **qj** | **wj** | **Innovation** | **sj** | **kj** | **qj** | **wj** |
| Cost | 0.353 | 1.000 | 1.000 | 0.432 | Infrastructure | 0.344 | 1.000 | 1.000 | 0.399 |
| Customer | 0.343 | 1.343 | 0.745 | 0.322 | Cost | 0.328 | 1.328 | 0.753 | 0.300 |
| Innovation | 0.304 | 1.304 | 0.571 | 0.247 | Customer | 0.328 | 1.000 | 0.753 | 0.300 |

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

**TABLE A8. Evaluations for the alternatives**

| Expert 1 | | | | |
|---|---|---|---|---|
| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
| ETMWS | G | G | B | B |
| PTLET | F | B | F | G |
| RTFZC | G | G | B | G |
| SOVFW | B | F | F | G |
| OECTG | G | G | G | F |
| **Expert 2** | | | | |
| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
| ETMWS | G | F | B | F |
| PTLET | F | B | F | G |
| RTFZC | G | B | B | B |
| SOVFW | B | F | F | B |
| OECTG | F | G | F | F |
| **Expert 3** | | | | |
| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
| ETMWS | G | G | B | B |
| PTLET | P | B | P | G |
| RTFZC | G | G | B | G |
| SOVFW | G | P | F | G |
| OECTG | G | G | G | F |

**TABLE A9. Quantum picture fuzzy numbers for the decision matrix**

| **Expert 1** | | | | |
|---|---|---|---|---|
| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
| ETMWS | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ |
| PTLET | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ |
| RTFZC | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ |
| SOVFW | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ |
| OECTG | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ |
| **Expert 2** | | | | |
| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

| | | | | |
|---|---|---|---|---|
| ETMWS | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ |
| PTLET | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ |
| RTFZC | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ |
| SOVFW | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ |
| OECTG | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ |
| **Expert 3** | | | | |
| | **Cost** | **Customer** | **Infrastructure** | **Innovation** |
| ETMWS | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ |
| PTLET | $\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ |
| RTFZC | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ |
| SOVFW | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ |
| OECTG | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$ | $\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$ |

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3374385

**TABLE A10.** Quantum picture fuzzy rough sets for the decision matrix

| | Cost | Customer | Infrastructure | Innovation |
|---|---|---|---|---|
| ETMWS | $\lceil\sqrt{0.30},\sqrt{0.30}\rceil e^{j2\pi.\lceil 0.55,0.55\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.34,0.34\rceil}$, $\lceil\sqrt{0.32},\sqrt{0.32}\rceil e^{j2\pi.\lceil 0.07,0.07\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.04,0.04\rceil}$ | $\lceil\sqrt{0.25},\sqrt{0.30}\rceil e^{j2\pi.\lceil 0.50,0.55\rceil}$, $\lceil\sqrt{0.15},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.31,0.34\rceil}$, $\lceil\sqrt{0.32},\sqrt{0.37}\rceil e^{j2\pi.\lceil 0.07,0.12\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.23}\rceil e^{j2\pi.\lceil 0.04,0.07\rceil}$ | $\lceil\sqrt{0.36},\sqrt{0.36}\rceil e^{j2\pi.\lceil 0.60,0.60\rceil}$, $\lceil\sqrt{0.22},\sqrt{0.22}\rceil e^{j2\pi.\lceil 0.37,0.37\rceil}$, $\lceil\sqrt{0.26},\sqrt{0.26}\rceil e^{j2\pi.\lceil 0.02,0.02\rceil}$, $\lceil\sqrt{0.16},\sqrt{0.16}\rceil e^{j2\pi.\lceil 0.01,0.01\rceil}$ | $\lceil\sqrt{0.25},\sqrt{0.36}\rceil e^{j2\pi.\lceil 0.50,0.60\rceil}$, $\lceil\sqrt{0.15},\sqrt{0.22}\rceil e^{j2\pi.\lceil 0.31,0.37\rceil}$, $\lceil\sqrt{0.32},\sqrt{0.37}\rceil e^{j2\pi.\lceil 0.07,0.12\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.23}\rceil e^{j2\pi.\lceil 0.04,0.07\rceil}$ |
| PTLET | $\lceil\sqrt{0.20},\sqrt{0.25}\rceil e^{j2\pi.\lceil 0.45,0.50\rceil}$, $\lceil\sqrt{0.13},\sqrt{0.15}\rceil e^{j2\pi.\lceil 0.28,0.31\rceil}$, $\lceil\sqrt{0.37},\sqrt{0.42}\rceil e^{j2\pi.\lceil 0.12,0.17\rceil}$, $\lceil\sqrt{0.23},\sqrt{0.25}\rceil e^{j2\pi.\lceil 0.07,0.10\rceil}$ | $\lceil\sqrt{0.36},\sqrt{0.36}\rceil e^{j2\pi.\lceil 0.60,0.60\rceil}$, $\lceil\sqrt{0.22},\sqrt{0.22}\rceil e^{j2\pi.\lceil 0.37,0.37\rceil}$, $\lceil\sqrt{0.26},\sqrt{0.26}\rceil e^{j2\pi.\lceil 0.02,0.02\rceil}$, $\lceil\sqrt{0.16},\sqrt{0.16}\rceil e^{j2\pi.\lceil 0.01,0.01\rceil}$ | $\lceil\sqrt{0.20},\sqrt{0.25}\rceil e^{j2\pi.\lceil 0.45,0.50\rceil}$, $\lceil\sqrt{0.13},\sqrt{0.15}\rceil e^{j2\pi.\lceil 0.28,0.31\rceil}$, $\lceil\sqrt{0.37},\sqrt{0.42}\rceil e^{j2\pi.\lceil 0.12,0.17\rceil}$, $\lceil\sqrt{0.23},\sqrt{0.25}\rceil e^{j2\pi.\lceil 0.07,0.10\rceil}$ | $\lceil\sqrt{0.30},\sqrt{0.30}\rceil e^{j2\pi.\lceil 0.55,0.55\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.34,0.34\rceil}$, $\lceil\sqrt{0.32},\sqrt{0.32}\rceil e^{j2\pi.\lceil 0.07,0.07\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.04,0.04\rceil}$ |
| RTFZC | $\lceil\sqrt{0.30},\sqrt{0.30}\rceil e^{j2\pi.\lceil 0.55,0.55\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.34,0.34\rceil}$, $\lceil\sqrt{0.32},\sqrt{0.32}\rceil e^{j2\pi.\lceil 0.07,0.07\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.04,0.04\rceil}$ | $\lceil\sqrt{0.30},\sqrt{0.36}\rceil e^{j2\pi.\lceil 0.55,0.60\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.22}\rceil e^{j2\pi.\lceil 0.34,0.37\rceil}$, $\lceil\sqrt{0.26},\sqrt{0.32}\rceil e^{j2\pi.\lceil 0.02,0.07\rceil}$, $\lceil\sqrt{0.16},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.01,0.04\rceil}$ | $\lceil\sqrt{0.36},\sqrt{0.36}\rceil e^{j2\pi.\lceil 0.60,0.60\rceil}$, $\lceil\sqrt{0.22},\sqrt{0.22}\rceil e^{j2\pi.\lceil 0.37,0.37\rceil}$, $\lceil\sqrt{0.26},\sqrt{0.26}\rceil e^{j2\pi.\lceil 0.02,0.02\rceil}$, $\lceil\sqrt{0.16},\sqrt{0.16}\rceil e^{j2\pi.\lceil 0.01,0.01\rceil}$ | $\lceil\sqrt{0.30},\sqrt{0.36}\rceil e^{j2\pi.\lceil 0.55,0.60\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.22}\rceil e^{j2\pi.\lceil 0.34,0.37\rceil}$, $\lceil\sqrt{0.26},\sqrt{0.32}\rceil e^{j2\pi.\lceil 0.02,0.07\rceil}$, $\lceil\sqrt{0.16},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.01,0.04\rceil}$ |
| SOVFW | $\lceil\sqrt{0.30},\sqrt{0.36}\rceil e^{j2\pi.\lceil 0.55,0.60\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.22}\rceil e^{j2\pi.\lceil 0.34,0.37\rceil}$, $\lceil\sqrt{0.26},\sqrt{0.32}\rceil e^{j2\pi.\lceil 0.02,0.07\rceil}$, $\lceil\sqrt{0.16},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.01,0.04\rceil}$ | $\lceil\sqrt{0.20},\sqrt{0.25}\rceil e^{j2\pi.\lceil 0.45,0.50\rceil}$, $\lceil\sqrt{0.13},\sqrt{0.15}\rceil e^{j2\pi.\lceil 0.28,0.31\rceil}$, $\lceil\sqrt{0.37},\sqrt{0.42}\rceil e^{j2\pi.\lceil 0.12,0.17\rceil}$, $\lceil\sqrt{0.23},\sqrt{0.25}\rceil e^{j2\pi.\lceil 0.07,0.10\rceil}$ | $\lceil\sqrt{0.25},\sqrt{0.25}\rceil e^{j2\pi.\lceil 0.50,0.50\rceil}$, $\lceil\sqrt{0.15},\sqrt{0.15}\rceil e^{j2\pi.\lceil 0.31,0.31\rceil}$, $\lceil\sqrt{0.37},\sqrt{0.37}\rceil e^{j2\pi.\lceil 0.12,0.12\rceil}$, $\lceil\sqrt{0.23},\sqrt{0.23}\rceil e^{j2\pi.\lceil 0.07,0.07\rceil}$ | $\lceil\sqrt{0.30},\sqrt{0.36}\rceil e^{j2\pi.\lceil 0.55,0.60\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.22}\rceil e^{j2\pi.\lceil 0.34,0.37\rceil}$, $\lceil\sqrt{0.26},\sqrt{0.32}\rceil e^{j2\pi.\lceil 0.02,0.07\rceil}$, $\lceil\sqrt{0.16},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.01,0.04\rceil}$ |
| OECTG | $\lceil\sqrt{0.25},\sqrt{0.30}\rceil e^{j2\pi.\lceil 0.50,0.55\rceil}$, $\lceil\sqrt{0.15},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.31,0.34\rceil}$, $\lceil\sqrt{0.32},\sqrt{0.37}\rceil e^{j2\pi.\lceil 0.07,0.12\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.23}\rceil e^{j2\pi.\lceil 0.04,0.07\rceil}$ | $\lceil\sqrt{0.30},\sqrt{0.30}\rceil e^{j2\pi.\lceil 0.55,0.55\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.34,0.34\rceil}$, $\lceil\sqrt{0.32},\sqrt{0.32}\rceil e^{j2\pi.\lceil 0.07,0.07\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.04,0.04\rceil}$ | $\lceil\sqrt{0.25},\sqrt{0.30}\rceil e^{j2\pi.\lceil 0.50,0.55\rceil}$, $\lceil\sqrt{0.15},\sqrt{0.19}\rceil e^{j2\pi.\lceil 0.31,0.34\rceil}$, $\lceil\sqrt{0.32},\sqrt{0.37}\rceil e^{j2\pi.\lceil 0.07,0.12\rceil}$, $\lceil\sqrt{0.19},\sqrt{0.23}\rceil e^{j2\pi.\lceil 0.04,0.07\rceil}$ | $\lceil\sqrt{0.25},\sqrt{0.25}\rceil e^{j2\pi.\lceil 0.50,0.50\rceil}$, $\lceil\sqrt{0.15},\sqrt{0.15}\rceil e^{j2\pi.\lceil 0.31,0.31\rceil}$, $\lceil\sqrt{0.37},\sqrt{0.37}\rceil e^{j2\pi.\lceil 0.12,0.12\rceil}$, $\lceil\sqrt{0.23},\sqrt{0.23}\rceil e^{j2\pi.\lceil 0.07,0.07\rceil}$ |

**TABLE A11.** Defuzzified values

| | Cost | Customer | Infrastructure | Innovation |
|---|---|---|---|---|
| ETMWS | 0.381 | 0.365 | 0.409 | 0.382 |
| PTLET | 0.332 | 0.409 | 0.332 | 0.381 |
| RTFZC | 0.381 | 0.396 | 0.409 | 0.396 |
| SOVFW | 0.396 | 0.332 | 0.346 | 0.396 |
| OECTG | 0.365 | 0.381 | 0.365 | 0.346 |

**TABLE A12.** Normalized values

| | Cost | Customer | Infrastructure | Innovation |
|---|---|---|---|---|
| ETMWS | 0.459 | 0.432 | 0.489 | 0.448 |
| PTLET | 0.399 | 0.484 | 0.398 | 0.448 |
| RTFZC | 0.459 | 0.470 | 0.489 | 0.465 |
| SOVFW | 0.477 | 0.393 | 0.415 | 0.465 |
| OECTG | 0.439 | 0.452 | 0.437 | 0.407 |

This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. For more information, see https://creativecommons.org/licenses/by-nc-nd/4