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ASSESSMENT OF THE QUALITY INSPECTORS FOR THE RAILWAY MANUFACTURING INDUSTRY IN INTERVAL-VALUED Q-RUNG ORTHOPAIR FUZZY ENVIRONMENT

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Abstract. *Selecting an independent quality control, test, and inspection firm (IQCTIF) as a strategic partner in railway wagons and locomotive manufacturing is critical for safety, compliance, and efficiency, as errors can lead to accidents, high maintenance costs, and reputational damage. Recent railway accidents in Germany, Spain, China, and Turkey highlight the risks of inadequate quality control. To mitigate these risks, multi-criteria decision-making (MCDM) approaches help balance security tests, certifications, cost, impartiality, and technological infrastructure. Despite its importance, optimizing these processes through outsourcing remains an underexplored research area. This study proposes an IVq-ROFS-based CRITIC-WASPAS model to identify the most suitable strategic partners in railway manufacturing. The proposed model was preferred in this study due to its advantages, such as having an extremely flexible structure, providing results at a high level of accuracy, and allowing effective and successful management of uncertainties. According to the results, "Railway Certifications" (C2) is the most critical criterion, and TÜV SÜD is the most suitable partner for the railway manufacturing industry. A comprehensive robustness check confirmed the model's reliability.*

Key words: *Railway manufacturing industry, Independent audit & quality control, test, and inspection firm (IQCTIF), CRITIC, WASPAS, Interval-Valued Q-Rung Orthopair Fuzzy Set*

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1. INTRODUCTION

Failures in railway vehicle manufacturing quality control processes have recently caused fatal accidents, injuries, financial losses, and damage to trust and reputation. In 1998, 101 people were killed, and 88 passengers were injured because of a high-speed train derailment in Germany [1]. Post-accident investigations showed that factors such as defects in the materials used in the production of the high-speed train (such as metal fatigue) [2] and poor management of quality control processes were primarily responsible for the accident.

The Wenzhou train accident in China in 2011 resulted in the death of more than 40 people due to a lack of quality control in the signaling system [3]. Official reports on this accident have cited serious design flaws and a lack of supervision and control as the main culprits [4]. Then, in the train accident that occurred in Spain in 2013, in which eighty people lost their lives [5], the railway authority claimed that the fault was with the train personnel, while technical reports cited inadequate testing of the brake systems as the most crucial cause of the accident [6]. Recently, railway accidents have occurred in some rail system projects in Turkey due to a lack of certification, resulting in significant losses [7].

While collision-type accidents in railway transportation generally occur due to human errors, the factors that cause derailment can be listed as deterioration in the wheels of the railway vehicle, deterioration on the rail surface, deterioration of the track geometry, etc. [8]. Therefore, derailment-type accidents are caused mainly by systemic problems. Cannon et al. [9] highlighted that the real cause of such accidents is improperly structured quality control and monitoring systems for rolling stock. According to the statistical data published by UIC, considering the accidents that occurred only in Turkey, more than three times as many derailment-type accidents took place as collision-type accidents.

A well-structured quality control and monitoring system enables the production of reliable locomotives and components that fully comply with international standards. This situation is critical in reducing risks and accidents in railway transportation and creating a safe, reliable, comfortable, and efficient transportation system [10]. The integration of preventive maintenance and production planning, particularly within the framework of Industry 4.0 and smart manufacturing, has been shown to significantly improve production efficiency and reduce operational disruptions, as emphasized by Babaeimorad et al. [11].

In this direction, accidents and externalities caused by production processes that do not comply with the standards, regulations, and certifications determined by international railway authorities or cannot meet the requirements specified in these regulations, and the defects of the wagons, locomotives, and bogies produced cause severe economic losses in addition to loss of trust and reputation in the eyes of all stakeholders of the industry [12]. A properly configured quality control and assurance system improves supply chain efficiency and effectiveness in the rolling stock manufacturing industries [13], optimizing the waste of materials used in production and maintenance and repair costs [14].

However, quality control, monitoring, auditing, and sustainability practices have expanded international and national legal regulations regarding the number and content. In this context, they have become more complex and sophisticated due to international organizations' and governments' increasing sanctions and pressures on safety, security, and sustainability [15]. In addition to the railway industry, it has become almost impossible for the departments and units to be established within the enterprise to undertake the responsibilities regarding these applications in nearly every sector and successfully manage these processes [16].

Therefore, manufacturers must meet these requirements, especially in the railway sector, through outsourcing and strategic partnerships with professional quality service providers [17]. In this context, selecting a strategic partner for quality control and process management of production enterprises in the railway industry is a critical and strategic decision regarding railway transportation safety, security, and sustainability [18]. This methodical technique improves motor selection and can be used as a template for similar assessments in other technical contexts, including strategic partner evaluation and process optimization in highly regulated industries [19].

On the other hand, it may be more rational to outsource these services to internationally professionalized sources, providing them with higher quality, more convenient, and continuous access [20]. First, professional organizations continuously and in real-time follow international standards related to quality control, sustainability, and safety associated with rolling stock production. They have deep and extensive expertise in this field. Accordingly, manufacturers adapt more quickly to changing and differentiating regulations in different markets [21] while increasing their competitiveness tremendously.

A professional IQCTIF conducts objective evaluations and identifies issues impartially, thanks to its independence [22]. In addition, professional businesses also have relationships with different industries and provide services for these industries as well. Accordingly, it can also use other industry experiences and practices for companies that are railway vehicle manufacturers, thus providing critical advantages.

In addition to the accelerating development of technology, the diversification and complexity of legal regulations have incredibly complicated the quality control and inspection processes, and accordingly, it has become challenging for production enterprises to produce these services by establishing departments within their bodies [23]. Considering the costs to be incurred for the establishment of the department in the first place, the employment of expert personnel to work in these departments and the costs of continuing education for these specialists, the provision of technologically advanced and highly sophisticated equipment and tools used in quality control processes, as well as the costs to carry out certification processes, such an approach can lead to excessively high and unbearable expenses [24]. On the other hand, professional businesses only demand payment from production enterprises for the services they provide, as they cover installation costs, etc. Therefore, production enterprises can provide higher-quality control and inspection services at very reasonable costs.

In addition, professional independent quality control, test, and inspection firms (IQCTIFs) produce and complete these services quickly and effectively as they standardize and simplify their quality control and inspection activities with the advantage of the experience they have gained over many years [25]. In the railway production industry, enterprises can obtain a significant competitive advantage by supplying their products to the market more easily and quickly, depending on the inspection processes that are completed quickly. Therefore, the services produced by such enterprises also increase the trust and reputation of the manufacturer regarding the products they make at an extraordinary level. More importantly, professional organizations produce more precise, detailed, and high-quality testing services by continuously investing in advanced technologies required for tests and inspections, as they have determined quality control and inspection activities as their main activities [26]. Establishing in-house infrastructure is costly, and equipment may quickly become outdated.

Regarding production enterprises, selecting the appropriate quality control and inspection company involves critical challenges and risks. Focusing solely on selecting IQCTIFs based on economic criteria and determining the most suitable option through static assessment models often reflects a tendency to address the short-term needs of businesses. For instance, practitioners may base their choices on subjective assessments and prioritize a criterion of limited relevance for longstanding objectives. Thereby, they risk overlooking critical factors and key criteria for sustainable success. Such an approach significantly hinders manufacturing enterprises from effectively achieving their long-term strategic goals.

The lack of a structured roadmap for selecting IQCTIFs can lead to critical challenges in modeling and managing existing and potential risks associated with the selection process. Failing to evaluate audit firms based on essential factors identified within a strategic framework increases the likelihood of making deficient choices. Such missteps can significantly increase the business's operational, financial, and reputational risks and have long-term consequences.

Evaluating IQCTIFs without a structured roadmap poses serious challenges and risks. Such an approach may expose businesses to inconsistency and indecisiveness in decision-making processes. Additionally, decisions made without a well-structured framework are prone to subjective biases, which can undermine the credibility and reliability of the outcomes. Moreover, this lack of transparency can tarnish the company's reputation among stakeholders, significantly erasing trust and credibility. This inefficiency can lead to wasted time and other resources that decision-makers could have utilized more effectively. Consequently, such mismanagement results in substantial time and labor losses and imposes significant financial costs on the organization.

In addition, determining whether stakeholders should outsource activities related to appropriate quality control and process management for production enterprises is a decision-making problem that is affected by highly complex uncertainties and needs to be balanced by considering contradictory criteria. Similarly, the presence of diverse and distinct service features in various application domains — such as e-services of brokerage firms — has resulted in multi-criteria decision-making dilemmas for users, as emphasized by Jana et al. [27]. Moreover, when addressing this decision-making problem, linear and nonlinear interactions and relationships between criteria also need to be considered. For example, C4 (Technological infrastructure and equipment) directly affects C3 (Safety testing capability). The development of technological infrastructure increases the accuracy of security tests. Likewise, there can be a nonlinear relationship between C7 (Cost and pricing) and C8 (Service timeliness and flexibility). Services with higher costs can often be faster, but after a certain level of cost, the increase in speed may become limited. In this context, IVq-ROF clusters precisely reflect nonlinear threshold effects and complex interactions by defining membership, anti-membership, and degrees of uncertainty over a wide range. Thanks to its capacity to manage ambiguities, it can analyze linear and nonlinear dependencies between criteria flexibly and dynamically. Hence, it produces more accurate and reliable results in multi-criteria decision-making processes.

In this context, selecting the most appropriate stakeholder requires using a robust, consistent, and reliable decision-making tool extended based on an advanced fuzzy set to model and manage uncertainties at a perfect level. At the same time, this model should handle the interactions between the selection criteria and be able to perform multidimensional and comprehensive analysis.

According to the authors' knowledge, no study has focused on selecting quality control and process management companies using multi-criteria decision-making approaches in the relevant literature. In recent literature, hybrid MCDM models that combine weight determination and ranking phases, such as the DIBR II–Rough MABAC method, have proven effective in evaluating organizational and technical strategies under uncertain and resource-constrained environments [28]. Generally, researchers have focused on issues such as inspection procedures in production processes [29], inspection and quality costs in the manufacturing sector, and the effects of quality management practices on performance and competitive advantage [30]. In conclusion, even though the selection of IQCTIF is a significant and critical research problem, it is an issue that has been largely neglected and ignored by members of the research community.

Accordingly, considering the above requirements and critical research gaps, this study aimed to develop and recommend a reliable, robust, and consistent decision-making tool for decision-makers of all manufacturing enterprises, especially the railway vehicle manufacturing industry. This proposed decision-making framework should also include an advanced fuzzy set to manage uncertainties effectively.

Following these requirements, this study developed an interval-valued q-ROF (q-Rung Orthopair Fuzzy) set based on CRiteria Importance Through Intercriteria Correlation (CRITIC) developed by Diakoulaki et al. [31] and Weighted Aggregated Sum Product Assessment (WASPAS) approaches introduced by Zavadskas et al. [32] to address this decision-making problem. Cronbach's alpha was calculated to verify the validity and relevance of the selected criteria, ensuring that the evaluation was based on relevant and influential factors. In this context, each of the nine experts was asked 14 questions to evaluate the criteria, and for each question, the experts were asked to rate between 1 and 10. Here, the total variance was calculated as 21.6944, while the variance value of the total scores was determined as 91.5. Then, using the formulation of the Cronbach alpha technique, the Cronbach alpha value was calculated as 0.82159. When the results are between 0.80 and 1.00, they are highly reliable [33]. The subjective weight coefficients derived from the mathematical framework of the fuzzy set were combined with the weights obtained by the CRITIC method. A range-valued q-ROF-based WASPAS method was used to rank and prioritize strategy alternatives.

The suggested model has a practical and straightforward procedure that allows practitioners to employ it effectively without requiring advanced mathematical knowledge. It is also highly trustworthy and robust for modeling ambiguities, structuring decision issues, and delivering consistent and dependable conclusions. These features make the model well-suited for applications that require precision and adaptability in complex decision-making scenarios.

The proposed model has identified ten alternatives and fourteen evaluation criteria for selecting an IQCTIF. The findings show that risk management practices emerged as the most critical and practical criterion, while the Independence and Impartiality Strategy was determined as the most appropriate strategic approach. The contributions of this study are essential and multifaceted. First, the integrated model proposed in this research improves the decision-making processes of enterprises by providing a more structured and practical framework for selecting IQCTIFs.

Furthermore, the versatile model can be adapted to address similar decision-making challenges in other industries, demonstrating its broader applicability. Furthermore, the proposed model provides a well-structured, effective, and reliable strategy-based framework, ensuring that resources are appropriately allocated and that evaluation processes are carried out systematically. It supports better decision-making and improves organizations' strategic alignment and operational efficiency.

In addition, the IVq-ROF-based Subjective & CRITIC & WASPAS integrated model proposed in the study has not been used in the relevant literature before, but has been developed for the first time to solve the decision problem addressed in this study. As such, it represents a comprehensive hybrid decision-making approach that is rare in the available literature.

This study has some critical managerial and political implications. Considering the findings and conclusions obtained in this study, decision-makers can strategically structure their decision-making processes rationally and systematically, especially regarding the selection of IQCTIFs. In addition, the study provides a comprehensive roadmap for decision-makers, emphasizing the need to focus on sustainable growth and long-term alliances, not just short-term operational goals. In addition, the results obtained in the study can further increase the trust environment in the sector by making the evaluation processes more transparent based on business models and determined strategies.

First, it underlines the need for businesses to adopt a more holistic framework for their decision-making processes while at the same time identifying the critical and practical criteria that affect the choice of IQCTIF and ensuring that the decision-making problem is structured more accurately and appropriately.

Given the identified research gap and objectives, this study aims to address the following key research questions: RQ1. What are the most critical evaluation strategies for selecting IQCTIFs in an Interval-Valued Q-Rung Orthopair Fuzzy (IVq-ROF) environment? RQ2. How do the CRITIC and WASPAS methods improve decision-making when selecting IQCTIFs? RQ3. How does the proposed model compare to other MCDM approaches regarding robustness, reliability, and accuracy?

After a comprehensive introduction, the rest of the study is structured as follows. Part 2 presents the results of a detailed literature review. Chapter 3 introduces the proposed integrated decision-making model and illustrates the implementation steps and mathematical operations. Chapter 4 describes the implications of the proposed decision-making model for addressing and resolving the decision-making problem related to evaluating and prioritizing IQCTIFs' choices. Chapter 5 summarizes and discusses the results obtained. Chapter 6 concludes the study and shows the limitations of the study and research guidelines for future studies.

2. Suggested Framework

This section outlines the mathematical formulation and implementation steps of the proposed IVq-ROFNs-based decision-making model. The model was chosen to identify strategies for IQCTIF selection, the core of the decision-making problem, and was designed to address certain structural limitations. The following subsections present the proposed approach's structural features, fundamental algorithms, and step-by-step implementation.

2.1 Preliminary Information about the IVq-ROFNs

Yager [34] introduced q-ROFSs, defined by the pair (q, ν), to manage complex uncertainties in decision-making. However, due to structural limitations, they may not fully capture or process uncertainties [35]. To overcome these issues, Joshi et al. [36] proposed

IVq-ROFSs as an improved version. Their flexible structure offers a broader and more accurate approach to handling uncertainty. The following section introduces the basics of IVq-ROFSs and their primary algebraic operations. A q-ROFS on the universal set *X* is given below [35]:

$$\varsigma_F(x) \in [0,1], \upsilon_F(x) \in [0,1], 0 \le \varsigma_F(x)^q + \upsilon_F(x)^q \le 1 \quad (1)$$

$$F = \left\{ \left\langle x, \left(\varsigma_F(x)^q\right), \left(\upsilon_F(x)^q\right) \right\rangle | x \in X \right\} \quad (2)$$

Here, $\varsigma_F(x)$ is the membership degree and $\upsilon_F(x)$ depicts the non-membership degree of $x \in X$. On the other hand, the degree of indeterminacy is calculated as:

$$\pi_F \le \sqrt[q]{1 - \varsigma_F(x)^q - \upsilon_F(x)^q} \quad (3)$$

An IV-q-ROFS on the universal set *X* is signified below [34, 35]:

$$\left[\varsigma_H^L(x), \varsigma_H^U(x)\right] \in [0,1], \left[\upsilon_H^L(x), \upsilon_H^U(x)\right] \in [0,1], 0 \le \left(\left(\varsigma_H^U(x)\right)^q + \left(\upsilon_H^U(x)\right)^q\right) \le 1 \quad (4)$$

$$H = \left\{ \left\langle x, \left[\varsigma_H^L(x)^q, \varsigma_H^U(x)^q\right], \left[\upsilon_H^L(x)^q, \upsilon_H^U(x)^q\right] \right\rangle | x \in X \right\} \quad (5)$$

In Eq. (5), the membership degree's lower and upper bound's lower and upper bounds of the non-membership degree are exhibited, respectively. Moreover, the indeterminacy membership degree is defined as follows:

$$\pi_F = \left[\pi_H^L(x), \pi_H^U(x)\right] = \left[\sqrt[q]{1 - \varsigma_H^U(x)^q - \upsilon_H^U(x)^q}, \sqrt[q]{1 - \varsigma_H^L(x)^q - \upsilon_H^L(x)^q}\right] \quad (6)$$

The IV-q-ROF number (IV-q-ROFN) can be written as $\varphi = ([\alpha, \beta], [\gamma, \delta])$ for simplicity. Moreover, the conditions given below are satisfied [34].

$$[\alpha, \beta] \in [0,1], [\gamma, \delta] \in [0,1], 0 \le \beta^q + \delta^q \le 1 \quad (7)$$

Let $\varphi_1 = ([\alpha_1, \beta_1], [\gamma_1, \delta_1])$ and $\varphi_2 = ([\alpha_2, \beta_2], [\gamma_2, \delta_2])$ be two IV-q-ROFNs. Next, some operations, score, and accuracy functions on IV-q-ROFSs are outlined below: $\zeta > 0$, $q \ge 1$ [34–36].

$$\varphi_1 \oplus \varphi_2 = \left(\left[\sqrt[q]{(\alpha_1)^q - (\alpha_2)^q - (\alpha_1)^q(\alpha_2)^q}, \sqrt[q]{(\beta_1)^q - (\beta_{22})^q - (\beta_{21})^q(\beta_{22})^q}\right], [\gamma_1\gamma_2, \delta_1\delta_2]\right) \quad (8)$$

$$\varphi_1 \otimes \varphi_2 = [\alpha_1\alpha_2, \beta_1\beta_2], \left(\left[\sqrt[q]{(\gamma_1)^q - (\gamma_2)^q - (\gamma_1)^q(\gamma_2)^q}, \sqrt[q]{(\delta_1)^q - (\delta_2)^q - (\delta_1)^q(\delta_2)^q}\right]\right) \quad (9)$$

$$\xi\varphi_1 = \left(\left[\sqrt[q]{1 - \left(1 - (\alpha_1)^q\right)^\xi}, \sqrt[q]{1 - \left(1 - (\beta_1)^q\right)^\xi}\right], \left[(\gamma_1)^\xi, (\delta_1)^\xi\right]\right) \quad (10)$$

$$\varphi_1^{\xi} = \left(\left[(\alpha_1)^{\xi}, (\beta_1)^{\xi} \right], \left[\sqrt[q]{1-\left(1-(\gamma_1)^q\right)^{\xi}}, \sqrt[q]{1-\left(1-(\delta_1)^q\right)^{\xi}} \right] \right), \lambda \geq 0, \tag{11}$$

$$(\varphi_1)^c = \left([\gamma_1, \delta_1], [\alpha_1, \beta_1] \right), \tag{12}$$

$$S(\varphi_1) = \frac{1+(\alpha_1)^q - (\gamma_1)^q + 1 + (\beta_1)^q - (\delta_1)^q}{4}; S(\varphi_1) \in [0,1] \tag{13}$$

$$A(\varphi_1) = \frac{(\alpha_1)^q + (\beta_1)^q (\gamma_1)^q + (\delta_1)^q}{2}; A(\varphi_1) \in [0,2] \tag{14}$$

The IVq-ROF Weighted Arithmetic Average (IVq-ROFWAA) operator is denoted below: Here, $\varphi_i = \varphi_1, \varphi_2, \ldots, \varphi_m$, $0 \leq \zeta_i \leq 1$. The sum of ζ_i should be equal to 1.

$$IVq-ROFWAA(\varphi_1, \varphi_2, \ldots \varphi_m) = \left(\left[\sqrt[q]{1-\prod_{i=1}^{m}\left(1-(\alpha_1)^q\right)^{\xi_i}}, \sqrt[q]{1-\prod_{i=1}^{m}\left(1-(\beta_1)^q\right)^{\xi_i}} \right] \left[\prod_{i=1}^{m}(\gamma_1)^{\xi_i}, \prod_{i=1}^{m}(\delta_1)^{\xi_i}, \right] \right) \tag{15}$$

The IVq-ROF Weighted Geometric Average (IVq-ROFWGA) operator is described below: Here, $\varphi_i = \varphi_1, \varphi_2, \ldots, \varphi_m$, $0 \leq \zeta_i \leq 1$. The sum of ζ_i should equal 1 [34, 35].

$$IVq-ROFWGA(\varphi_1, \varphi_2, \ldots \varphi_m) = \left(\left[\prod_{i=1}^{m}(\alpha_1)^{\xi_i}, \prod_{i=1}^{m}(\beta_1)^{\xi_i} \right], \left[\sqrt[q]{1-\prod_{i=1}^{m}\left(1-(\gamma_1)^q\right)^{\xi_i}}, \sqrt[q]{1-\prod_{i=1}^{m}\left(1-(\delta_1)^q\right)^{\xi_i}} \right] \right) \tag{16}$$

Eq. (17) gives the Minkowski distance between φ_1 and φ_2 are indeterminacy membership degrees of φ_1 and φ_2, respectively [34-36]:

$$M_p(\varphi_1, \varphi_2) = \left(\frac{1}{4} \left| (\alpha_1)^q - (\alpha_2)^q \right|^p + \left| (\beta_1)^q - (\beta_2)^q \right|^p + \left| (\gamma_1)^q - (\gamma_2)^q \right|^p + \left| (\delta_1)^q - (\delta_2)^q \right|^p + \left| (\pi_1^L)^q - (\pi_2^L)^q \right|^p + \left| (\pi_1^U)^q - (\pi_2^U)^q \right|^p \right)^{1/p} \tag{17}$$

When p =1, Eq. (17) is employed to compute the Hamming distance, while with p =2, it determines the Euclidean distance.

2.2 Identifying the Experts' Reputations

At this stage, each expert's weight values (reputation) are calculated by considering various characteristics of the experts, such as age, title, industry in which the expert works, field of expertise, graduation degree, graduated department, and industry experience of the participant. It is recommended that professionals with higher expertise and knowledge, like the esteemed members of our audience, evaluate the experts proposed by the researchers to obtain more logical and rational results in this study.

Step 1: Evaluation of the characteristics of the experts: To include the knowledge, experience, and other characteristics of the members of the expert committee that are expected to affect the results, the determined professionals evaluate each feature of the experts as well as the impact of these characteristics separately for each expert. For this, the linguistic assessment scale given in Table 1 is used.

Table 1 The linguistic appraisal scale for IVq-ROFNs

System	Abbr.	μL	μU	vL	vU	System	Abbr.	μL	μU	vL	vU
Extremely Low	EL	0.05	0.1	0.85	0.9	Medium-high	MH	0.55	0.65	0.3	0.35
Very low	VL	0.1	0.2	0.7	0.75	High	H	0.65	0.75	0.2	0.25
Low	L	0.2	0.3	0.55	0.65	Very high	VH	0.75	0.8	0.15	0.2
Medium-low	ML	0.3	0.4	0.45	0.55	Very very high	VVH	0.8	0.85	0.1	0.15
Medium	M	0.45	0.55	0.35	0.4	Extremely high	EH	0.85	0.9	0.05	0.1

Step 2: Conversion of assessments into IVq-ROF numbers: Researchers convert linguistic assessments of traits and experts into numerical equivalents corresponding to Table 1 in the second round. Then, matrices for characteristics and specialists are prepared.

Step-3: Aggregating the IVq-ROF numbers for the assessments and calculating the score values and weights: With the help of Eq. (15), first, the IVq-ROF number values are combined in matrices for the features, and then the score values are calculated using Eq. (13) for each feature. Then, with the help of Eq. (18), the final weight values of the features are calculated. The same operations are carried out to determine the characteristics of specialists. In the process of combining IVq-ROF numbers, the relative weight coefficients of the features are included in the calculations.

$$\lambda_k = \frac{S\left(Q_{kg}\right) x\ w_g}{\sum_{g=1}^{z} S\left(Q_{kg}\right) x\ w_g} \tag{18}$$

2.3 IVq-ROF-Subjective & CRITIC & WASPAS

This chapter shows the mathematical notion of the extended form of the hybrid model consisting of a combination of Subjective & CRITIC, and WASPAS methods with the help of IVq-ROFNs and the basic implementation steps. In the first stage, subjective weights of the criteria are identified with the help of the structure of the IVq-ROFNs.

Step-4: Identify the subjective weights of the criteria: At this stage, it uses the mathematical notion of IVq-ROF sets to evaluate the weight values and impact levels of the criteria that affect IQCTIF selection. Below are the implementation steps for this.

Step-4.1: Perform the linguistic evaluations for the criteria by the experts: In this step, each expert considers the criteria individually and evaluates them separately, considering the linguistic evaluation scale given in Table 1. The researchers then collect these assessments to create linguistic matrices converted into the corresponding q-ROF numbers on the rating scale.

Step-4.2: Aggregating the experts' evaluations: After the linguistic assessments are converted into q-ROF numbers, the researchers combine these numbers using Eq. (10).

Step-4.3: Calculation of score function values of criteria: Eq. (13) is used to determine the score function values of the criteria. Afterward, the final subjective weights of the criteria are identified with the help of Eq. (19).

$$w_j^{Sub} = \frac{\varphi_j^{Sub} x \lambda_k}{\sum_{j=1}^{n} \varphi_j^{Sub} x \lambda_k} \tag{19}$$

Step-5: Assessment of the alternatives by the experts: In this process, r number of experts evaluate m number of alternatives, considering n number of criteria. While making these assessments, experts consider the linguistic assessment scale shown in Table 1. Next, the linguistics appraisals are converted to the IVq-ROFNs corresponding to the linguistics scale, and the initial IVq-ROF matrices involving IVq-ROFNs are formed. After the linguistic evaluations are completed, the initial IVq-ROF decision matrices $X^{(k)}$ including matrix elements as follows:

$$x_{ij}^{k} = \left(\left[\alpha_{ij}^{(k)}, \beta_{ij}^{(k)} \right], \left[\gamma_{ij}^{(k)}, \delta_{ij}^{(k)} \right] \right) \tag{20}$$

Step 6: Aggregation of the IVq-ROF matrices: In this step, the researchers aggregate these matrices with the help of Eq. (15), generating the initial IVq-ROF decision matrix. In this process, the reputation degrees of the experts are considered when implementing Eq. (15).

Step 7: Computation of the score function values of the alternatives: In this step, the score function of the ith alternative, considering the jth criterion**,** is computed with the help of Eq. (13), and the score matrix is constructed.

Step 8: Criterion weighting with the IVq-ROF-CRITIC approach: In this step, the application steps of the CRITIC method [28] are followed. The score matrix determined in the previous steps is the initial decision matrix when applying the CRITIC method.

Step-8.1: Normalization of the elements of the initial decision-making matrix: In this step, the initial decision matrix elements are normalized by employing Eq. (21). Then, the normalized matrix is constructed [35].

$$r_{ij} = \begin{cases} \dfrac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})}; x_{ij} \in C \\ \dfrac{max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})}; x_{ij} \in B \end{cases} \tag{21}$$

Here, C denotes the cost criteria and B denotes the benefit criteria. Besides, r_{ij} denotes normalized values, and $min(x_{ij})$ is the minimum value of j^{th} criterion concerning alternatives, $max(x_{ij})$ is the maximum value of j^{th} criterion concerning alternatives.

Step-8.2: Calculate the correlation and sum of information for each criterion: The researchers compute correlation coefficients between each criterion pair in the normalized matrix. For this purpose, standard deviations for each criterion are calculated with the help of Eq. (22).

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{r} \left(r_{ij} - \bar{r}_{ij} \right)^2}{n}} \tag{22}$$

Here, r_{ij} is computed as $\sum r_{ij}/n$.

Next, each criterion's sum of information (K_j) is identified by employing Eq. (23).

$$K_j = \sigma_j \sum_{k=1}^{n} \left(1-\tau_{jk}\right);\ j = 1,2,...,n \tag{23}$$

***Step-8.3*:** Identification of the final weights of the criteria: In the final step of the procedure, the weight coefficients of the criteria are calculated using Eq. (24). Next, the criteria are sorted considering their relative weight coefficients.

$$w_j^{Obj} = \frac{K_j}{\sum_{k=1}^{n} K_j} \tag{24}$$

Step 9: Combine the subjective and objective weights: In this step, the criteria's subjective and objective weight values are combined with the help of the β coefficient. It takes a value between 0 and 1. Both weight coefficients are combined, as follows:

$$w_j = \beta . w_j^{Sub} + \left(1-\beta\right) . w_j^{Obj} \tag{25}$$

Step 10: Ranking the performance of alternatives: The IVq-ROF-based WASPAS method was used to compute and rank the relative importance of each alternative. The following outlines the method's application steps and calculation procedure.

***Step-10.1*:** Construction of the initial decision matrix: Like the CRITIC approach, the same initial decision matrix (score matrix) is used. Therefore, to avoid duplication, the operations in the CRITIC method's first step are again not shown at this stage.

***Step-10.2*:** Normalization of the initial decision matrix elements: In the second step, the matrix elements are normalized by employing Eq. (26), generating the normalized matrix.

$$\rho_{ij} = \begin{cases} \dfrac{x_{ij}}{max\left(x_{ij}\right)};\ x_{ij} \in B \\ \dfrac{min\left(x_{ij}\right)}{x_{ij}};\ x_{ij} \in C \end{cases} \tag{26}$$

where ρ_{ij} symbolizes the normalized value of each element.

Step-10.3: Calculate the measures of WSM and WPM: In this step, the weighted sum model (WSM) and weighted product model (WPM) measures for each option are computed with the help of Eqs. (27) and (28).

$$\eta_{ij}^{(1)} = \rho_{ij}\ x\ w_j \tag{27}$$

$$\eta_{ij}^{(2)} = \prod_{m=1}^{n} \left(\rho_{ij}\right)^{w_j} \tag{28}$$

Step-10.4: Compute the aggregated measures of the WASPAS method: By implementing Eq. (29), the combined measures for each option are identified as follows:

$$\eta_{ij} = \alpha . \eta_{ij}^{(1)} + \left(1-\alpha\right) . \eta_{ij}^{(2)} \tag{29}$$

Here, α denotes the parameter of the WASPAS technique taking a value between 0 and 1. The combined measures are calculated, and decision alternatives ranked based on these values.

3. Numerical Illustration

This section applies to the proposed IVq-ROFNs-based decision-making model to identify strategies for selecting IQCTIFs and presents the results. The researchers assembled an expert panel to ensure the model's effective implementation and produce realistic results. The panel, comprising three professionals and nine experienced managers, was selected through a rigorous screening process. The panel included a professor affiliated with two universities' rail systems departments and an expert consultant from the industry. Other members included a professional with 35 years of experience who served twice as general manager of I.E.T.T. and once as director general of TULOMSAŞ, a 30-year veteran who led another railway vehicle manufacturing company for two terms, and an electrical engineer who served as R&D manager at TUVASAŞ. The researchers and the professionals identified the key characteristics and skills required for expert participation in the evaluation process. As a result, seven essential factors were identified: age (F1), title (F2), industry (F3), field of expertise (F4), degree (F5), department (F6), and industry experience (F7). Detailed expert information is provided in Table 2.

Table 2 Profile of the experts

DMs	F1	F2	F3	F4	F5	F6	F7
DM1	62	Former Gen. Man.	Railway	Manufacturing	Ph. D	Mechanical Eng.	35
DM2	60	Former Gen. Man.	Railway	Manufacturing	Bachelor's	Mechanical Eng.	25
DM3	57	Professor	University	Rail Systems	Ph. D	Mechanical Eng.	20
DM4	54	Professor	University	Rail Systems	Ph. D	Electrical Eng.	17
DM5	47	R&D Manager	Railway	Technics	Master's	Electric Eng.	20

Then, together with researchers, professionals, and experts, they defined the problem of making decisions. Accordingly, the determination and prioritization of IQCTIF alternatives have been determined as the primary research problem. Then, the application steps of the proposed model were started.

After identifying the expert panel, the researchers discussed and determined the alternatives to meet the requirements with professionals and experts. Alternatives were determined according to the fact that each option can be matched with two or more factors. Below are the alternatives chosen at the end of the negotiations and the factors with which each is matched (Table 3). Initially, ten alternatives were identified. In the pre-selection process, considering the requirement, it was discussed whether the other options could respond to the determined factors (i.e., E1Certifications, E2 Rolling Stock Expertise, E3 Presence in Turkey, E4 Digital Capabilities, and E5 Major Rail Clients, and after the pre-selection process, experts and researchers decided to continue with five alternatives.

After the IQCTIF selection strategies were determined, the experts and professionals were asked to choose the criteria that affect the evaluation of these alternatives, and they were given a blank questionnaire form; it was stated that they could write as many criteria as they wished in this form. Then, the forms were collected and combined to prepare a list of criteria. Then, with the help of experts, the researchers eliminated the same repetitive criteria covered by another criterion and updated the list. In the next stage, each criterion was discussed separately with the experts. The criteria on which an entire agreement and consensus were reached were left on the list, and the others were eliminated. The table below shows the criteria set. The identified criteria are presented in Table 4.

Table 3 Alternatives and eligibility for pre-selection criteria

DMs	Candidates	E1	E2	E3	E4	E5	Result
A_{c1}	Applus+	✓	✓	*x*	*x*	✓	*x*
A_{c2}	Bureau Veritas	✓	✓	✓	✓	✓	✓
A_{c3}	DNV GL	✓	*x*	✓	✓	✓	*x*
A_{c4}	ENSCO	*x*	✓	*x*	✓	✓	*x*
A_{c5}	Intertek	*x*	*x*	✓	✓	*x*	*x*
A_{c6}	Lloyd's Register	✓	✓	✓	✓	✓	✓
A_{c7}	Mermec	*x*	✓	*x*	✓	✓	*x*
A_{c8}	Ricardo Rail	✓	✓	*x*	✓	✓	✓
A_{c9}	SGS	✓	✓	✓	✓	✓	✓
A_{c10}	TÜV SÜD	✓	✓	x	✓	✓	✓

Table 4 The criteria to assess the IQCTIF alternatives

Code	Criteria	Definitions
C1	Experience and references	The firm's past projects, references, and customer feedback.
C2	Railway certifications	Certifications like ISO 9001, IRIS, and ECM are required for compliance.
C3	Safety testing capability	Performing crash, braking, EMC, and fire safety tests effectively.
C4	Technological infrastructure and equipment	Accuracy of equipment and use of advanced testing technologies.
C5	International recognition	Global recognition and compliance with TSI and FRA standards.
C6	Independence and objectivity	No conflict of interest between quality firms and manufacturers.
C7	Cost and pricing	Competitive service fees, budget-friendly, and long-term agreements.
C8	Service timeliness and flexibility	Completing inspections promptly and responding to urgent testing.
C9	Railway material testing	Mechanical and chemical testing of components.
C10	Digital reporting and data analytics	Digital test result sharing and data analytics for optimization.
C11	Local and regional offices	Offices or labs in Turkey or Europe for on-site services.
C12	Regulatory compliance	Compliance with TCDD, UIC, ERA, and local regulatory standards.
C13	Training and consultancy services	Providing training and consultancy for the company's engineers.
C14	Sustainability and environmental policies	Reducing carbon footprint, green production, and eco-friendly testing.

After the alternatives and criteria were determined, the practices related to the determination of the reputation ratings of the experts, which is the next stage of the proposed model, were implemented.

3.1 Computing the Experts' Weights (Reputation)

Steps 1- 3: The professionals first evaluated the characteristics they identified with the help of the linguistic terms in Table 1. Then, he assessed the characteristics of the experts involved in the evaluation process. First, the relative weight values of the determined characteristics were calculated to marginalize the analysis process in which the reputation of the experts was determined. Table 5 shows the weight values for the characteristics and the results obtained.

Table 5 The weight values of the features

	PR1	PR2	PR3	μL	μU	vL	vU	Score V.	Weights
F1	MH	M	H	0.5655	0.6661	0.2965	0.3449	0.5190	0.1292
F2	VVH	H	VVH	0.7693	0.8264	0.1713	0.2154	0.6056	0.1508
F3	H	MH	VVH	0.7149	0.7801	0.2585	0.3032	0.5677	0.1414
F4	VH	VH	VH	0.7500	0.8000	0.1500	0.2000	0.5858	0.1459
F5	H	VVH	MH	0.7149	0.7801	0.2585	0.3032	0.5677	0.1414
F6	VH	H	VH	0.7259	0.7858	0.1768	0.2247	0.5728	0.1426
F7	VVH	MH	VVH	0.7623	0.8156	0.2565	0.2994	0.5973	0.1487

The table shows that F2 and F7 were identified as the most influential expert characteristics. The remaining characteristics were ranked with varying values. The researchers used linguistic variables based on this information to assess the experts' characteristics. These evaluations are presented in Appendix Table A. The linguistic assessments were then converted into IVq-ROF number values according to Table 2 and aggregated using Eq. (10). Next, the score function for each expert was calculated using Eq. (13), and their reputation was determined with Eq. (18). The calculated score function values and weight coefficients are presented in Table 8 (see also Table 6).

Table 6 The weight values of the experts (reputation degrees)

Weights	*0.1292*	*0.1508*	*0.1414*	*0.1459*	*0.1414*	*0.1426*	*0.1487*			
	F1	F2	F3	F4	F5	F6	F7	SV	W	Rank
DM1	0.7483	0.7714	0.7707	0.7546	0.8006	0.7483	0.7865	0.7690	0.2138	1
DM2	0.6904	0.7105	0.7300	0.7105	0.6682	0.7483	0.7112	0.7102	0.1975	3
DM3	0.7546	0.7546	0.7105	0.7714	0.8189	0.7649	0.6682	0.7485	0.2082	2
DM4	0.6891	0.6891	0.6440	0.7105	0.8189	0.7483	0.5928	0.6983	0.1942	4
DM5	0.6023	0.6193	0.6682	0.6678	0.7306	0.7300	0.6682	0.6699	0.1863	5

As shown in the table, after determining the reputation of each expert, the other implementation steps of the proposed IVq-ROF-Subjective & CRITIC & WASPAS model were implemented.

3.2 Implementation of the Suggested Model

At this stage, the IVq-ROF-Subjective and CRITIC methods were used to determine the criteria weights. In contrast, the IVq-ROF-WASPAS methods evaluated and ranked the strategy alternatives. The applied procedure is presented below.

Step 4: The experts evaluated the criteria using the linguistic terms provided in Table 1. These evaluations were then aggregated by the researchers and converted into IVq-ROF numbers. Table 7 presents the experts' linguistic assessment of the criteria.

Table 7 The linguistic evaluations of the experts for the criteria

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
DM1	VH	VVH	EH	VVH	VH	H	H	H	VVH	H	H	VVH	H	M
DM2	VVH	EH	VVH	VVH	VVH	VVH	VVH	VVH	VVH	VVH	VH	EH	VH	VH
DM3	EH	EH	EH	EH	VVH	VVH	VH	VH	EH	VVH	VH	EH	VH	VH
DM4	VVH	VVH	EH	VVH	VVH	VVH	VH	VH	VVH	VH	VH	EH	VH	VH
DM5	VH	VVH	VVH	VH	VH	VH	H	VH	VVH	VH	H	VVH	MH	MH

Steps 4.1- 4.3: The researchers then combined these values with the help of Eq. (15). The obtained combined IVq-ROF values were converted into score function values using Eq. (13) and then weighed to calculate the final relative weighting values (Table 8).

Table 8 The weight values of the experts (reputation degrees)

	μL	μU	vL	vU	φ_j^{Sub}	w_j^{Sub}	Rank
C1	0.79511	0.84632	0.12094	0.16792	0.77559	0.07341	6
C2	0.82246	0.87314	0.08641	0.13411	0.80474	0.07617	3
C3	0.83287	0.88350	0.07725	0.12412	0.81625	0.07726	1
C4	0.80434	0.85520	0.10803	0.15529	0.78521	0.07432	5
C5	0.78175	0.83209	0.12495	0.17356	0.76167	0.07209	7
C6	0.76733	0.82449	0.14331	0.19009	0.75061	0.07105	8
C7	0.72922	0.79445	0.16822	0.21651	0.71857	0.06801	11
C8	0.74477	0.80255	0.15738	0.20587	0.72935	0.06904	10
C9	0.81195	0.86244	0.09352	0.14229	0.79327	0.07509	4
C10	0.75680	0.81431	0.15043	0.19802	0.74056	0.07010	9
C11	0.71591	0.78175	0.17356	0.22279	0.70710	0.06693	12
C12	0.83209	0.88273	0.07804	0.12495	0.81538	0.07718	2
C13	0.70494	0.76926	0.20650	0.25312	0.69512	0.06580	13
C14	0.68271	0.74341	0.25387	0.29911	0.67149	0.06356	14

***Step 5*:** In the second step of the model, the researchers converted the expert evaluations of the strategy alternatives into the corresponding IVq-ROFNs in Table 1, and these numerical values were combined with the help of Eq. (15). Then, the IVq-ROF decision matrix shown in Appendix, Table C, was created.

***Steps 6- 7*:** In this step, they combined the matrices created according to each expert's opinion with the help of Eq. (15) and included the degree of prestige of the experts in this process.

***Step 7*:** Then, with the help of Eq. (13), the score function value of each alternative was calculated according to each criterion. Table 9 shows the options' score function values.

Table 9 The score matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
A1	0.7768	0.6086	0.6086	0.6826	0.6948	0.7421	0.7421	0.7421	0.6394	0.7421	0.7081	0.6086	0.7076	0.7206
A2	0.7626	0.6815	0.6672	0.7306	0.6682	0.7804	0.7306	0.7804	0.6672	0.7804	0.6948	0.7075	0.7064	0.7419
A3	0.7736	0.5610	0.6063	0.7082	0.8148	0.7804	0.8259	0.7542	0.7070	0.7509	0.8259	0.5610	0.8148	0.8259
A4	0.6550	0.7706	0.7706	0.7500	0.6531	0.7306	0.6682	0.7071	0.7706	0.6682	0.5928	0.7706	0.5928	0.6550
A5	0.7982	0.6115	0.6115	0.7111	0.7445	0.7445	0.7599	0.7599	0.6115	0.7599	0.7339	0.6115	0.7339	0.7599

***Step 8*:** After the score matrix was created, the application steps of the IVq-ROF-CRITIC approach were employed to determine the criteria's relative weight coefficients.

***Step-8.1*:** The initial decision matrix elements were normalized using Eq. (21). Next, the normalized decision matrix is constructed as shown in Table 10. Then, the standard deviation for each vector that makes up the matrix is calculated using Eq. (22).

Table 10 The normalized matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
A1	0.8508	0.2274	0.0140	0.0000	0.2581	0.2307	0.4688	0.4775	0.1755	0.6585	0.4947	0.2274	0.5173	0.3840
A2	0.7518	0.5751	0.3707	0.7121	0.0937	1.0000	0.3959	1.0000	0.3503	1.0000	0.4377	0.6992	0.5119	0.5084
A3	0.8286	0.0000	0.0000	0.3798	1.0000	1.0000	1.0000	0.6429	0.6004	0.7369	1.0000	0.0000	1.0000	1.0000
A4	0.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000
A5	1.0000	0.2412	0.0315	0.4221	0.5652	0.2779	0.5813	0.7194	0.0000	0.8166	0.6055	0.2412	0.6357	0.6136
SD	0.3940	0.3890	0.4294	0.3760	0.4062	0.4669	0.3598	0.3694	0.3905	0.3808	0.3587	0.4059	0.3583	0.3628

***Step 8.2*:** A correlation matrix is created by calculating the correlation between each pair of criteria. Table 11 shows the correlation matrix. Then, after the correlation matrix is constructed, the total amount of information for each criterion is determined using Eq. (23). To do this, the difference ($1-\tau_{ik}$) between each element of the correlation matrix is calculated, and the sum of each vector ($\sum(1-\tau_{jk})$) is multiplied by the standard deviation value (σ_j). The resulting value exhibits the total amount of information (K_j) for a criterion.

Table 11 The correlation matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
C1	1.000	-0.873	-0.960	-0.765	0.575	0.453	0.754	0.792	-0.892	0.891	0.783	-0.824	0.816	0.755
C2	-0.873	1.000	0.966	0.827	-0.846	-0.455	-0.938	-0.528	0.613	-0.660	-0.944	0.991	-0.940	-0.880
C3	-0.960	0.966	1.000	0.875	-0.698	-0.409	-0.843	-0.637	0.790	-0.771	-0.861	0.941	-0.874	-0.797
C4	-0.765	0.827	0.875	1.000	-0.456	-0.074	-0.596	-0.302	0.695	-0.486	-0.610	0.835	-0.607	-0.475
C5	0.575	-0.846	-0.698	-0.456	1.000	0.460	0.939	0.296	-0.215	0.373	0.923	-0.865	0.892	0.904
C6	0.453	-0.455	-0.409	-0.074	0.460	1.000	0.652	0.766	-0.104	0.709	0.667	-0.355	0.704	0.753
C7	0.754	-0.938	-0.843	-0.596	0.939	0.652	1.000	0.548	-0.389	0.629	0.999	-0.919	0.991	0.981
C8	0.792	-0.528	-0.637	-0.302	0.296	0.766	0.548	1.000	-0.672	0.980	0.587	-0.417	0.653	0.658
C9	-0.892	0.613	0.790	0.695	-0.215	-0.104	-0.389	-0.672	1.000	-0.769	-0.426	0.573	-0.469	-0.388
C10	0.891	-0.660	-0.771	-0.486	0.373	0.709	0.629	0.980	-0.769	1.000	0.667	-0.561	0.727	0.705
C11	0.783	-0.944	-0.861	-0.610	0.923	0.667	0.999	0.587	-0.426	0.667	1.000	-0.920	0.996	0.984
C12	-0.824	0.991	0.941	0.835	-0.865	-0.355	-0.919	-0.417	0.573	-0.561	-0.920	1.000	-0.905	-0.842
C13	0.816	-0.940	-0.874	-0.607	0.892	0.704	0.991	0.653	-0.469	0.727	0.996	-0.905	1.000	0.987
C14	0.755	-0.880	-0.797	-0.475	0.904	0.753	0.981	0.658	-0.388	0.705	0.984	-0.842	0.987	1.000

***Step-8.3*:** In this step, the total amount of information for each criterion is divided by the total amount of information of the criteria to determine the relative weight values. Eq. (24) is used for this. Table 12 shows the values obtained at the end of the implementation.

Table 12 The absolute value matrix and weights of the criteria

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
C1	0.000	1.873	1.960	1.765	0.425	0.547	0.246	0.208	1.892	0.109	0.217	1.824	0.184	0.245
C2	1.873	0.000	0.034	0.173	1.846	1.455	1.938	1.528	0.387	1.660	1.944	0.009	1.940	1.880
C3	1.960	0.034	0.000	0.125	1.698	1.409	1.843	1.637	0.210	1.771	1.861	0.059	1.874	1.797
C4	1.765	0.173	0.125	0.000	1.456	1.074	1.596	1.302	0.305	1.486	1.610	0.165	1.607	1.475
C5	0.425	1.846	1.698	1.456	0.000	0.540	0.061	0.704	1.215	0.627	0.077	1.865	0.108	0.096
C6	0.547	1.455	1.409	1.074	0.540	0.000	0.348	0.234	1.104	0.291	0.333	1.355	0.296	0.247
C7	0.246	1.938	1.843	1.596	0.061	0.348	0.000	0.452	1.389	0.371	0.001	1.919	0.009	0.019
C8	0.208	1.528	1.637	1.302	0.704	0.234	0.452	0.000	1.672	0.020	0.413	1.417	0.347	0.342
C9	1.892	0.387	0.210	0.305	1.215	1.104	1.389	1.672	0.000	1.769	1.426	0.427	1.469	1.388
C10	0.109	1.660	1.771	1.486	0.627	0.291	0.371	0.020	1.769	0.000	0.333	1.561	0.273	0.295
C11	0.217	1.944	1.861	1.610	0.077	0.333	0.001	0.413	1.426	0.333	0.000	1.920	0.004	0.016
C12	1.824	0.009	0.059	0.165	1.865	1.355	1.919	1.417	0.427	1.561	1.920	0.000	1.905	1.842
C13	0.184	1.940	1.874	1.607	0.108	0.296	0.009	0.347	1.469	0.273	0.004	1.905	0.000	0.013
C14	0.245	1.880	1.797	1.475	0.096	0.247	0.019	0.342	1.388	0.295	0.016	1.842	0.013	0.000
Sum	11.495	16.668	16.278	14.139	10.720	9.234	10.192	10.276	14.653	10.566	10.156	16.268	10.030	9.655
K	4.529	6.484	6.989	5.316	4.354	4.311	3.667	3.796	5.722	4.024	3.643	6.603	3.594	3.503
w_{ij}	0.0681	0.0975	0.1050	0.0799	0.0654	0.0648	0.0551	0.0571	0.0860	0.0605	0.0548	0.0992	0.0540	0.0526

Step 9: In this step, the subjective and objective weights of the criteria were combined by employing Eq. (25). Table 13 demonstrates the subjective, objective, and final weights of the criteria. In this work, the β parameter value is accepted as 0.5.

Table 13 The subjective, objective, and final weights of the criteria

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
w_j^{Sub}	0.0734	0.0762	0.0773	0.0743	0.0721	0.0710	0.0680	0.0690	0.0751	0.0701	0.0669	0.0772	0.0658	0.0636
w_j^{Obj}	0.0681	0.0975	0.1050	0.0799	0.0654	0.0648	0.0551	0.0571	0.0860	0.0605	0.0548	0.0992	0.0540	0.0526
w_j	0.0707	0.0868	0.0912	0.0771	0.0688	0.0679	0.0616	0.0630	0.0805	0.0653	0.0608	0.0882	0.0599	0.0581

According to the results regarding the relative significance of the criteria, Safety Testing Capability (C3) is determined as the most effective criterion with a weight value of 0.09116, followed by Regulatory Compliance (C12) with a weight value of 0.08821 and Railway Certifications (C2) with a weight value of 0.08681. Other criteria are ranked as (C9) Railway Material Testing (0.08054) > C4 Technological Infrastructure and Equipment (0.07711) > C1 Experience and References (0.07074) > C5 International Recognition (0.06877) > C6 Independence and Objectivity (0.06792) > C10 Digital Reporting and Data Analytics (0.06529) > C8 Service Timeliness and Flexibility (0.06305) > C7 Cost and Pricing (0.06157) > C11 Local and Regional Offices (0.06084) > C13 Training and Consultancy Services (0.05990) > C14 Sustainability and Environmental Policies (0.05810). Then, the second stage of the proposed model started, and the ranking performances of the IQCTIFs were determined using the IVq-ROF set-based WASPAS approach.

Step 10: At this stage, the application steps of the IVq-ROF-WASPAS method, which is the second part of the proposed model and used to determine the ranking performance of the alternatives, were started.

Step 10.1: The decision matrix used in the first application step of the IVq-ROF-CRITIC method was also used. Therefore, these processes for creating the first and second decision matrix (Table 12) are not shown here again to avoid repetition.

Step-10.2: The elements of the first decision matrix were normalized using Eq. (26), and the normalized decision matrix shown in Table 14 was generated.

Table 14 The normalized matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
A1	0.9732	0.7898	0.7898	0.8858	0.8527	0.9509	0.9004	0.9509	0.8298	0.9509	0.8574	0.7898	0.8685	0.8726
A2	0.9555	0.8844	0.8659	0.9481	0.8201	1.0000	0.9146	1.0000	0.8659	1.0000	0.8413	0.9182	0.8670	0.8983
A3	0.9693	0.7280	0.7869	0.9191	1.0000	1.0000	0.8091	0.9664	0.9175	0.9622	1.0000	0.7280	1.0000	1.0000
A4	0.8207	1.0000	1.0000	0.9733	0.8015	0.9362	1.0000	0.9060	1.0000	0.8562	0.7178	1.0000	0.7275	0.7932
A5	1.0000	0.7936	0.7936	0.9228	0.9137	0.9539	0.8794	0.9736	0.7936	0.9736	0.8887	0.7936	0.9007	0.9201

Step 10.3-10.4 At this stage, each alternative's weighted sum model (WSM) and weighted product model (WPM) measurements were calculated using Eqs. (27) and (28). Then, using these values, the total distance of each alternative was determined with the help of Eq. (29), and the other options were ranked according to this value. Table 15 shows the results for ranking the alternatives with WSM, WPM, and the total distance of each alternative.

Table 15 The normalized matrix

	WSM	WPM	η_{ij}	Rank
A1	0.8698	0.8675	0.8687	5
A2	0.9114	0.9097	0.9105	1
A3	0.9016	0.8951	0.8983	3
A4	0.9065	0.9005	0.9035	2
A5	0.8852	0.8821	0.8837	4

As shown in Table 15, TUV-SUD (A2) has been identified as the most valuable and priority option to be a collaborator of the Turkish railway vehicle manufacturing industry. It is followed by SGS (A4) and Ricardo Rail (A3), respectively. Other alternatives have been ranked as Lloyd's Register (A5) and Bureau Veritas (A1).

4. Robustness Check

A comprehensive robustness test assessed the proposed model's validity and reliability. In the first stage of the process, the effect of changes in the criteria weights on the final ranking results was examined. Each criterion's weight was gradually reduced by 10% to zero, while the reduced value was equally redistributed to the others to maintain a total weight sum of 1. In this context, a total of 140 scenarios were created. The impact of varying expert weights on the rankings was also examined.

As shown in Figure 1, the place of the worst alternative (A1) in the ranking did not change in any scenario, while the A5 alternative could not maintain its place in the ranking in only one scenario. The best alternative, A2, maintained its place in the ranking, except for eleven scenarios. The similarity between the 140 scenarios and the original ranking results was calculated as 0.8643. The expert weights changed similarly in the second stage, and the results obtained were evaluated. The similarity between the original ranking results and the rankings that occurred when the expert weights were changed was determined as 1.0.

In sources such as Saaty [37] and Belton and Stewart [38], it is recommended that consistency and similarity values should be above 85-90%, and it is emphasized that such ratios provide reliable results in the decision processes of MCDM methods. In this study, the average similarity rates were computed as high as 86.43% and 100.00%. It shows that the model's results exceed the reliability standards accepted in the literature.

In the second step, we tested the resistance of the proposed model against the rank reversal problem, an essential limitation in decision-making approaches. In n-1 scenarios, the lowest-ranked alternative was excluded, and rankings were recalculated to test for rank reversal. We meticulously compared the alternatives' ranking results with the previous scenario's ranking performance in each scenario. The results of this thorough comparison process are presented in Table 16.

Table 16 The results of the test for the rank reversal problem

Scenarios	**Ranking results in the scenarios**
Original	A2 > A4 > A3 > A5 > A1
SC1	A2 > A4 > A3 > A5
SC2	A2 > A4 > A3
SC3	A2 > A4

SC4	A2

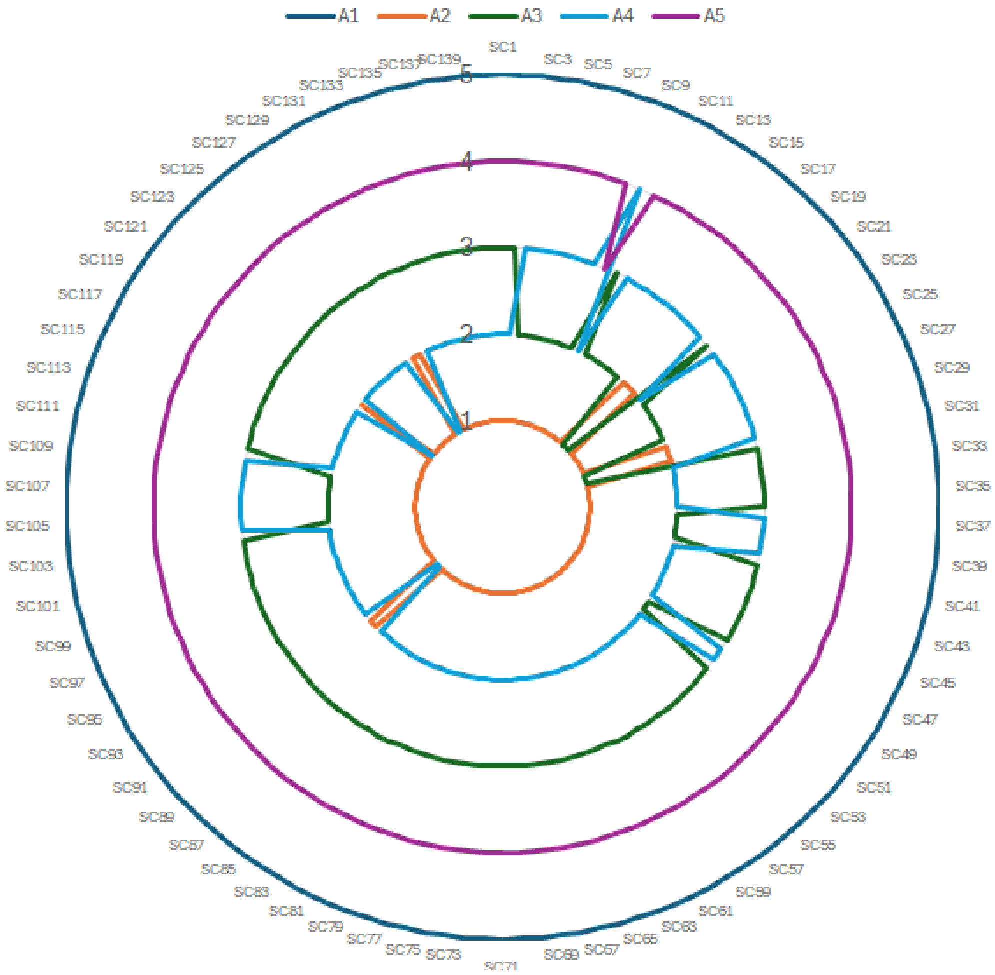

Fig. 1 New ranking results based on modified criterion weights

In the third stage, the results of the proposed decision-making model were compared with the IVq-ROFNs-based decision-making approaches used in the relevant literature. In this context, ARAS [39], TOPSIS [40], COPRAS [41], VIKOR [42], and TODIM [43] methods were applied based on IVq-ROF. The results are shown in Fig. 2. As seen in this figure, when only the IVq-ROF-based TOPSIS method was used, there was a displacement between the first two alternatives, and the other options remained in place. On the other hand, the ranking results obtained for all other methods remained the same as those obtained using the proposed model, and all alternatives showed the same ranking performance.

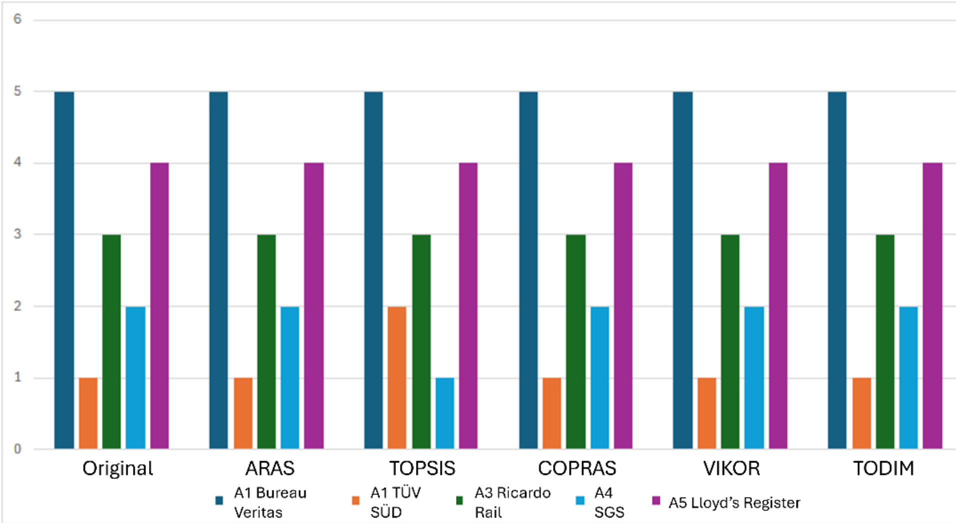

Fig. 2 Comparative analysis results

The parameter value was changed in the last stage, and the ranking results were examined. Figure 3 shows the new ranking results obtained according to the scenarios. When the results were examined, it was observed that there was no change in the ranking performance of A1 and A5 for all scenarios. At the same time, the best alternative, A2, lost its place only in the 11th scenario, where the objective weight value was zero, and maintained its place in the other ten scenarios. A3 ranked second when the subjective weight value was 1 to 0.70, falling to third place when the objective weights increased. A4, on the other hand, shows a similar trend, but when the subjective weight values are accepted as zero, they rise to the top of the ranking.

To solve this highly complex decision-making problem, which is highly affected by uncertainties, the CRITIC & WASPAS procedure based on Range Value Q-Rung Orthopair Fuzzy (IVq-ROF) sets was developed in this study. The proposed model effectively manages uncertainties in the dynamic structure of the sector. To solve the decision-making problem reasonably and logically, these requirements discussed above highlight the necessity of decision models that can accommodate subjective and ambiguous criterion evaluations in a decision-making environment where complex uncertainties and ambiguities are effective, as Sudha et al. [44] stated in their study.

The proposed decision-making model allows the uncertainties and contradictory information that arise in the decision-making processes and affect the results to be handled more effectively and sensitively. In addition, the CRITIC approach, a part of the model used to assess criterion weights, deals with the interactions and relationships between criteria in more depth, enabling the relative weights of the criteria to be determined more objectively, effectively, and with high accuracy.

The IVq-ROF-WASPAS approach produces more balanced, reliable, and comprehensive results when considering both the additive and multiplicative properties of the strategy alternatives. This framework makes it possible to evaluate strategies multidimensionally and prioritize them according to the importance of the scores they achieve. In addition, the decision-making model developed in this study has an advantageous and practical basic algorithm and can be easily applied by almost any decision-maker without the need for advanced mathematical knowledge. Moreover, despite the highly reliable and robust structure of the model, the fact that it can be easily applied to this extent systematizes the evaluation processes, reduces the time to be spent on the evaluation processes, and makes significant contributions to the reputation of the company because it produces results at a high level of accuracy.

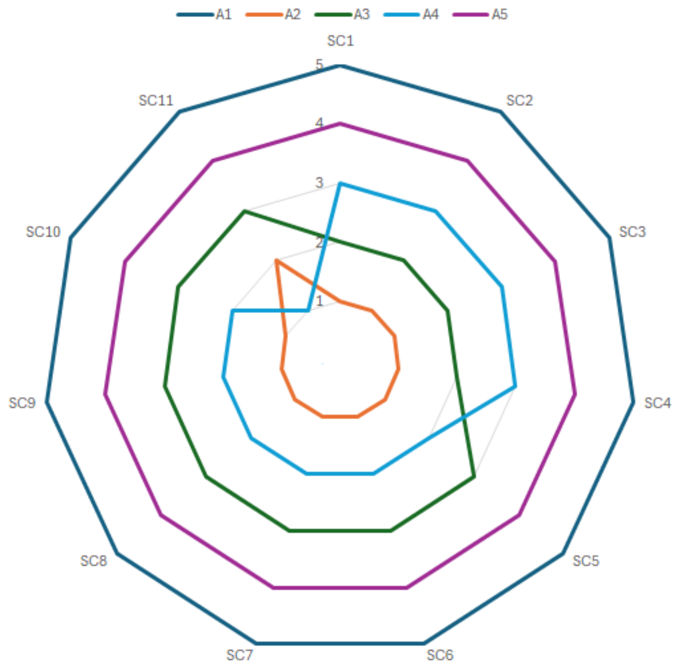

Fig. 3 New ranking results based on modified β parameters

5. Results and Discussion

The results and findings obtained in this study show that criteria such as Safety Test Capability (C3), Regulatory Compliance (C12), and Railway Certificates (C2) are the most effective and critical criteria in the evaluation and selection of IQCTIFs for industries producing products such as railway wagons, locomotives, and railroads. These results are consistent with the fact that the railway industry is an industry that is subject to the most legal regulations and standards at national and international levels, and that safety is the most critical and vital factor. When the findings obtained for each criterion are evaluated separately, the requirement for producing railway vehicles by safety and security standards explains the Safety Test Capability (C3) criterion in the first place. It is critical and vital for production enterprises to be able to perform essential tests such as crash tests, braking tests, electromagnetic compatibility, and fire safety tests to prevent a railway accident that can cause fatal disasters. In addition, businesses that carry out such security tests and practices in a very robust and impartial manner gain customers' trust and significantly increase their reputation.

One of the most crucial elements in railway transportation is the concept of interoperability. While this ensures that transportation is uninterrupted, it provides significant advantages in terms of safety and costs. The most essential condition is that the tools and equipment comply with international standards. Therefore, compliance with legal regulations and standards determined by international railway authorities is extraordinarily critical and vitally important. Deficiencies in the compliance of the producer enterprises with these obligations may lead to significant problems such as certificate cancellations, penalties, and sanctions to be applied, the inability of wagons to cross the border in cross-border transportation, and the obligation to transfer to other wagons. Accordingly, the extent to which these firms comply with regulatory requirements and standards is critical in selecting IQCTIFs.

To achieve this, the fact that the companies that will be stakeholders have internationally accepted certificates such as ISO 9001, IRIS (International Railway Industry Standard), and ECM (Maintenance Responsible Entity) regarding testing, control, and inspection can be considered as an essential proof that the determined quality standards are met, and reliable service is provided. In addition, criteria such as Railway Material Testing (C9) and Technological Infrastructure and Equipment (C4) are also directly related to safety, security, and compliance with regulations in the railway industry. In this context, high-quality and technological elements guarantee the durability of railway vehicle components while increasing the accuracy and reliability of the results obtained.

Although Experience and References (C1), which are listed as an essential criterion at a medium level, are decisive in terms of reliability in the evaluation and selection processes of the companies in question, considering the technical criteria, it is not enough for the partner company to have experience and references. In addition, according to the study's findings, the Cost and Pricing (C7) criterion is of low importance. The main reason is that a cost-oriented choice is unreliable enough to meet safety and technical competence requirements. Given the consequences of accidents, especially in the railway industry, reducing costs at the expense of safety and regulatory compliance is unacceptable.

These findings and conclusions have critically important policy and managerial implications. First, safety, certification, and regulatory compliance should be prioritized when selecting partners to receive quality control, testing, and inspection services. The evaluation process should include businesses that can fully meet these requirements. In addition to regulations and legal regulations, the enterprises' certificates should be considered in the selection processes. Besides, the technological saturation levels of businesses and their investment in technological requirements are another essential focus.

In addition, the findings provide valuable insights for all stakeholders. First, companies to be included in the selection processes should consider strategies to increase their security testing capabilities and competitiveness regarding their certifications. Processors that meet these requirements long-term and sustainably can establish strategic alliances with businesses in the railway industry. At the same time, businesses should constantly review and update their compliance with regulations regarding testing, control, and verification processes. Otherwise, these businesses may significantly lose their competitiveness in the market. At the same time, data analytics, artificial intelligence, and digital reporting systems can dramatically improve the quality of service by making testing, control, and inspection processes faster and more accurate, and such technological elements can improve quality control processes.

The findings highlight TUV-SUD (A2) as the top alternative due to its leadership in rail safety testing and regulatory compliance. The fact that the company takes an active role in many railway projects in Europe and other major markets and fully complies with the standards set by regulatory organizations such as TCDD, ERA, and UIC, as well as the company's advanced test laboratories and technology infrastructure, which offers a great advantage for companies in the sector, is in line with the findings obtained in this study.

It was followed by SGS (A4) and Ricardo Rail (A3), while other alternatives were Lloyd's Register (A5) and Bureau Veritas (A1). In this context, SGS is a global business that provides a wide range of industrial testing and certification services, specializing in safety, material durability testing, and conformity assessments in the railway sector. Ricardo Rail is an engineering-oriented company with in-depth know-how in railway technology and system safety. It has a strong structure and knowledge, especially in vehicle dynamics, signaling systems, and infrastructure engineering. However, his specialization in a more specific area caused him to take third place.

Lloyd's Register (A5) and Bureau Veritas (A1) focus mainly on the maritime and energy sectors. Their experience in the railway field is relatively small, and their expertise in railway vehicles and systems is limited. In addition to having deficiencies, especially in technical and railway safety certificates, their market experience is minimal.

The study's findings clarify that the most critical components of the railway industry's quality control and inspection processes are safety testing capability, regulatory compliance, and railway certifications. These criteria are essential because rail transport requires high safety standards and strict adherence to international regulations. This company stands out as one of the most reliable options in the sector with its advanced test infrastructure, competence in international certification processes, and many years of experience in the railway sector. SGS (A4) and Ricardo Rail (A3) were ranked second and third due to their wide range of testing and certification services, strong engineering infrastructure, and industry expertise. On the other hand, Lloyd's Register (A5) and Bureau Veritas (A1) focus more on the maritime and energy sectors, lagging due to their limited expertise in the railway sector.

These results provide essential policy and managerial implications for manufacturers, authorities, and other stakeholders. It is emphasized that safety, regulatory compliance, and technical competence should be prioritized instead of cost-oriented approaches when selecting IQCTIFs. In addition, railway manufacturers need to increase their technological investments and continuously improve their inspection processes to comply fully with safety standards. The digitalization of testing, control, and certification processes, the use of artificial intelligence-supported analysis, and cooperation with internationally certified enterprises are among the main strategies that will increase the competitiveness of the railway sector.

Although this study presents essential findings on evaluating and selecting quality control and inspection firms in the railway sector, it contains some limitations. The alternative companies assessed in the study were chosen according to specific criteria and do not cover all global quality control and inspection firms. Therefore, more comprehensive analyses can be made by considering a wider pool of firms in future research.

Regulatory requirements in the railway sector may vary from country to country. Although the study is based on international standards, examining local regulations and practices in different countries in more detail will be helpful. In addition, although the methods used in the study were based on objective criteria, the evaluation of some factors was carried out based on expert opinions. In future research, subjective biases can be minimized by taking the views of more industry experts and company representatives.

Given the increasing use of technologies such as artificial intelligence, machine learning, and automation in quality control and inspection processes, it will be helpful to evaluate the impact of these technologies on the performance of IQCTIFs in future research.

Some topics are proposed for future research. Comparison of the method used in the study with different Multi-Criteria Decision Making (MCDF) methods may help test the consistency and reliability of the results obtained. The effects of regulatory requirements in the European, US, and Asian markets on different IQCTIF selection processes can be analyzed. In addition, the effectiveness of artificial intelligence, big data analytics, and digital certification processes in quality control and inspection processes can be examined. In addition, creating a comprehensive strategic roadmap on how the quality control and inspection processes in the railway sector will be shaped in the future can also be an essential research topic. Such research will help rail manufacturers, regulatory authorities, and IQCTIFs make more informed decisions and contribute to improving safety and efficiency in the industry.

6. Conclusion

This investigation proposes a comprehensive and robust decision-making model in which IVq-ROF (Interval-Valued q-Rung Orthopair Fuzzy Set) based CRITIC and WASPAS methods are integrated to address the highly complex decision-making problem affected by uncertainties and ambiguities, such as the evaluation and selection of independent quality control, testing, and inspection firms (IQCTIF) in the rolling stock manufacturing industry, and to produce reasonable solutions. This decision model developed in this study can manage multidimensional criteria with remarkable interactions between them by integrating subjective expert evaluations and analyses based on objective data.

According to the findings obtained in this study, Safety Test Competence (C3), Regulatory Compliance (C12), and Railway Certificates (C2) criteria stand out in the selection of IQCTIF in terms of their significance and influence. These outcomes indicate the need for the railway industry's high safety requirements and strict compliance with international regulations. Evaluations of alternative IQCTIFs show that TÜV SÜD (A2) is the most suitable strategic partner regarding safety testing, compliance with regulatory standards, and advanced technological infrastructure.

The proposed decision-making framework for evaluating IQCTIFs has been confirmed by robustness checks to be ten-degree consistent, stable, and reliable. The proposed integrated decision-making approach stands out as a robust evaluation and decision-making tool for real-world applications by overcoming structural problems that point to the most fundamental limitation of traditional decision-making approaches, such as the rank reversal problem.

This research makes significant contributions in terms of theoretical and industrial applications. A new hybrid framework has been developed in the theoretical context, considering uncertainties and inter-criteria relationships. It offers a transparent, systematic, and easily applicable method to decision-makers regarding managerial and policy implications. It provides a model for selecting strategic partners for the railway production sector and other sectors that require high regulation. In addition, the importance of decision processes based on long-term sustainability, compliance, and technical competence instead of short-term cost-oriented approaches was emphasized. This model can be developed in future studies with sectoral risk indicators, dynamic assessment frameworks, and artificial intelligence-supported decision support systems, and tested with wider applications in different sectors.

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APPENDICES

Appendix Table A: Linguistics assessments of the professionals for the experts

	F1			F2			F3			F4			F5			F6			F7		
DM	*PR1*	*PR2*	*PR3*	*PR1*	*PR2*	*PR3*	*PR1*	*PR2*	*PR3*	*PR1*	*PR2*	*PR3*	*PR1*	*PR2*	*PR3*	*PR1*	*PR2*	*PR3*	*PR1*	*PR2*	*PR3*
1	VVH	VH	VH	EH	VH	VH	EH	H	VVH	EH	H	VH	EH	VVH	VVH	VVH	VH	VH	EH	VH	VVH
2	VH	H	H	VVH	H	H	VVH	H	VH	VVH	H	H	H	H	H	VVH	VH	VH	VH	H	VH
3	H	EH	VH	VH	EH	H	H	VVH	H	VH	EH	VH	EH	EH	VVH	VVH	VVH	VH	H	H	H
4	MH	VVH	H	H	VVH	MH	MH	VH	MH	H	VVH	H	EH	EH	VVH	VH	VVH	VH	MH	MH	MH
5	M	H	MH	MH	H	MH	H	H	H	MH	H	VH	VH	VH	VH	H	VH	VVH	H	H	H

Appendix Table B: Linguistics assessments of the experts for the alternatives

		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**	**C14**
A1	**DM1**	EH	MH	MH	VH	H	VVH	VVH	VVH	MH	VVH	VH	MH	VH	VVH
A1	**DM2**	VVH	H	H	H	H	VH	VH	VH	H	VH	H	H	H	VH
A1	**DM3**	VVH	MH	MH	H	VH	VH	VH	VH	H	VH	VH	MH	VH	VH
A1	**DM4**	VVH	MH	MH	H	VH	VH	VH	VH	H	VH	VH	MH	H	VH
A1	**DM5**	H	MH	MH	H	H	VH	VH	VH	MH	VH	H	MH	VH	MH
A2	**DM1**	VVH	H	H	VH	H	VVH	VH	VVH	H	VVH	H	H	H	VH
A2	**DM2**	VVH	VH	VH	VH	H	VVH	VH	VVH	VH	VVH	H	VH	H	VH
A2	**DM3**	VVH	H	MH	VH	H	VVH	VH	VVH	MH	VVH	VH	VVH	VH	VVH
A2	**DM4**	VVH	H	H	VH	H	VVH	VH	VVH	H	VVH	VH	H	VH	VVH
A2	**DM5**	H	H	H	VH	H	VVH	VH	VVH	H	VVH	H	H	VH	H
A3	**DM1**	VH	MH	MH	VVH	VVH	VVH	EH	VH	MH	VH	EH	MH	VVH	EH
A3	**DM2**	VH	MH	MH	VH	VVH	VVH	VVH	VH	MH	H	VVH	MH	VVH	VVH
A3	**DM3**	VVH	M	VH	H	EH	VVH	EH	VH	EH	VVH	EH	M	EH	EH
A3	**DM4**	VVH	M	M	H	EH	VVH	EH	VH	EH	VVH	EH	M	EH	EH
A3	**DM5**	EH	M	M	H	EH	VVH	EH	EH	M	VVH	EH	M	EH	EH
A4	**DM1**	H	VH	VH	H	MH	VH	H	H	VH	H	MH	VH	MH	H
A4	**DM2**	H	VVH	VVH	VH	H	VH	H	VH	VVH	H	MH	VVH	MH	H
A4	**DM3**	H	VVH	VVH	VVH	H	VH	H	VH	VVH	H	MH	VVH	MH	H
A4	**DM4**	H	VVH	VVH	VVH	H	VH	H	VH	VVH	H	MH	VVH	MH	H
A4	**DM5**	MH	VVH	VVH	VVH	H	VH	H	H	VVH	H	MH	VVH	MH	MH
A5	**DM1**	EH	H	H	VVH	VVH	VVH	EH	EH	H	EH	VVH	H	VVH	EH
A5	**DM2**	EH	H	H	VH	VVH	VVH	VVH	VVH	H	VVH	VH	H	VH	VVH
A5	**DM3**	EH	MH	MH	VH	VVH	VVH	VVH	VVH	MH	VVH	VVH	MH	VVH	VVH
A5	**DM4**	EH	MH	MH	VH	VVH	VVH	VVH	VVH	MH	VVH	VVH	MH	VVH	VVH
A5	**DM5**	VVH	MH	MH	VH	VVH	VVH	VVH	VVH	MH	VVH	VVH	MH	VVH	VVH