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Research article

A new hybrid MCDM approach for mitigating risks of hazardous material road transportation

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Abstract: Given the ongoing development of the global economy, the demand for hazardous materials, which serve as essential components for numerous industrial products, is steadily increasing. Consequently, it becomes imperative to devise a methodology for mitigating the risks associated with the road transportation of hazardous materials. The objective of this study is to establish an integrated quality function deployment and multicriteria decision-making (QFD-MCDM) framework and identify the pivotal factors that propel Industry 5.0 (I5.0), thus fortifying supply chain resilience (SCR) and ameliorating the hazardous material transportation risks (HMTR). These measures encompass various strategic areas, including “establish a safe and inclusive work environment”, “customized products and services”, “enhance production flexibility and strengthen control redundancy”, and “real-time data collection and analysis”. By adopting these measures, enterprises can lead to sustainable and stable business operations. The findings of this study demonstrate the synergistic potential of integrating I5.0 and SCR in effectively mitigating HMTR. Additionally, these findings offer valuable insights and practical implications for enterprises across diverse industries.

Keywords: hazardous material transportation risks; supply chain resilience; Industry 5.0; quality function deployment; multicriteria decision-making

1. Introduction

The transportation of hazardous materials is witnessing a continuous rise due to the growing demand for substances like chemical raw materials [1]. Hazardous materials can be transported via road, railway, waterway, aviation, and pipeline, with road transportation currently serving as the primary mode [2–5]. In the event of a road transportation accident involving hazardous materials, the leaked substances pose significant risks to individuals, the environment, and infrastructure [6]. The leakage of hazardous materials and subsequent environmental pollution can trigger a chain reaction while also demanding substantial time and effort for environmental remediation. The road transportation of hazardous materials has emerged as a critical concern for governments, the public, and businesses due to the potential for substantial losses resulting from accidents [7]. Consequently, conducting an analysis of the risk factors associated with road transportation of hazardous materials holds paramount importance in mitigating accident occurrences.

Hazardous material supply chains pose greater risks compared to other supply chains, potentially resulting in environmental pollution, financial losses, and even casualties. Hence, it is crucial to give greater attention to hazardous material supply chains throughout their entire lifecycle and within the supply chain [8]. In such circumstances, enterprises should establish resilient supply chains to enhance their crisis response capabilities and mitigate adverse impacts [9]. SCR refers to the supply chain's capacity for continuous adaptation or transformation in response to changing circumstances [10]. Amidst the rapidly changing market environment, enterprises must proactively seize opportunities and dynamically adjust their resources and capabilities to ensure prompt and effective responses, thereby enhancing SCR [11].

Industry 4.0 (I4.0) is an important technology for enhancing the supply chain resilience, and it can have a profound and broader impact in enhancing supply chain resilience and visibility [12,13]. Moreover, I5.0 also plays a positive role in improving supply chain resilience [14]. I5.0 is not a chronological continuation or replacement of existing I4.0, but rather a complementary and extension to the existing I4.0 paradigm [15]. The introduction of I5.0 is based on the principle that I4.0 focuses less on social equity and sustainability and more on leveraging digital and artificial intelligence-driven technologies to improve production efficiency and flexibility [16]. I5.0 can improve efficiency and productivity, while also enhancing the resilience, sustainability, and feasibility of manufacturing and supply chains, making next-generation manufacturing and logistics more cost-effective and responsive [17].

In this study, we aim to investigate the interrelationships between HMTR factors, SCR indicators, and I5.0 enablers in the transportation of hazardous materials by enterprises. There are several innovations. In previous studies, the majority focused solely on the HMTR factors, SCR indicators, and I5.0 enablers. Currently, there is a scarcity of articles studying SCR indicators in the context of I5.0, and there are also limited articles combining SCR indicators with HMTR factors, let alone simultaneous studies that combine the three. This study is the first to combine the three and identify crucial I5.0 enablers to enhance SCR, ultimately mitigating the HMTR factors.

In recent years, QFD has been successfully applied in many fields to solve the MCDM problems, such as the design of medical auxiliary equipment [18], CNC machine tool product design [19], and supplier selection [20], and mobile transportation [21]. However, achieving the integration of QFD and MCDM to develop two quality houses to connect HMTR, SCR, and I5.0 enablers has not yet been achieved.

To address this gap, this study addresses the following research issues:

(a) What are the HMTR, SCR, and I5.0 enablers?

(b) How can we connect QFD, MCDM, and three sets of variables to provide decision support for hazardous material transportation enterprises?

(c) How can enterprises utilize I5.0 enablers to effectively improve SCR and mitigate HMTR?

Hence, the aim of this study is to devise an integrated QFD-MCDM framework tailored for hazardous goods road transportation within the supply chain, aimed at uncovering pivotal managerial insights. Through the application of this framework, crucial I5.0 enablers can be identified, fostering improved SCR and mitigating HMTR. Additionally, it seeks to elucidate the interplay between three vital sets of variables: HMTR, SCR, and I5.0 enablers. This will ascertain the priority sequence, aiding enterprises to strategically allocate limited resources toward the most critical applications. Notably, this study has chosen a hazardous goods transportation enterprise in China as its focal point to showcase the efficacy of the proposed framework. Looking forward, the integration of I5.0 into the supply chains of diverse industries is inevitable. Therefore, this framework serves as a valuable guide for enterprise managers across various industries.

The structure of this study is as follows: Section 2 provides a literature review, exploring the relationship between HMTR factors, SCR indicators, and I5.0 enablers. Section 3 introduces the QFD-MCDM method. Section 4 presents an empirical study and result analysis of a business case. Finally, Sections 5 includes a discussion of the study's results, and Section 6 concludes the study.

2. Literature review

2.1. Hazardous material transportation risks (HMTR)

Given the flammability, explosiveness, corrosiveness, and toxicity of hazardous materials, accidents involving transportation vehicles often lead to more serious secondary injuries, resulting in a series of social problems such as ecological environmental damage, casualties, and property losses [22]. Therefore, in order to alleviate HMTR, it is necessary to first understand the reasons for their occurrence and develop specific countermeasures to improve the safety of transporting hazardous materials on roads.

The transportation of dangerous goods is intricately linked to the safety of human lives and property. It is renowned worldwide for its stringent requirements and rigorous oversight. Stakeholders involved in the transportation of dangerous goods are obligated to adhere to the relevant provisions of international agreements and applicable laws and regulations [23]. This compliance is crucial in preventing the occurrence of adverse events or mitigating their impact. To prioritize the safety of personnel and the environment, these regulations encompass a range of transportation-related behaviors. They address crucial aspects including transportation access for dangerous goods, packaging selection, labeling requirements, as well as stringent regulations imposed on drivers and transportation vehicles [24]. The comprehensive international regulations governing the transport of hazardous materials are presented in Table1. The content of this table has been derived from reputable sources, including the website of the United Nations Economic Commission for Europe [25] and the official website of the Intergovernmental Organization for International Railway Transport (OTIF) [26].

Table1. Legal acts on the transport of dangerous goods.

Abbreviation	International Regulations on the Transport of Dangerous Goods
TDG	Recommendations on the Transport of Dangerous Goods
GHS	Globally Harmonized System of Classification and Labelling of Chemicals
ADR	European Agreement Concerning the International Carriage of Dangerous Goods by Road
ADN	European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways
RID	The Regulation concerning the International Carriage of Dangerous Goods by Rail
IMDG Code	International Maritime Dangerous Goods Code
ICAO-TI	The International Civil Aviation Organization Technical Instructions on the Safe Transport of Dangerous Goods by Air

Several main causes of collisions between dangerous goods vehicles, such as human factors, institutional factors, and equipment factors, have been identified. Yang et al. [27] employed QFD for analyzing the risks of hazardous material transportation. Research has shown that special attention should be given to several aspects, including equipment maintenance, employee training, emergency planning, and the provision of hazardous material transportation services. Guo et al. [28] conducted data mining and analysis of 362 accidents, revealing that driver factors, meteorological environmental factors, vehicle factors, and road environmental factors emerge as the primary causes of hazardous material transportation accidents. Yang et al. [29] conducted a study using Bayesian network models, revealing that the likelihood of accidents is influenced by various factors, such as driver fatigue, degradation of vehicles and fuel tanks, adverse weather conditions, and the absence of street lights at night. Ma et al. [30] found through a logistics regression scorecard model that the safety of hazardous chemical transportation is influenced by driver behavior, driving performance, and environmental conditions.

The presence of loopholes in the security management system composed of these factors escalates the likelihood of accidents. The aforementioned research presents the characteristics and causes of hazardous material transportation accidents. This study develops a risk factor evaluation system for road transportation of hazardous materials by drawing on various risk classification methods and integrating objective reality. The risk is categorized into three types (personnel, systems, and equipment) and further subdivided into 25 factors across the aforementioned types.

2.2. Supply chain resilience (SCR)

Resilience refers to the capacity of a system, such as a supply chain, to promptly and efficiently bounce back from interruptions [31]. According to the majority of scholars, given the inevitability of supply chain disruptions, it is crucial for supply chain management to prioritize enhancing resilience, which involves fortifying the capacity to withstand interruptions while concurrently striving to minimize their occurrence [32].

Ahmed et al. [33] proposed four factors—namely, robustness, agility, lean, and flexibility—to guide the design of green and resilient supply chain networks. In their case study, Hosseini et al. [34] examined an international plastic raw material supplier for a US manufacturer and identified robustness, reliability, and rerouting as the primary driving factors for SCR. In their study, Zhang et al. [35] explored the driving factors affecting cross-border e-commerce SCR and identified seven factors—namely, supply chain agility, supply chain structure, supply chain visibility, information sharing, risk and revenue sharing, geographical distribution, and cooperation with supply chain partners—as potentially crucial for managing SCR. In their research on promoting SCR in the UK perishable goods market, Ozdemir et al. [36] identified innovation as the primary driver, with robustness, authorization, and risk management also playing significant roles.

Zhao et al. [37] examined the distinct effects of absorption capacity, response capacity, and recovery capacity on supply chain performance. The research highlights the diverse impacts of digitalization on these three dimensions of SCR, which are influenced by various resource and structural adjustment measures. Liu et al. [38] developed a resilience framework specifically for the supply chain of the shipping industry. They utilized the MCDM method to comprehensively analyze the key resilience factors. The findings highlight the significance of adaptability and robustness as the primary resilience goals. Moreover, the study emphasizes the need for increased focus on collaborative and flexible resilience strategies in the post-COVID-19 era. Liu et al. [39] identified the crucial indicators that impact the robustness of prefabricated building supply chains. The research comprehensively examines five key dimensions of resilience, namely predictive ability, absorption potential, adaptability, inherent resilience, and growth ability. The study highlights several highly influential secondary factors, including risk perception, logistics support level, collaboration intensity, supply chain restructuring ability, and management strategic decision-making ability. Wang et al. [40] identified the influential factors that impact the resilience of green supply chains for agricultural products. The study reveals that key drivers for enhancing the resilience of these supply chains include government environmental policies, financial subsidies, collaborative capabilities and business sustainability goals, agility, digital infrastructure construction, sustainable development beliefs of senior managers, and public opinion on environmental information disclosure.

This study employs the classification methods of various scholars to classify SCR into 34 indicators, which will be thoroughly examined in Section 4.

2.3. Industry 5.0 (I5.0)

In the context of enhancing I5.0, Ghobakhloo et al. [41] employed an explanatory structural model to reveal that promoting I5.0 transformation relies on development-driven driving factors. These factors comprise active government support, resource availability capabilities, digital transformation capabilities, sustainability orientation and thinking, and stakeholder integration. The study also highlighted the interdependence among these driving factors in facilitating I5.0 transformation. In their study, Sharma et al. [42] put forward an I5.0 framework specifically designed for the German pharmaceutical industry. They identified "linking virtual reality with reality" as the key factor in I5.0. Lo et al. [43] constructed a supplier evaluation framework grounded in I5.0. By utilizing data from a multinational medical equipment manufacturer as an example, the findings revealed that digital transformation, real-time information sharing, and organizational culture transformation emerge as the three primary factors influencing enterprises to transition towards I5.0. In their study, Nayeri et al. [44] constructed a decision-making framework for analyzing healthcare supply chains with a focus on the I5.0 dimension. The findings revealed that high service levels, cost mitigation, recycling, and security emerge as the most important standards. Moreover, employing advanced technology, fostering collaboration, and promoting information sharing are considered the optimal approaches.

In 2021, the European Commission introduced I5.0 as a complement to the existing I4.0 approach, aiming to shape operations and supply chains into resilient, sustainable, and human-centric systems [45]. I5.0 emphasizes human-centric outcomes within the system to create a resilient and sustainable framework, thus addressing the shortcomings of I4.0 [46]. This study draws from a total of 105 relevant sources spanning from 2016 to 2022 and consolidates 123 I5.0 enablers, categorized as “human-centric”, “sustainable”, “resilience”, and “technology”. Given that I5.0 evolves from the foundation of the prior industrial revolution, it is logical for its technology to build upon that of I4.0. These enablers will undergo comprehensive evaluation in chapter 4. As a result, rooted in extensive literature and expert consultations, our framework will analyze the impact of I5.0 and its influence on the transportation of hazardous goods and SCR. A comprehensive evaluation of these enablers will be provided in Section 4, delving into their intricacies and effectiveness.

2.4. HMTR, SCR and I5.0

Enhancing resilience to mitigate risks has emerged as a prominent trend in global business operations and research [47]. Chiou [48] proposed a resilient signal control system for urban road networks associated with the transportation of hazardous materials. Behzad et al. [49] proposed a dual-objective mathematical programming model that incorporates SCR and perishability for designing hazardous material transportation networks, thereby advancing the field. Chao Chen et al. [50] developed a dynamic stochastic method for quantifying the resilience of hazardous material storage facilities. Wang et al. [51] proposed a multi-objective model for hazardous material transportation route planning that incorporates road traffic resilience and low-carbon considerations, thus contributing to the growing body of research on the transportation of hazardous substances within the low-carbon domain.

In summary, it is evident that the concept of SCR is crucial for mitigating the risks associated with the transportation of hazardous material. However, in current research, the consideration and quantification of transportation resilience from the perspective of hazardous materials' SCR remains incomplete. Most studies solely concentrate on one or two segments of the hazardous material transportation process, lacking a systematic and universally applicable approach. Furthermore, despite the abundance of studies on the HMTR and SCR, there is a scarcity of research that integrates the two and applies them to logistics enterprises. Therefore, investigating how logistics companies can enhance SCR to mitigate the HMTR is of paramount importance.

Previous research has demonstrated that emerging technologies, including big data, artificial intelligence, blockchain, cloud computing, and virtual reality in I5.0, exert a positive influence on risk management in the supply chain [52]. For instance, by leveraging artificial intelligence and blockchain technology, enterprises can develop robust systems, ensure uninterrupted business operations, and enhance resilience to disruptions [53]. By employing intelligent digital twins, which are artificial intelligence systems capable of assisting supply chains in preparation and resilience enhancement to mitigate the risks of interruptions [54]. Incorporating additive manufacturing can bolster the state of the supply chain and positively influence specific capabilities, thereby contributing to the improvement of SCR [55].

I5.0, which complements and advances I4.0, is currently in its early stages of exploration [56]. Currently, there is limited literature available on the correlation between I5.0 and SCR. Therefore, this study draws upon existing literature on both I4.0 and SCR. While I5.0, similar to I4.0, can influence SCR, existing research primarily focuses on individual technologies within I5.0 and falls short of comprehensively enhancing SCR from an overarching I5.0 perspective.

Based on the aforementioned, it is evident that previous research has provided limited insights into the intersection of HMTR, SCR, and I5.0. Notably, there is a dearth of studies that comprehensively investigate the interplay among these three factors. Consequently, this study aims to comprehensively investigate pivotal strategies to bolster SCR from the overarching standpoint of I5.0. The objective is to mitigate HMTR and offer valuable insights for decision-making processes in hazardous material transportation enterprises' supply chains.

3. Methodology

This section begins with an introduction to QFD-MCDM, followed by a detailed ex-planation of the employed methodologies. The employed methods in this study encompass fuzzy Delphi method (FDM), decision making trial and evaluation laboratory (DEMATEL), analysis network procedure (ANP), and entropy weight method (EWM).

3.1. Introduction to the QFD-MCDM Method

QFD is a structured methodology employed to convert qualitative customer requirements into quantitative product features and align product functions with design concepts [57]. The house of quality (HoQ) serves as a design tool within the framework of QFD, facilitating the definition of the relationship between customer requirements and design specifications [58]. In the development of a system framework for QFD, the utilization of the MCDM methodology has gained popularity [59]. From a practical standpoint, the feasibility of QFD-MCDM has been substantiated. For instance, Erol et al. [60] employed an integrated decision-making framework of MCDM within QFD to investigate the influence of blockchain technology in alleviating barriers to the adoption of a circular economy. In order to incorporate a greater number of factors into the assessment of importance, several studies have extended the traditional QFD approach to multi-stage QFD [61]. Multi-stage QFD evaluates importance by taking into account multiple factors and their interrelationships [62].

Assigning appropriate weights to standards is a crucial step in the decision-making process of MCDM problems. Two types of weights, subjective and objective, are commonly defined in MCDM problems [63]. For instance, Mahdi et al. [64] proposed a hybrid MCDM method that integrates subjective and objective standard weights to derive more reasonable weightings. This approach was applied to case studies involving the evaluation of building equipment based on sustainability standards. Nico et al. [65] combined fuzzy and rough uncertainty theories to develop an MCDM model. This model was specifically designed to meet the regulatory and operational requirements for the successful transportation of dangerous goods. Its primary application is to comprehensively evaluate the performance of companies engaged in the transportation of dangerous goods. Amir et al. [66] established a mixed two-stage QFD and MCDM framework. This framework was applied to evaluate and select the optimal licensor from a targeted Iranian lubricant producer, showcasing its decision-making efficacy within a practical industrial context.

This study employs a two-stage QFD approach to examine the correlation among HMTR, SCR, and I5.0, aiming to provide a visual representation of the analysis results. The constructed QFD model is presented in Figure 1. The research process is illustrated in Figure 2.

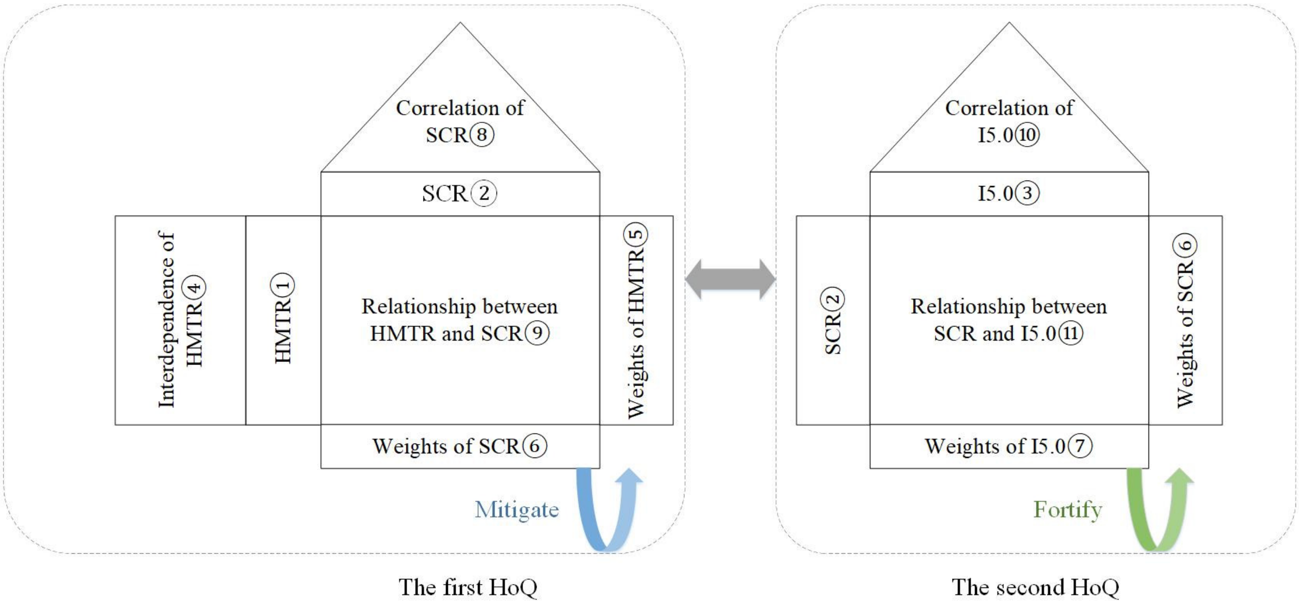

Figure 1. Two-stage QFD.

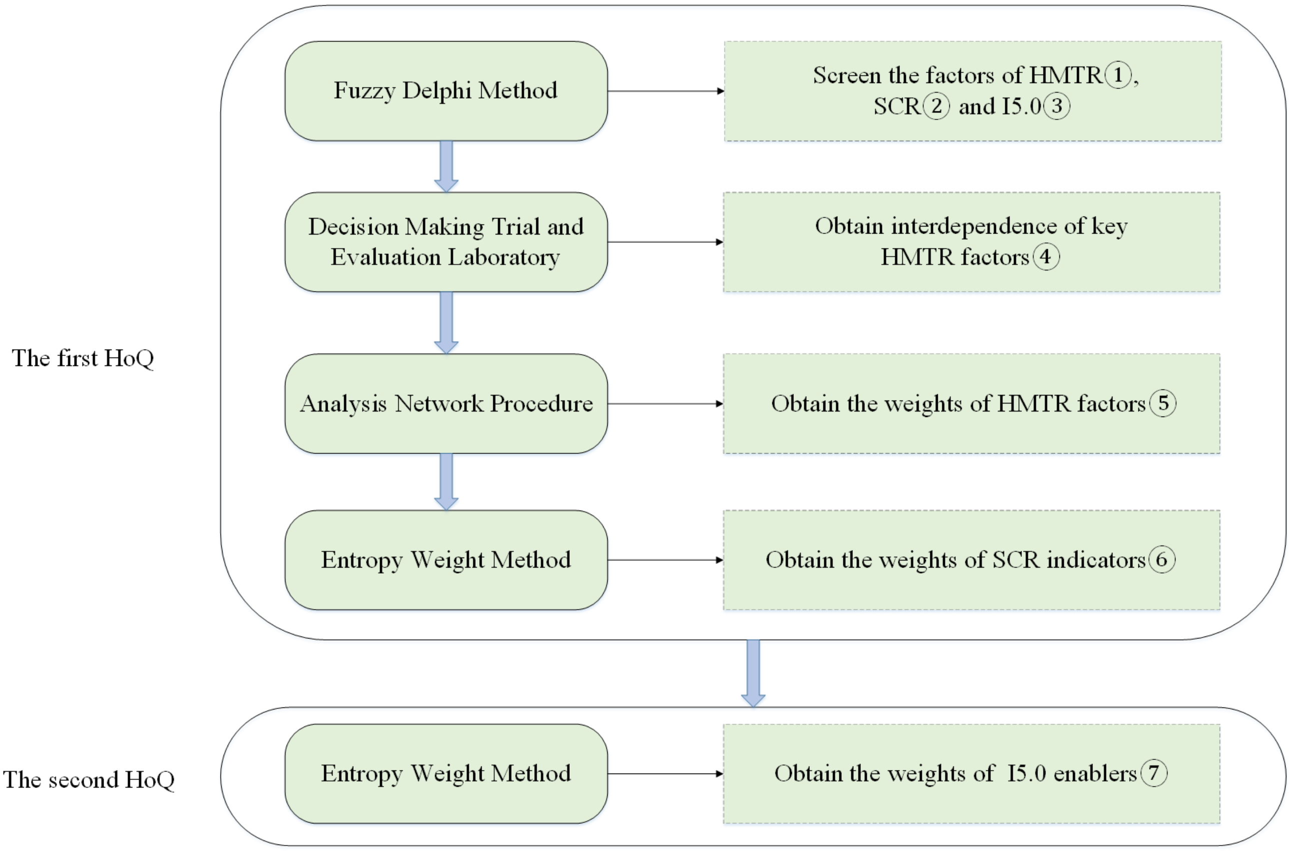

Figure 2. Research flow chart.

The first HoQ establishes a connection between HMTR and SCR, aiming to identify the SCR indicators that can effectively mitigate HMTR. The second HoQ establishes a link between SCR and

I5.0, with the objective of identifying the I5.0 enablers that can substantially enhance SCR.

In this study, FDM was initially employed to conduct a preliminary screening of factors associated with HMTR (1), SCR (2), and I5.0 (3). Subsequently, the ranking weights of HMTR factors (4)(5) were determined using the DEMATEL-ANP method. Through data processing and analysis of the correlation matrix between HMTR and SCR using the EWM, the ranking weights of SCR indicators (6) were obtained. Similarly, the ranking weights of I5.0 enablers (7) were derived using the same method. The internal correlation matrix (8), (10) of these factors, as well as the correlation matrix (9), (11) between two factors, were obtained through questionnaire analysis and integration.

The choice to utilize this combination method is primarily driven by the following factors:

(a) All the data in this study is derived from survey questionnaires, and FDM is presently one of the predominant approaches for analyzing such data.

(b) This study utilizes a fusion of the DEMATEL method and the ANP to dissect the hazards associated with the transportation of dangerous goods and to derive composite weights. Using only DEMATEL and ANP has certain limitations. While the DEMATEL method can analyze the causal relationships between indicators and identify key factors, it fails to consider varying weights for each evaluation indicator when used in isolation for risk assessment. In contrast, the ANP method effectively determines indicator weights for each factor, presupposing a clear hierarchical relationship between indicators. However, in situations with numerous influencing factors, ANP cannot guarantee the independence between these indicators, potentially leading to biased results.

The DEMATEL-ANP method addresses these shortcomings by deriving the mixed weights of factors. This not only reflects the magnitude of the influence relationships among factors but also considers the weight of each factor, remedying the limitations of solely employing the DEMATEL method. Our study strategically combines these two methods to leverage their complementary advantages. Despite the subjective nature of the DEMATEL-ANP methodology, the amalgamation of these two approaches markedly curtails subjective bias. Consequently, this union yields evaluations that are more scientifically sound and precise compared to the use of either method in isolation, concurrently boasting strong applicability. Notably, the integrated DEMATEL-ANP method adeptly manages and accounts for the interrelationships among distinct criteria, underscoring its efficacy in handling the interdependence between divergent standards. The blended DEMATEL-ANP method effectively manages and accounts for the interdependencies among various criteria [67,68].

(c) Acknowledging the inherent subjectivity of survey questionnaires, this study seeks to employ more objective evaluation methods to counterbalance the subjective influence inherent in the data. In this pursuit, the EWM emerges as a formidable option. Notably, from a data-centric standpoint, this method offers an objective evaluation of the assessment object by eschewing the need for presumptions about data distribution, thereby facilitating relatively straightforward calculations. Given the multifaceted nature of risk assessment, characterized by numerous complex indicators, the EWM is harnessed to assign indicator weights based on the degrees of disparity among each indicator. This not only streamlines the calculation process but also upholds a certain level of rationality and scientific rigor. By employing EWM and QFD, the interrelationships between the two indicators are established, leading to the derivation of conclusions regarding essential SCR indicators and I5.0 enablers.

3.2. Fuzzy Delphi method (FDM)

FDM integrates the Delphi method and fuzzy theory analysis, enabling the generation of robust consensus among a panel of experts. This approach enhances the efficiency and quality of traditional Delphi method investigations while addressing scenarios where judgments cannot be precisely articulated [69]. The specific steps involved in FDM are outlined below.

1) Validate all risks associated with HMTR, SCR, and I5.0 enablers. Create a questionnaire to assess all relevant projects, assemble an appropriate panel of experts, and request each expert to provide a possible range of values for each improvement measure.

2) Calculate σ、C^i、O^i. Among σ, extreme values beyond "two standard deviations" will be excluded. C_L^i、C_U^i、C_M^i represent the minimum, maximum, and geometric mean, respectively, of the "most conservative value" C^i. O_L^i、O_U^i、O_M^i represent the minimum, maximum, and geometric mean, respectively, of the "most optimistic value" O^i.

3) Calculate the consensus level G^i by considering expert opinions and classify it into the following three categories: Z^i represents the ambiguous region of fuzzy relationships, while M^i represents the range of optimistic and conservative perceptions. When $Z^i = 0$, G^i is the arithmetic mean of C_M^i and O_M^i.When $Z^i > 0$ and $Z^i \geqslant M^i$, it suggests that expert opinions tend to align, and the outcome achieves convergence. When $Z^i > 0$ and $Z^i < M^i$, it signifies that expert opinions have not reached convergence, requiring the repetition of above steps until all factors have achieved convergence and the value of G^i can be calculated.

$$G^i = \left[\frac{(C_U^i \times O_M^i) - (O_L^i \times C_M^i)}{(C_U^i - C_M^i) + (O_M^i - O_L^i)}\right] \tag{1}$$

4) Establish an appropriate threshold and exclude any factors that fall below it.

3.3. Decision making trial and evaluation laboratory (DEMATEL)

DEMATEL method is a MCDM approach employed to identify key factors and assign weights to indicators. DEMATEL enables effective analysis of the degree of direct impact and causal relationships among different factors and presents the direct impact degree between various factors in matrix form [70]. The specific steps for implementing DEMATEL are as follows.

1) Represent the expert opinions in matrix form using a questionnaire survey.
2) The questionnaire can generate a direct relationship matrix *Z*.
3) Normalize the matrix and obtain *X*.
4) Compute the comprehensive impact matrix *T*.

$$T = X \times (I - X)^{-1} \tag{2}$$

5) Assess the centrality and causal degree of each factor.
6) Wi represents the weight of the factor.

$$w_i = \sqrt{(D+R)^2 + (D-R)^2}, W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{3}$$

7) Define the threshold value.

3.4. Analysis network procedure (ANP)

Professor Saaty proposed the ANP method, which was developed based on analytic hierarchy process (AHP) and is one among several MCDM methods [71]. ANP addresses the issue of element interdependence in AHP, allowing for a more robust evaluation of the interrelationships among factors, ensuring objectivity and accuracy in the evaluation process. Consequently, ANP surpasses AHP in terms of priority allocation and the significance of research outcomes [72]. ANP consists of the following specific steps.

1) Construct a pairwise comparison matrix.

$$A_{ij} = \begin{bmatrix} 1 & \cdots & a_{1m} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \cdots & a_{1m} \\ \vdots & \ddots & \vdots \\ {}^{1}/_{a_{1m}} & \cdots & 1 \end{bmatrix} \tag{4}$$

2) Compute the feature vectors of the matrix.

$$W_m = \frac{1}{n} \times \sum_j^n a_{ij} = \frac{a_{ij}}{\sum_{i-1}^n a_{ij}} \tag{5}$$

3) Consistency assessment involves examining the consistency of expert judgments on evaluation values, calculating the consistency index (C.I.) and consistency ratio (C.R.) values. In complex problems with multiple factors, the C.R. value can be utilized to assess consistency, with a threshold of C.R. < 0.1. Otherwise, further discussions with experts are needed to determine the degree of impact. The formula for consistency assessment is as follows.

$$\lambda_{max} = \left(\frac{1}{m}\right) \times \left(\frac{w_1'}{w_1} + \frac{w_2'}{w_2} + \frac{w_3'}{w_3} + \cdots + \frac{w_m'}{w_m}\right) \tag{6}$$

$$C.I = \frac{\lambda_{max} - m}{m-1} \tag{7}$$

$$C.R = \frac{C.I}{R.I} \tag{8}$$

4) Determine the super matrix values.

3.5. Entropy weight method (EWM)

EWM is a MCDM technique employed to determine the weights of criteria. EWM offers several advantages, allowing for the calculation of relative weights of responses in a straightforward and unbiased manner, effectively evaluating indicators [73]. The weights of the criteria are adjusted using entropy weighting based on the degree of variation exhibited by each alternative solution, resulting in more objective criterion weights [74]. The following presents a method for determining criterion weights using EWM.

1) Create the initial matrix.

$$X_{ij}' = \begin{bmatrix} X_{11}' & \cdots & X_{1n}' \\ \vdots & \ddots & \vdots \\ X_{m1}' & \cdots & X_{mn}' \end{bmatrix} \tag{9}$$

2) Standardize the data.

$$X_{ij} = \begin{bmatrix} \frac{X'_{ij}-X_{min}}{X_{max}-X_{min}} (Positive\ \ values) \\ \frac{X_{max}-X'_{ij}}{X_{max}-X_{min}} (Negative\ \ values) \end{bmatrix} \tag{10}$$

3) Compute the P_{ij} value for transportation resilience.

$$P_{ij} = X_{ij} / \sum_{i=1}^{n}(X_{ij})(j = 1,2,3,\cdots m) \tag{11}$$

4) The calculation method for entropy value E_j.

$$E_j = -\frac{1}{ln\, n} \times \sum_{i=1}^{n} P_{ij}\, ln(P_{ij})(0 \le E_{ij} \le 1) \tag{12}$$

5) Computing the coefficient of variation G_j.

$$G_j = 1 - E_j \tag{13}$$

6) Determine the weight W_j for each indicator.

$$W_j = G_j / \sum_{j=1}^{m}(G_j)(j = 1,2,3,\cdots m) \tag{14}$$

7) Compute the overall score U_i.

$$U_i = \sum_{j=1}^{m} W_j * P_{ij} \tag{15}$$

4. Empirical study

In this study, we chose a Chinese logistics company as a research case to evaluate its performance in a risk environment. The selected company is a contemporary logistics enterprise that integrates hazardous chemicals, general cargo, warehousing, containers, international freight forwarding, and import and export goods trade. Eight experienced supply chain experts from the company participated in a survey questionnaire, which assisted managers in establishing a fresh perspective for supply chain analysis. Consequently, we applied the QFD-MCDM algorithm to examine this particular case, identify the most critical key factors, and assess their impact on the entire supply chain, thereby providing valuable insights for managers.

This study seeks to address the impact of risk factors in the transportation of hazardous materials, with a focus on bolstering SCR and leveraging I5.0 enablers. Our objective is to mitigate HMTR by integrating I5.0 into supply chain operations. To achieve this, our study draws from comprehensive literature sources spanning from 2016 to 2023. We have collated 25 identified HMTR factors, 34 SCR indicators, and 123 I5.0 enablers. These elements are gleaned from scholarly articles and have been thoroughly vetted through discussions with supply chain experts to ensure alignment with practical industry requirements. Additionally, a targeted questionnaire has been developed for completion by supply chain experts to pinpoint key factors and indicators.

This study centers on employing the expert questionnaire method, engaging eight seasoned supply chain experts within the industry. These experts, each possessing over a decade of experience in hazardous material transportation across various departmental roles, were selected for their capability to provide pertinent insights. We conducted in-depth interviews and employed comprehensive survey questionnaires to obtain their perspectives, subsequently utilizing the QFD-MCDM algorithm to process and analyze the acquired data. Through this approach, we discerned critical factors and evaluated their impact on the entire supply chain, enabling a fresh, holistic vantage point for managerial decision-making. The detailed professional backgrounds of the participating experts are delineated in Table 2.

Table 2. Relevant information of questionnaire respondents.

Respondent	Years of Experience
Chief Engineer	22 years
Supply Chain Manager	15 years
Production Manager	17 years
Quality Manager	15 years
Materials Supervisor	18 years
Inventory Control Supervisor	20 years
Industrial Engineer Manager	12 years
Logistics Coordinator	15 years

4.1. First HoQ

4.1.1. FDM

In this study, we initially identified 25 HMTR factors, 34 SCR indicators, and 123 I5.0 enablers from recent literature. FDM was then employed to screen the key factors. Firstly, we compiled the summarized indicators into a questionnaire and distributed it for data collection. For the collected questionnaire data, we calculated the standard deviation σ to identify extreme values beyond two standard deviations. Next, we utilized the definition of fuzzy numbers to determine the triangular fuzzy numbers for each indicator. Subsequently, we classified and discussed the results of the aforementioned analysis and calculations, and applied Eq (1) to calculate the consensus value and perform sorting. Finally, we established threshold values for screening based on expert discussions. For the HMTR factors, the threshold value was set at 5.95. The threshold value for the SCR indicators was set at 6.005. Regarding the four aspects of I5.0 enablers, specific threshold values were assigned for each aspect. For the first aspect, "human-centric", the threshold value was set at 6.00. For dimension 2, "sustainable", the threshold value was set at 6.00. For dimension 3, "resilience", the threshold value was set at 5.92. Lastly, for dimension 4, "technology", the threshold value was set at 6.00. The final selection of key factors is presented in Table 3–5.

Table 3. Key HMTR factors selected by FDM.

NO.	HMTR Factors	G^i
A1	Awareness of Personnel Safety Responsibility	7.376
A2	Overspeeding of Vehicles	7.002
A3	Loading Capacity of Hazardous Material	6.782
A4	Leakage	6.529
A5	Security Screening	6.515
A6	Safety Operation Regulations	6.513
A7	Capability for Emergency Rescue	6.454

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NO.	HMTR Factors	G^i
A8	System for Emergency Management	6.433
A9	Performance of Vehicles	6.242
A10	Properties of Hazardous Materials	6.133
A11	Condition of Hazardous Materials Containers	6.061
A12	Physical and Psychological Qualities of Personnel	5.980

Table 4. Key SCR indicators selected by FDM.

NO.	SCR Indicators	G^i
B1	Sensitivity	6.468
B2	Financial Capability	6.454
B3	Human Resource Management	6.402
B4	Efficiency	6.370
B5	Communication	6.283
B6	Innovation Capability	6.164
B7	Sustainability	6.152
B8	Flexibility	6.149
B9	Excellent Customer Service	6.122
B10	Predictive Ability	6.116
B11	Speed	6.115
B12	Authority	6.026
B13	Risk Awareness	6.008
B14	Production Capacity	6.005

Table 5. Key I5.0 enablers selected by FDM.

Dimension	NO.	I5.0 Enablers	G^i
Human-centric	C1	Establish a Safe and Inclusive Work Environment	6.429
	C2	Prioritize Employee Safety, Management, and Training	6.167
	C3	Humanize Technology and Provide Training for New Technology Adoption	6.037
	C4	Prioritizing Human Needs (Worker Welfare and Basic Rights)	6.006
Sustainable	C5	Customized Products and Services	6.337
	C6	Sustainable Consumption and Production	6.286
	C7	Advanced Digital Technology Reduces Waste and Lowers Production Costs	6.023
	C8	Business Model Innovation	6.007
Resilience	C9	Enhance Production Flexibility and Strengthen Control Redundancy	6.275
	C10	Agile and Adaptable Business Processes	6.260
	C11	Efficiently Accomplish Precise and Creative Tasks in Less Time	5.967
	C12	Self-Recovery and System-Wide Recovery	5.923
Technology	C13	Ensuring Traceability in Raw Materials and Production	7.264
	C14	Real-Time Data Collection and Analysis	7.232
	C15	Governmental and Policy Support	6.950
	C16	Automated Recognition Technology and Sensor Technology	6.618

Table 6. The direct relationship matrix for HMTR factors.

NO.	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
A1	0.000	1.889	2.111	1.778	2.167	2.000	1.611	2.06	1.667	1.444	1.222	2.222
A2	1.778	0.000	2.000	1.444	1.667	2.111	1.389	2.11	2.167	1.611	2.000	1.722
A3	1.778	2.389	0.000	2.556	2.000	1.667	1.444	1.67	1.722	2.167	1.722	1.667
A4	1.722	1.722	2.056	0.000	2.556	2.167	1.944	1.67	1.500	1.500	2.611	1.389
A5	2.556	1.667	2.556	2.111	0.000	1.667	1.667	2.17	2.167	1.611	2.222	1.500
A6	2.556	2.500	2.611	2.111	2.167	0.000	2.111	2.11	2.056	1.500	1.611	1.500
A7	1.167	1.167	1.556	1.111	2.056	1.944	0.000	2.22	1.556	1.611	1.500	1.944
A8	2.056	1.611	2.111	2.056	2.056	1.611	2.167	0.00	1.333	1.444	1.556	1.444
A9	1.611	1.889	2.056	1.667	2.000	1.500	1.500	1.33	0.000	1.389	2.000	1.444
A10	1.778	1.833	2.056	1.944	2.056	1.667	1.500	2.00	1.333	0.000	1.444	1.444
A11	1.500	1.889	1.556	2.278	2.111	1.500	1.556	1.50	2.056	1.611	0.000	1.278
A12	2.500	2.444	1.167	1.389	1.278	1.111	1.389	1.94	1.111	1.333	1.389	0.000

To delve into the indirect impact relationships between factors, standardizing the direct impact matrix to obtain a normalized relationship matrix is essential. Normalization, a standard routine, is crucial in this context. The method chosen for normalization is pivotal and focuses on how to acquire the maximum value. Ensuring that the values in the matrix align within closed intervals of 0–1 necessitates that they surpass any directly affecting value within the matrix. Typically, averaging is employed in the normalization process, emphasizing the use of a maximum value as the standard.

There exist numerous methods for obtaining normalized relationship matrices. For instance, these include the row and maximum value method, which corresponds to the column and maximum method. Additionally, the row sum, column sum, and maximum value method involve taking the maximum value derived from all row and column sums. Another approach, the chord method, operates by treating the row sum and maximum value as one side of a right-angled triangle, the column sum and maximum value as another side, and the diagonal side (chord), as the maximum value.

Commonly used and more readily understood methods are those associated with trigonometric functions. For example, the maximum right-angled edge method involves fuzzy operator-related methods that employ the maximum value. In essence, prevalent methods impacting matrix normalization are rules governed by linear geometry.

In this study, we adopt a standardization method that entails extracting the maximum sum of elements in each row of the matrix and subsequently dividing it by the direct relationship matrix to obtain the normalized relationship matrix.

The literature review revealed that HMTR factors and SCR indicators not only interact with each other, but different HMTR factors also exhibit interrelationships. For instance, a significant correlation exists between security screening (A5) and performance of vehicles (A9). Therefore, this study employs DEMATEL methodology to enhance the understanding of the interrelationships among different HMTR factors. By organizing the questionnaire, a direct impact matrix can be derived, and by utilizing Eq (2), a comprehensive impact matrix T can be generated, as shown in Table 7.

Table 7. Comprehensive impact matrix T for HMTR factors.

NO.	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
A1	0.521	0.595	0.625	0.581	0.631	0.553	0.522	0.596	0.535	0.492	0.533	0.529
A2	0.587	0.514	0.616	0.564	0.607	0.553	0.509	0.592	0.550	0.494	0.557	0.505
A3	0.606	0.627	0.556	0.625	0.641	0.555	0.529	0.596	0.551	0.532	0.567	0.519
A4	0.607	0.605	0.642	0.527	0.665	0.576	0.550	0.599	0.547	0.509	0.602	0.511
A5	0.660	0.626	0.684	0.634	0.588	0.578	0.560	0.639	0.591	0.532	0.608	0.535
A6	0.684	0.681	0.711	0.656	0.699	0.533	0.597	0.661	0.609	0.548	0.607	0.556
A7	0.512	0.510	0.544	0.500	0.566	0.498	0.406	0.545	0.479	0.450	0.489	0.469
A8	0.584	0.566	0.608	0.575	0.610	0.524	0.528	0.497	0.508	0.478	0.530	0.485
A9	0.542	0.552	0.578	0.535	0.580	0.496	0.480	0.526	0.430	0.455	0.523	0.462
A10	0.566	0.567	0.597	0.563	0.601	0.518	0.496	0.569	0.500	0.412	0.518	0.477
A11	0.549	0.562	0.572	0.569	0.597	0.506	0.492	0.543	0.522	0.472	0.454	0.465
A12	0.541	0.537	0.509	0.489	0.516	0.450	0.445	0.516	0.445	0.423	0.466	0.375

Utilize Eq (3) for calculating *wi* and *WI*. The results obtained are presented in Table 8.

Table 8. Centrality analysis of HMTR factors.

NO.	Row D	Column R	CentralityD+R	CausalityD–R	wi	WI	Rank
A1	6.711	6.959	13.670	–0.248	13.732	0.086	5
A2	6.649	6.940	13.589	–0.292	13.674	0.085	6
A3	6.903	7.243	14.146	–0.339	14.261	0.089	3
A4	6.941	6.818	13.759	0.123	13.774	0.086	4
A5	7.235	7.301	14.536	–0.066	14.541	0.091	2
A6	7.543	6.341	13.883	1.202	15.328	0.096	1
A7	5.968	6.115	12.082	–0.147	12.104	0.076	11
A8	6.492	6.878	13.370	–0.386	13.519	0.084	7
A9	6.159	6.266	12.425	–0.107	12.437	0.078	10
A10	6.386	5.798	12.184	0.588	12.529	0.078	9
A11	6.301	6.453	12.753	–0.152	12.776	0.080	8
A12	5.712	5.889	11.601	–0.177	11.633	0.073	12

4.1.2. ANP

1) Categorize the 12 factors into three categories: personnel, systems, and equipment. Personnel factors include: A1–awareness of personnel safety responsibility, A12–physical and psychological qualities of personnel, and A7–capability for emergency rescue. Systems factors include: A5–security screening, A6–safety operation regulations, and A8–system for emergency management. Equipment factors include: A2–overspeeding of vehicles, A9–performance of vehicles, A3–loading capacity of hazardous material, A10–properties of hazardous materials, A4–leakage, and A11–condition of hazardous materials containers.

2) Determine the threshold value for the comprehensive impact matrix (*T*) through expert discussion, setting it to 0.545. As a result, a total of 74 data points were obtained.

3) Assess the relationship between the row data and column data using SuperDecisions software.

4) Enter the questionnaire data into the software, calculate the data weights given by eight experts, and then calculate the arithmetic average to obtain the average weights, as displayed in Table 9.

5) Apply the formula $z = \omega + T\omega$ (here, z represents the mixed weight, ω obtained for ANP, T obtained for DEMATEL) normalize the weights to obtain the data required for the first HoQ. The results are presented in Table 10.

Table 9. Average weights of experts (ω).

NO.	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
ω	0.342	0.168	0.112	0.034	0.124	0.066	0.026	0.055	0.015	0.001	0.041	0.015

To address the issue of the DEMATEL method assuming uniform weights for each indicator during calculation, neglecting the diverse actual weight proportions of each indicator, we introduce the concept of mixed weight [75]. Here, Z embodies the mixed weight matrix of each indicator following the integration of DEMATEL and ANP, weight indicates the weight of each indicator obtained through the ANP method, and T represents the comprehensive impact matrix derived from the DEMATEL method.

The specific resolution involves leveraging the causal relationship between various indicators. This method utilizes the DEMATEL approach to acquire the comprehensive impact matrix T and subsequently amalgamates the weights (w) of each element procured through the ANP method to derive the mixed weight (z).

Table 10. The final weights of HMTR factors.

NO.	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
Tw	0.568	0.572	0.599	0.608	0.633	0.668	0.518	0.571	0.543	0.565	0.550	0.515
z	0.910	0.741	0.711	0.642	0.757	0.734	0.544	0.627	0.558	0.566	0.590	0.530
z’	0.115	0.094	0.090	0.081	0.096	0.093	0.069	0.079	0.071	0.072	0.075	0.067
rank	1	3	5	6	2	4	11	7	10	9	8	12

4.1.3. EWM

1) After distributing questionnaires to experts, the collected responses were used to compile a correlation matrix that examines the relationship between risk factors and resilience factors in Table 11.

2) Employ Eq (11) to compute the weight P_{ij} of each sample for the indicator in Table 12.

3) Utilize Eqs (12), (13), and (14) to calculate the entropy values E_j, difference coefficient G_j, and weight W_j of the respective indicators in Table 13.

4) Combine the row data from the comprehensive score table to generate the ranking of resilience indicators in Tables 14 and 15.

Table 11. Standardized matrix of HMTR and SCR.

NO.	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
B1	4.875	5.000	5.750	6.125	5.375	5.625	4.375	3.875	4.250	4.875	4.500	4.250
B2	5.125	4.375	4.250	3.500	4.750	4.250	3.625	3.625	4.000	3.500	3.500	3.875
B3	5.000	3.875	4.250	3.250	5.000	4.250	4.250	3.625	4.250	3.125	3.750	3.875
B4	6.500	5.875	4.750	6.000	6.250	5.875	4.875	4.000	4.125	4.625	4.000	4.125
B5	4.250	4.500	4.750	3.875	5.625	4.375	5.125	5.375	5.125	4.625	3.875	5.250
B6	4.125	4.375	4.625	5.500	5.750	5.750	4.750	5.750	4.750	5.750	5.250	5.750
B7	4.125	4.500	3.750	4.000	4.750	4.875	3.250	5.500	5.250	4.875	3.625	5.250
B8	5.750	3.375	4.750	3.250	4.750	3.000	5.625	5.500	3.375	4.000	5.750	5.250
B9	4.875	4.125	4.000	3.250	4.750	3.000	5.125	3.875	3.750	4.250	6.250	5.125
B10	6.000	3.500	4.125	4.875	4.250	4.875	4.375	3.875	3.500	4.000	3.875	5.625
B11	6.125	5.250	6.125	5.875	4.750	4.875	5.375	3.500	4.500	5.750	3.250	6.125
B12	4.000	4.000	4.250	4.625	4.875	6.750	3.500	5.500	3.500	4.250	3.375	5.625
B13	5.500	6.625	6.000	6.875	5.875	6.375	5.625	4.250	3.750	5.000	4.375	6.000
B14	5.750	4.125	4.500	4.375	4.750	6.250	6.250	3.375	4.125	3.750	5.125	3.375

Table 12. Pij of HMTR and SCR.

NO.	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
B1	0.05	0.10	0.15	0.14	0.09	0.09	0.05	0.03	0.08	0.09	0.08	0.02
B2	0.07	0.06	0.04	0.01	0.04	0.04	0.02	0.01	0.06	0.02	0.02	0.00
B3	0.06	0.03	0.04	0.00	0.06	0.04	0.05	0.01	0.08	0.00	0.03	0.00
B4	0.16	0.15	0.07	0.14	0.17	0.10	0.08	0.04	0.07	0.08	0.05	0.02
B5	0.02	0.07	0.07	0.03	0.11	0.05	0.09	0.15	0.16	0.08	0.04	0.09
B6	0.01	0.06	0.07	0.11	0.12	0.10	0.07	0.18	0.12	0.14	0.13	0.12
B7	0.01	0.07	0.00	0.04	0.04	0.07	0.00	0.16	0.17	0.09	0.03	0.09
B8	0.11	0.00	0.07	0.00	0.04	0.00	0.12	0.16	0.00	0.05	0.17	0.09
B9	0.05	0.05	0.02	0.00	0.04	0.00	0.09	0.03	0.03	0.06	0.20	0.08
B10	0.12	0.01	0.03	0.08	0.00	0.07	0.05	0.03	0.01	0.05	0.04	0.11
B11	0.13	0.12	0.18	0.13	0.04	0.07	0.10	0.00	0.10	0.14	0.00	0.15
B12	0.00	0.04	0.04	0.07	0.05	0.13	0.01	0.16	0.01	0.06	0.01	0.11
B13	0.09	0.20	0.17	0.18	0.14	0.12	0.12	0.06	0.03	0.10	0.07	0.14
B14	0.11	0.05	0.06	0.06	0.04	0.12	0.15	–0.01	0.07	0.03	0.12	–0.03

Table 13. E_j, G_j, and W_j of HMTR and SCR.

NO.	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
E_j	0.85	0.68	0.68	0.63	0.73	0.69	0.69	0.72	0.74	0.76	0.66	0.74
G_j	0.15	0.32	0.32	0.37	0.27	0.31	0.31	0.28	0.26	0.24	0.34	0.26
W_j	0.10	0.08	0.08	0.07	0.08	0.08	0.08	0.08	0.09	0.09	0.08	0.09

Table14. Comprehensive scores of HMTR and SCR.

NO.	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
B1	0.005	0.008	0.012	0.011	0.008	0.008	0.004	0.003	0.007	0.008	0.006	0.002
B2	0.007	0.005	0.003	0.001	0.004	0.004	0.001	0.001	0.005	0.002	0.001	0.000
B3	0.006	0.002	0.003	0.000	0.005	0.004	0.004	0.001	0.007	0.000	0.003	0.000
B4	0.015	0.012	0.006	0.010	0.014	0.008	0.006	0.003	0.006	0.007	0.004	0.001
B5	0.002	0.006	0.006	0.002	0.010	0.004	0.007	0.013	0.014	0.007	0.003	0.008
B6	0.001	0.005	0.005	0.008	0.011	0.008	0.006	0.015	0.011	0.013	0.010	0.011
B7	0.001	0.006	0.000	0.003	0.004	0.005	0.000	0.013	0.015	0.008	0.002	0.008
B8	0.011	0.000	0.006	0.000	0.004	0.000	0.009	0.013	0.000	0.004	0.013	0.008
B9	0.005	0.004	0.001	0.000	0.004	0.000	0.007	0.003	0.003	0.005	0.015	0.007
B10	0.012	0.001	0.002	0.006	0.000	0.005	0.004	0.003	0.001	0.004	0.003	0.010
B11	0.013	0.009	0.014	0.010	0.004	0.005	0.008	0.000	0.009	0.013	0.000	0.013
B12	0.000	0.003	0.003	0.005	0.004	0.011	0.001	0.013	0.001	0.005	0.001	0.010
B13	0.009	0.016	0.013	0.013	0.012	0.010	0.009	0.005	0.003	0.009	0.006	0.012
B14	0.011	0.004	0.004	0.004	0.004	0.009	0.012	–0.001	0.006	0.003	0.010	–0.003

Table 15. Ranking of SCR indicators based on comprehensive scores.

NO.	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14
score	0.082	0.033	0.035	0.094	0.081	0.103	0.064	0.068	0.055	0.052	0.097	0.058	0.117	0.062
rank	5	14	13	4	6	2	8	7	11	12	3	10	1	9

4.2. Second HoQ

The standardized matrix of SCR and I5.0, similar to the first stage of HoQ, are presented in Table16. The calculation process is similar to the first stage, so we will not elaborate on it again.

Table16. Standardized matrix of SCR and I5.0.

NO.	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14
C1	4.5	5.625	5.375	6.125	5.25	3.5	4.375	5.5	4.625	5	4.875	3	4.375	5.875
C2	4.125	4.875	5.375	4.625	4.375	5.25	3.25	2.75	5.125	2.5	4.75	3.5	4	4.25
C3	3.375	3.75	3.625	4.125	2.375	3.25	5.875	5.375	5.875	3.625	4.75	2	3.75	4.75
C4	2.875	5.25	4.875	5.75	3.25	3.75	5.125	4	2.25	2.5	5.875	4.375	3.5	4.625
C5	4.25	5.625	5.375	2.125	4.125	5	4	4	5.375	3.5	3.25	5.25	4.625	3.625
C6	5	2.625	1.75	4	2	4.125	6.625	5.125	5.75	1.875	5.375	2.625	2.625	6.375
C7	4	2.625	2.875	5.125	1.375	3.625	4.125	5.125	3.625	5.75	4.875	2.625	4.375	5.5
C8	4.75	4.5	1.875	5.25	3.875	5.875	6.25	6.5	2.5	5.75	3.5	4.375	6	4.625
C9	5.125	6.75	3.125	6.625	3.125	4.875	5.25	5.625	2.875	2.75	4.75	2.125	5.125	6.625
C10	5.125	5.13	2.25	4.5	4.875	4	4	5.25	2.75	4.25	4.5	4.25	4	6.25
C11	3.75	2.625	4.125	6.625	5.375	2.375	4.375	5	6.5	2.125	5.625	2.75	2	5
C12	4.25	5.5	3.75	3	1.875	3	4.125	5.25	3.25	5	4.625	3.875	5.125	3.5

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NO.	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14
C13	4	4.5	2.375	3.875	4.875	2.75	4.25	5.25	2.25	2.25	4.875	3.25	5	4.875
C14	4.125	4.5	3	5.625	5.25	4.375	4.125	6.125	2.125	5.125	4.625	4	4.75	4.375
C15	4.625	5.75	1.625	4.875	2.25	5.5	5.5	3.75	3.25	2.25	4	2.125	3	4.625
C16	4.75	5.375	3.375	4.75	3.25	3.75	4.375	5.75	2.75	3.75	5	3.625	5.5	5

Table 17. Ranking of I5.0 enablers based on comprehensive scores.

NO.	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
score	0.080	0.068	0.057	0.062	0.071	0.054	0.058	0.068	0.069	0.064	0.061	0.059	0.052	0.064	0.049	0.063
rank	1	5	13	9	2	14	12	4	3	6	10	11	15	7	16	8

5. Discussion

The Pareto principle suggests that approximately 80% of the impact arises from 20% of the causes in many events [76]. By leveraging the Pareto effect, greater expected effects can be achieved by focusing on a few key factors when resources are limited. Given the constraints of limited resources in enterprises, it becomes challenging to simultaneously enhance all aspects of I5.0 enablers and SCR. To effectively address the HMTR, enterprise managers should prioritize factors and gradually allocate resources to maximize benefits. In this article, we apply the Pareto effect to the QFD-MCDM framework to determine the importance ranking of these three variables. The utilization of key I5.0 enablers aims to fortify SCR and mitigate HMTR in logistics enterprises, as depicted in Figure3.

5.1. First HoQ

In addressing HMTR, it is crucial to prioritize attention on four key factors that significantly impact enterprise operations: (1) awareness of personnel safety responsibility, (2) security screening, (3) capability for emergency rescue, and (4) safety operation regulations. These factors should be the primary focus for enterprise decision-makers. The subsequent discussion delves into these four factors influencing HMTR.

(1) Awareness of personnel safety responsibility: Regardless of whether transporting hazardous material or other ordinary goods, drivers' awareness of safety responsibility holds paramount importance in actual transportation. Drivers should remain vigilant even when driving on unmanned roads or familiar routes, avoiding complacency. A study by Ambisisi et al. [77] examined 2318 accidents and revealed that over 75% of accidents resulted from human factors associated with reckless driving. Hence, enterprises should regularly conduct safety education programs to familiarize employees with the gravity of accidents and augment their safety responsibility awareness.

(2) Security screening: Vehicles lacking transportation qualifications fail to meet vehicle stability, braking performance, fuel tank pressure resistance, and impact force requirements, increasing the risk of leaks, fires, or explosions. Enterprises should regularly and meticulously inspect vehicles engaged in hazardous material transportation to avert accidents. Similarly, tools employed for loading and unloading hazardous materials should undergo regular inspections to mitigate equipment-related risks. Consequently, the establishment of a robust safety management system proves to be an effective approach in enhancing safety factors [78].

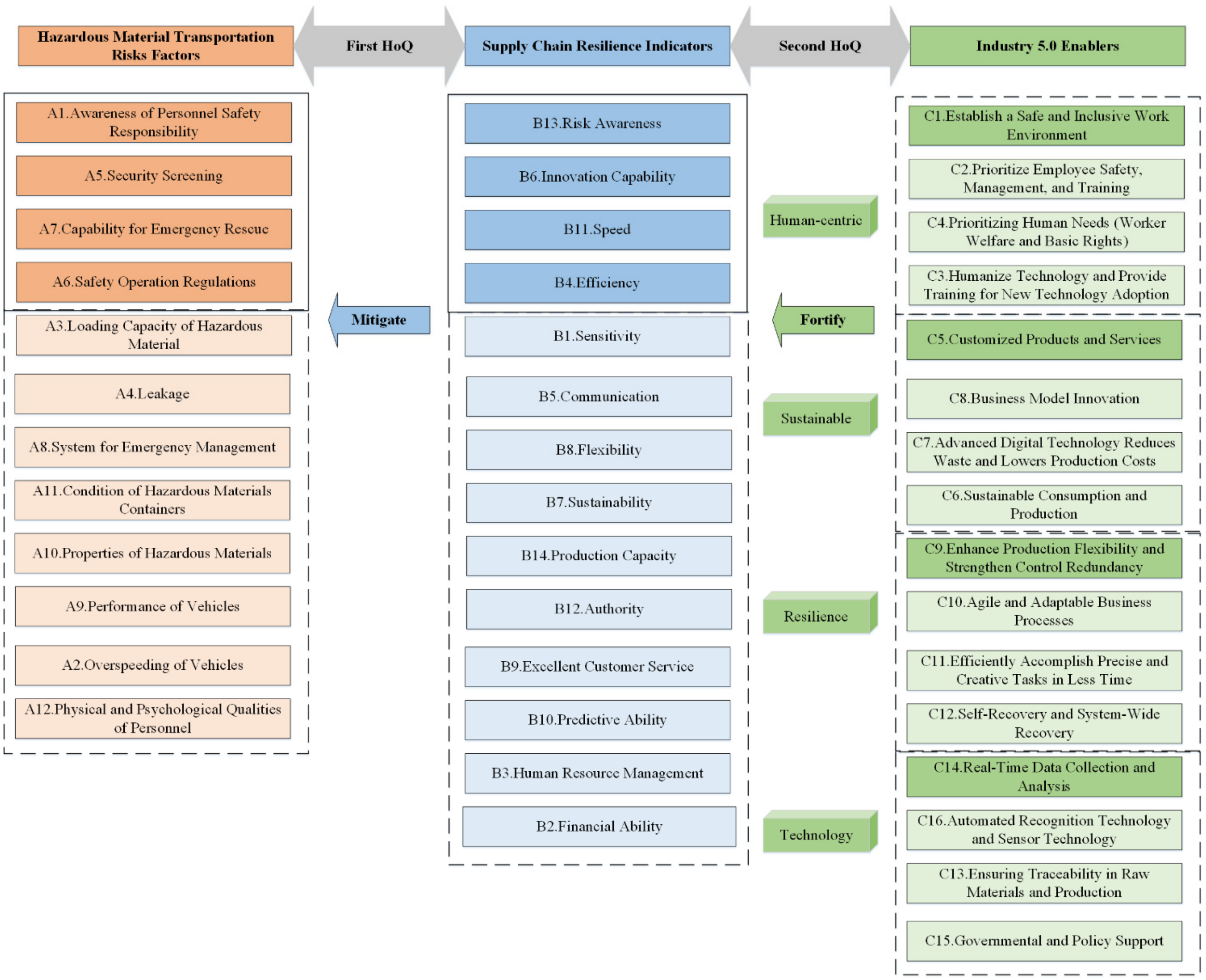

Figure3. Key I5.0 enablers to fortify SCR and mitigate HMTR.

(3) Capability for emergency rescue: Professional departments and transportation companies should regularly conduct emergency rescue training and drills specific to hazardous material transportation accidents. In the event of unforeseen circumstances during the transportation of dangerous goods, enterprises can swiftly and effectively manage hazardous material leaks, providing significant assistance to both the company and society. Hence, enterprises should prioritize the reinforcement of personnel's emergency rescue capabilities through comprehensive training to mitigate the escalation of accidents.

(4) Safety operation regulations: Owing to the specific nature of hazardous material, transportation requires stricter operating procedures, comprehensive safety facilities, and well-designed management systems compared to ordinary goods. Certain hazardous materials possess unstable chemical properties, and non-compliant behavior by loading and unloading personnel and drivers can heighten HMTR. Consequently, enterprises must diligently enforce safety operation regulations to establish standardized and secure transportation processes for hazardous materials.

To assist the case enterprise in mitigating HMTR, an analysis using the HoQ approach provides valuable insights. The analysis identifies four priority SCR indicators that require strengthening: (1)

risk awareness, (2) innovation capability, (3) speed, and (4) efficiency. A higher ranking denotes a superior overall score, indicating the effectiveness of these indicators in measuring SCR and mitigating the HMTR.

(1) Risk awareness: Risk awareness is a crucial aspect for enterprises, encompassing not only awareness of external environmental policies but also internal vigilance regarding personnel and equipment to mitigate risks. It is essential to proactively and reactively deploy appropriate measures before any risk event arises. Proactive tools are employed to minimize the likelihood of negative events occurring, while reactive tools are utilized to mitigate the damages caused by such events.

(2) Innovation capability: Companies that possess strong innovative capabilities are more adept at withstanding disruptions, as innovation directly and indirectly enhances their overall capabilities. The introduction of innovative products or services renders enterprises more resilient, enabling them to effectively confront and address risks. Expediting the development of innovation capabilities proves advantageous for supply chain companies, facilitating the creation of new revenue streams and cost reduction, consequently enhancing supply chain efficiency [79].

(3) Speed: Increased speed enables swift decision-making in combat, tactical, and strategic contexts, as well as rapid adaptation to market dynamics. Within the supply chain, risks can emerge unpredictably, and the speed with which enterprises handle transactions, comprehend the occurrence of accidents, and address them directly influences the level of risks they encounter. Crucially, when operational changes with detrimental effects arise during business processes, the time taken to halt such detrimental behavior becomes paramount [80].

(4) Efficiency: Researchers have extensively investigated the synergistic development and trade-offs between efficiency and the establishment of resilient supply chains [81]. When a company successfully enhances its efficiency, optimally utilizes social resources, and maintains effective operations, it can generate higher profits. This, in turn, provides the company with additional resources to improve its physical infrastructure, bolster SCR, and proactively mitigate various HMTR.

5.2. Second HoQ

Considering that SCR acts as a mediator between HMTR and I5.0 enablers, the second HoQ is employed to establish a connection between these variables.

Under the “human-centric” perspective, the focus lies in establishing a safe and inclusive work environment (C1). Within the “sustainable” dimension, the emphasis is on customized products and services (C5). In terms of “resilience”, the objective is to enhance production flexibility and strengthen control redundancy (C9). Lastly, within the “technology” dimension, the key factor is real-time data collection and analysis (C14).

The following is a discussion of four I5.0 enablers.

(1) Establish a safe and inclusive work environment: The core focus of I5.0 lies in establishing a collaborative work environment between humans and machines, leading to the formation of an intelligent society [82]. This paradigm embraces advanced technology, digital skills, and distinct human capabilities to achieve optimal productivity within a symbiotic relationship between humans and machines [83]. In the era of I5.0, companies can prioritize their employees by fostering a safe and inclusive work environment that nurtures a sense of belonging. This approach promotes active engagement of employees in their work, consequently enhancing the operational efficiency of the company.

(2) Customized products and services: The feasibility of achieving high-quality and distinctive

products stems from the utilization of information physics systems enabled by mass customization, which renders them affordable. Furthermore, the synergistic collaboration between humans and machines enhances efficiency and distinctiveness. Within the framework of I5.0, technological advancements contribute to enhancing personalized customer experiences, thereby bolstering economic growth and comfort. To effectively respond to market demand, enterprises should offer customers differentiated and customized products and services, thereby establishing their presence in the market.

(3) Enhance production flexibility and strengthen control redundancy: To enhance their ability to respond to supply chain disruptions, enterprises can enhance their supply chain design by integrating redundant and flexible resources [84]. Incorporating a flexible transportation system or adjusting production levels based on supplier capacity can significantly enhance the flexibility of the enterprise's supply chain. Our findings align with the research conducted by Reza et al., highlighting that efficient management and mitigation of inventory costs represent a critical strategy for developing resilient and sustainable supply chains [85].

(4) Real-time data collection and analysis: By providing real-time and accurate information, organizations can effectively identify bottlenecks and vulnerable areas, empowering them to make well-informed decisions [86]. Object tracking has gained significant traction in the transportation domain, facilitating improved planning and scheduling, streamlined and flexible processes, inventory reduction, and the potential for innovative business models [87].

5.3. Managerial implementation

This study developed a two-stage QFD model and implemented the model's outcomes throughout the entire supply chain process, empowering managers to enhance their supply chain management capabilities. Subsequent to this implementation, follow-up visits were conducted with managers to assess the effectiveness of its application. Managers reported that through the evaluation model established in this study and the resulting analyses, they were able to identify key indicators and comprehend the interrelationships between various factors. These enabled managers to pinpoint weaknesses in the transportation of hazardous materials and take targeted measures to improve them. Applying the Pareto principle, managers analyzed and synthesized the model's results, progressively allocating more time and resources to critical factors. Consequently, the enterprise's supply chain management capability saw significant improvement, leading to enhanced performance, thereby reinforcing the significance of this model.

Utilizing the outcomes of this model, managers are able to augment positive factors, curtail negative impacts, conduct comprehensive risk assessments, and scrutinize early warning signals. Subsequent follow-up visits confirmed the model's efficacy in mitigating HMTR. By amalgamating quantitative and qualitative methodologies, the QFD-MCDM model adeptly identifies key influential factors, offering managers scientific and theoretical guidance, thereby facilitating continuous performance enhancement.

6. Conclusions and recommendations

6.1. Conclusions

This study primarily focuses on examining HMTR factors, SCR indicators, and improvement measures within the context of I5.0, thereby broadening the scope of enterprise supply chain management perspective. Empirical validation of these factors has yielded the following key findings:

The study identifies the four primary HMTR factors as "awareness of personnel safety responsibility", "security screening", "capability for emergency rescue", and "safety operation regulations".

Additionally, the top four SCR indicators encompass "risk awareness", "innovation capability", "speed", and "efficiency".

In the context of I5.0, the study reveals the top four enablers: "establish a safe and inclusive work environment", "customized products and services", "enhance production flexibility and strengthen control redundancy", and "real-time data collection and analysis".

This study presents a novel approach by integrating the FDM-DEMATEL-ANP-EWM method within QFD framework to mitigate HMTR. The proposed method offers valuable insights to practitioners, enabling them to gain a deeper understanding of the risk factors associated with vehicle collisions during the transportation of hazardous materials. By leveraging these insights, practitioners can make informed decisions aimed at reducing the frequency and severity of collisions involving vehicles transporting hazardous material on the road.

Second, this study introduces a pioneering integration of HMTR, SCR, and I5.0 enablers within the QFD-MCDM framework. By examining the interrelationships between these variables, the study constructs practical and viable SCR solutions for enterprises to effectively mitigate the HMTR.

Lastly, when faced with limited resources, business managers can strategically allocate their resources towards key I5.0 enablers to bolster SCR and effectively address HMTR.

6.2. Research limitations and future directions

While this study offers valuable insights, it is important to acknowledge limitations and potential deficiencies in certain aspects due to the researchers' limited knowledge and experience.

The participants who completed the questionnaire for this study were employees of the company. To enhance the comprehensiveness and innovation of future research, it is advisable to incorporate not only company employees but also suppliers and customers of the enterprises into the survey. Such an approach will enable a more comprehensive analysis of the interplay between HMTR, SCR, and I5.0, thereby providing a more innovative perspective.

Our research findings solely focus on the road transportation of dangerous goods. If transportation methods change, such as using railway transportation or inland waterway transportation, a reanalysis of the first factor in the quality house will be needed. Nevertheless, the model employed in this study remains applicable. Our research results are also relevant when transporting hazardous materials with varying levels of danger or different appearances, such as packaging or storage tanks, as long as the transportation method remains road transportation. Therefore, the model utilized in this study is adaptable and can be extended to different environments, serving as a valuable reference for logistics enterprises in various fields. In future research, it would be highly valuable to explore other modes of dangerous goods transport and address additional factors such as multimodal transport and different transport environments.

In future research, the integration of grey correlation analysis, WINGS, and VIKOR methods can be employed to combine three variables and rank factors from diverse perspectives, thus offering multiple reference plans for enterprise managers. Future research can explore the mutual influence relationships between evaluation indicators by utilizing the DEMATEL method in conjunction with techniques such as Z-number and D-number. It is recommended to broaden the research scope by considering diverse types and quantities of variables, and to construct a comprehensive framework to enhance enterprises' agility in responding to real-life situations.

In the future, it is highly likely that supply chains across various industries will integrate with I5.0. It is valuable to explore the application of the QFD framework in supply chain systems across diverse industries. This model can be used by supply chain systems in various industries to strengthen their resilience. This integration will facilitate the development of customized I5.0 solutions for specific industries, thereby enhancing their capabilities for sustainable development. Future research can be enhanced by incorporating a broader and more diverse range of companies from different countries to improve the generalizability of research findings.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare there is no conflict of interest.

References

1. Y. Liu, L. Fan, X. Li, S. Shi, Y. Lu, Trends of hazardous material accidents (HMAs) during highway transportation from 2013 to 2018 in China, *J. Loss Prev. Process Ind.*, **66** (2020), 104150. https://doi.org/10.1016/j.jlp.2020.104150
2. A. Ghaderi, R. L. Burdett, An integrated location and routing approach for transporting hazardous materials in a bi-modal transportation network, *Transp. Res. Part E Logist. Transp. Rev.*, **127** (2019), 49–65. https://doi.org/10.1016/j.tre.2019.04.011
3. S. Ghaleh, M. Omidvari, P. Nassiri, M. Momeni, S. M. M. Lavasani, Pattern of safety risk assessment in road fleet transportation of hazardous materials (oil materials), *Saf. Sci.*, **116** (2019), 1–12. https://doi.org/10.1016/j.ssci.2019.02.039
4. N. Holeczek, Hazardous materials truck transportation problems: A classification and state of the art literature review, *Transp. Res. Part D Transp. Environ.*, **69** (2019), 305–328. https://doi.org/10.1016/j.trd.2019.02.010
5. S. S. Mohri, M. Mohammadi, M. Gendreau, A. Pirayesh, A. Ghasemaghaei, V. Salehi, Hazardous material transportation problems: A comprehensive overview of models and solution approaches, *Eur. J. Oper. Res.*, **302** (2022), 1–38. https://doi.org/10.1016/j.ejor.2021.11.045

6. N. Stojanovic, B. Boskovic, M. Petrovic, I. Grujic, O. I. Abdullah, The impact of accidents during the transport of dangerous good, on people, the environment, and infrastructure and measures for their reduction: A review, *Environ. Sci. Pollut. Res.*, **30** (2023), 32288–32300. https://doi.org/10.1007/s11356-023-25470-2
7. Y. L. Li, Q. Yang, K. S. Chin, A decision support model for risk management of hazardous materials road transportation based on quality function deployment, *Transp. Res. Part D Transp. Environ.*, **74** (2019), 154–173. https://doi.org/10.1016/j.trd.2019.07.026
8. H. Ma, X. Li, Y. Liu, Multi-period multi-scenario optimal design for closed-loop supply chain network of hazardous products with consideration of facility expansion, *Soft Comput.*, **24** (2020), 2769–2780. https://doi.org/10.1007/s00500-019-04435-z
9. A. Norrman, A. Wieland, The development of supply chain risk management over time: Revisiting Ericsson, *Int. J. Phys. Distrib. Logist. Manage.*, **50** (2020), 641–666. https://doi.org/10.1108/IJPDLM-07-2019-0219
10. A. Wieland, C. F. Durach, Two perspectives on supply chain resilience, *J. Bus. Logist.*, **42** (2021), 315–322. https://doi.org/10.1111/jbl.12271
11. S. Wei, W. Xu, X. Guo, X. Chen, How does business-IT alignment influence supply chain resilience?, *Inf. Manage.*, **60** (2023), 103831. https://doi.org/10.1016/j.im.2023.103831
12. A. Spieske, M. Gebhardt, M. Kopyto, H. Birkel, E. Hartmann, The future of industry 4.0 and supply chain resilience after the COVID-19 pandemic: Empirical evidence from a Delphi study, *Comput. Ind. Eng.*, **181** (2023), 109344. https://doi.org/10.1016/j.cie.2023.109344
13. G. Qader, M. Junaid, Q. Abbas, M. S. Mubarik, Industry 4.0 enables supply chain resilience and supply chain performance, *Technol. Forecast. Soc. Change*, **185** (2022), 122026. https://doi.org/10.1016/j.techfore.2022.122026
14. R. Sindhwani, S. Afridi, A. Kumar, A. Banaitis, S. Luthra, P. L. Singh, Can industry 5.0 revolutionize the wave of resilience and social value creation? A multi-criteria framework to analyze enablers, *Technol. Soc.*, **68** (2022), 101887. https://doi.org/10.1016/j.techsoc.2022.101887
15. *European Commission Directorate General for Research and Innovation*, Industry 5.0: Towards a sustainable, human centric and resilient European industry, 2021. Available from: https://data.europa.eu/doi/10.2777/308407.
16. X. Xu, Y. Lu, B. Vogel-Heuser, L.Wang, Industry, 4.0 and Industry 5.0—inception, conception and perception, *J. Manuf. Syst.*, **61** (2021), 530–535. https://doi.org/10.1016/j.jmsy.2021.10.006
17. D. Ivanov, The Industry 5.0 framework: Viability-based integration of the resilience, sustainability, and human-centricity perspectives, *Int. J. Prod. Res.*, **61** (2023), 1683–1695. https://doi.org/10.1080/00207543.2022.2118892
18. M. Z. Mistarihi, R. A. Okour, A. A. Mumani, An integration of a QFD model with fuzzy-ANP approach for determining the importance weights for engineering characteristics of the proposed wheelchair design, *Appl. Soft Comput.*, **90** (2020), 106136. https://doi.org/10.1016/j.asoc.2020.106136
19. Y. Chen, Y. Ran, G. Huang, L. Xiao, G. Zhang, A new integrated MCDM approach for improving QFD based on DEMATEL and extended MULTIMOORA under uncertainty environment, *Appl. Soft Comput.*, **105** (2021), 107222. https://doi.org/10.1016/j.asoc.2021.107222

20. J. P. Chang, Z. S. Chen, X. J. Wang, L. Martínez, W. Pedrycz, M. J. Skibniewski, Requirement-driven sustainable supplier selection: Creating an integrated perspective with stakeholders' interests and the wisdom of expert crowds, *Comput. Ind. Eng.*, **175** (2023), 108903. https://doi.org/10.1016/j.cie.2022.108903
21. A. E. Torkayesh, M. Yazdani, D. Ribeiro-Soriano, Analysis of Industry 4.0 implementation in mobility sector: An integrated approach based on QFD, BWM, and stratified combined compromise solution under fuzzy environment, *J. Ind. Inf. Integr.*, **30** (2022), 100406. https://doi.org/10.1016/j.jii.2022.100406
22. X. Shen, S. Wei, Application of XGBoost for hazardous material road transport accident severity analysis, *IEEE Access*, **8** (2020), 206806–206819. https://doi.org/10.1109/ACCESS.2020.3037922
23. N. Vojinović, S. Sremac, D. Zlatanović, A novel integrated fuzzy-rough MCDM model for evaluation of companies for transport of dangerous goods, *Complexity*, **2021** (2021), e5141611. https://doi.org/10.1155/2021/5141611
24. A. Baryłka, M. Chmieliński, Innovative technologies supporting the safety of the transport of dangerous goods, *Mod. Eng.*, **2020** (2020), 3.
25. *UNECE*, Dangerous goods publications. Available from: https://unece.org/publications/transport/dangerous%20goods.
26. *OTIF*, Intergovernmental organisation for international carriage by rail. Available from: https://otif.org/en/.
27. Q. Yang, K. S. Chin, Y. L. Li, A quality function deployment-based framework for the risk management of hazardous material transportation process, *J. Loss Prev. Process Ind.*, **52** (2018), 81–92. https://doi.org/10.1016/j.jlp.2018.02.001
28. J. Guo, C. Luo, K. Ma, Risk coupling analysis of road transportation accidents of hazardous materials in complicated maritime environment, *Reliability Eng. Syst. Saf.*, **229** (2023), 108891. https://doi.org/ 10.1016/j.ress.2022.108891
29. Z. Yang, X. Yan, Y. Tian, Z Pu, Y Wang, C Li, et al., Risk assessment of sudden water pollution accidents associated with dangerous goods transportation on the cross-tributary bridges of Baiyangdian lake, *Water*, **15** (2023), 2993. https://doi.org/10.3390/w15162993
30. F. Ma, D. Yu, B. Xue, X. Wang, J. Jing, W. Zhang, Transport risk modeling for hazardous chemical transport companies—a case study in China, *J. Loss Prev. Process Ind.*, **84** (2023), 105097. https://doi.org/10.1016/j.jlp.2023.105097
31. G. Behzadi, M. J. O'Sullivan, T. L. Olsen, On metrics for supply chain resilience, *Eur. J. Oper. Res.*, **287** (2020), 145–158. https://doi.org/10.1016/j.ejor.2020.04.040
32. A. Llaguno, J. Mula, F. Campuzano-Bolarin, State of the art, conceptual framework and simulation analysis of the ripple effect on supply chains, *Int. J. Prod. Res.*, **60** (2022), 2044–2066. https://doi.org/10.1080/00207543.2021.1877842
33. A. Mohammed, I. Harris, A. Soroka, R. Nujoom, A hybrid MCDM-fuzzy multi-objective programming approach for a G-resilient supply chain network design, *Comput. Ind. Eng.*, **127** (2019), 297–312. https://doi.org/10.1016/j.cie.2018.09.052
34. S. Hosseini, A. A. Khaled, A hybrid ensemble and AHP approach for resilient supplier selection. *J. Intell. Manuf.*, **30** (2019), 207–228. https://doi.org/10.1007/s10845-016-1241-y

35. H. Zhang, F. Jia, J. X. You, Striking a balance between supply chain resilience and supply chain vulnerability in the cross-border e-commerce supply chain, *Int. J. Logist. Res. Appl.*, **26** (2023), 320–344. https://doi.org/10.1080/13675567.2021.1948978
36. D. Ozdemir, M. Sharma, A. Dhir, T. Daim, Supply chain resilience during the COVID-19 pandemic, *Technol. Soc.*, **68** (2022), 101847. https://doi.org/10.1016/j.techsoc.2021.101847
37. N. Zhao, J. Hong, K. H. Lau, Impact of supply chain digitalization on supply chain resilience and performance: A multi-mediation model, *Int. J. Prod. Econ.*, **259** (2023), 108817. https://doi.org/10.1016/j.ijpe.2023.108817
38. J. Liu, J. Wu, Y. Gong, Maritime supply chain resilience: From concept to practice, *Comput. Ind. Eng.*, **182** (2023), 109366. https://doi.org/10.1016/j.cie.2023.109366
39. W. Liu, Z. Liu, Simulation analysis of supply chain resilience of prefabricated building projects based on system dynamics, *Buildings*, **13** (2023), 2629. https://doi.org/10.1016/j.acme.2017.04.011
40. J. Wang, M. Yu, M. Liu, Influencing factors on green supply chain resilience of agricultural products: An improved gray-DEMATEL-ISM approach, *Front. Sustainable Food Syst.*, **7** (2023). https://doi.org/10.3389/fsufs.2023.1166395
41. M. Ghobakhloo, M. Iranmanesh, M. E. Morales, M. Nilashi, A. Amran, Actions and approaches for enabling Industry 5.0-driven sustainable industrial transformation: A strategy roadmap, *Corporate Soc. Responsib. Environ. Manage.*, **30** (2023), 1473–1494. https://doi.org/10.1002/csr.2431
42. M. Sharma, R. Sehrawat, S. Luthra, T. Daim, D. Bakry, Moving towards Industry 5.0 in the pharmaceutical manufacturing sector: Challenges and solutions for Germany, *IEEE Trans. Eng. Manage.*, **2022** (2022), 1–18. https://doi.org/10.1109/TEM.2022.3143466
43. H. W. Lo, A data-driven decision support system for sustainable supplier evaluation in the Industry 5.0 era: A case study for medical equipment manufacturing, *Adv. Eng. Inf.*, **56** (2023), 101998. https://doi.org/10.1016/j.aei.2023.101998
44. S. Nayeri, Z. Sazvar, J. Heydari, Towards a responsive supply chain based on the Industry 5.0 dimensions: A novel decision-making method, *Expert Syst. Appl.*, **213** (2023), 119267. https://doi.org/10.1016/j.eswa.2022.119267
45. E. H. Grosse, F. Sgarbossa, C. Berlin, W. P. Neumann, Human-centric production and logistics system design and management: transitioning from Industry 4.0 to Industry 5.0, *Int. J. Prod. Res.*, **61** (2023), 7749–7759. https://doi.org/10.1080/00207543.2023.2246783
46. D. Ivanov, The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives, *Int. J. Prod. Res.*, **61** (2023), 1683–1695. https://doi.org/10.1080/00207543.2022.2118892
47. H. R. Soufi, A. Esfahanipour, M. A. Shirazi, Risk reduction through enhancing risk management by resilience, *Int. J. Disaster Risk Reduction*, **64** (2021), 102497. https://doi.org/10.1016/j.ijdrr.2021.102497
48. S. W. Chiou, A resilience-based signal control for a time-dependent road network with hazmat transportation, *Reliab. Eng. Syst. Saf.*, **193** (2020), 106570. https://doi.org/10.1016/j.ress.2019.106570
49. B. Zahiri, N. C. Suresh, J. de Jong, Resilient hazardous-materials network design under uncertainty and perishability, *Comput. Ind. Eng.*, **143** (2020), 106401. https://doi.org/10.1016/j.cie.2020.106401

50. C. Chen, M. Yang, G. Reniers, A dynamic stochastic methodology for quantifying HAZMAT storage resilience, *Reliab. Eng. Syst. Saf.*, **215** (2021): 107909. https://doi.org/10.1016/j.ress.2021.107909
51. Z. Wang, Y. Wang, Y. Jiao, Uncertain Multi-objective hazardous materials transport route planning considering resilience and low-carbon, *IEEE Access*, **11** (2023), 26921–26931. https://doi.org/10.1109/ACCESS.2023.3236796
52. S. Modgil, R. K. Singh, S. Agrawal, Developing human capabilities for supply chains: an industry 5.0 perspective, *Ann. Oper. Res.*, **2023** (2023), 1–31. https://doi.org/10.1007/s10479-023-05245-1
53. S. Gupta, S. Modgil, T. M. Choi, A. Kumar, J. Antony, Influences of artificial intelligence and blockchain technology on financial resilience of supply chains, *Int. J. Prod. Econ.*, **261** (2023), 108868. https://doi.org/10.1016/j.ijpe.2023.108868
54. D. Ivanov, Intelligent digital twin (iDT) for supply chain stress-testing, resilience, and viability, *Int. J. Prod. Econ.*, **263** (2023), 108938. https://doi.org/10.1016/j.ijpe.2023.108938
55. B. Naghshineh, H. Carvalho, The implications of additive manufacturing technology adoption for supply chain resilience: A systematic search and review, *Int. J. Prod. Econ.*, **247** (2022), 108387. https://doi.org/10.1016/j.ijpe.2021.108387
56. J. Leng, W. Sha, B. Wang, P. Zheng, C. Zhuang, Q. Liu, et al., Industry 5.0: Prospect and retrospect, *J. Manuf. Syst.*, **65** (2022), 279–295. https://doi.org/10.1016/j.jmsy.2022.09.017
57. H. R. Fazeli, Q. Peng, Integrated approaches of BWM-QFD and FUCOM-QFD for improving weighting solution of design matrix, *J. Intell. Manuf.*, **34** (2023), 1003–1020. https://doi.org/10.1007/s10845-021-01832-w
58. Y. Luo, M. Ni, F. Zhang, A design model of FBS based on interval-valued Pythagorean fuzzy sets, *Adv. Eng. Inf.*, **56** (2023), 101957. https://doi.org/10.1016/j.aei.2023.101957
59. L. Ocampo, A. M. Jumao-as, J. J. Labrador, A. M. Rama, Transforming the means-end chain model of the QFD into interconnected hierarchical network structures for sustainable product design, *Int. J. Sustainable Eng.*, **14** (2021), 552–573. https://doi.org/10.1080/19397038.2021.1934182
60. I. Erol, I. M. Ar, I. Peker, C. Searcy, Alleviating the impact of the barriers to circular economy adoption through blockchain: An investigation using an integrated MCDM-based QFD with hesitant fuzzy linguistic term sets, *Comput. Ind. Eng.*, **165** (2022), 107962. https://doi.org/10.1016/j.cie.2022.107962
61. M. M. H. Chowdhury, M. A. Quaddus, A multi-phased QFD based optimization approach to sustainable service design, *Int. J. Prod. Econ.*, **171** (2016), 165–178. https://doi.org/10.1016/j.ijpe.2015.09.023
62. L. Zheng, Z. He, S. He, Detecting and prioritizing product defects using social media data and the two-phased QFD method, *Comput. Ind. Eng.*, **177** (2023), 109031. https://doi.org/10.1016/j.cie.2023.109031
63. R. Ghlala, Z. K. Aouina, L. B. Said, MC-DMN: Meeting MCDM with DMN involving multi-criteria decision-making in business process, in *Computational Science and Its Applications–ICCSA 2017: 17th International Conference*, (2017), 3–16. https://doi.org/10.1007/978-3-319-62407-5_1
64. M. K. Ghorabaee, M. Amiri, E. K. Zavadskas, J. Antucheviciene, A new hybrid fuzzy MCDM approach for evaluation of construction equipment with sustainability considerations, *Arc. Civil Mech. Eng.*, **18** (2018), 32–49. https://doi.org/10.1016/j.acme.2017.04.011

65. N. Vojinović, S. Sremac, D. Zlatanović, A novel integrated fuzzy-rough MCDM model for evaluation of companies for transport of dangerous good, *Complexity*, **2021** (2021), 1–16. https://doi.org/10.1155/2021/5141611
66. A. H. Sarfaraz, A. K. Yazdi, T. Hanne, R. S. Hosseini, Decision support for technology transfer using fuzzy quality function deployment and a fuzzy inference system, *J. Intell. Fuzzy Syst.*, **44** (2023), 7995–8014. https://doi.org/10.3233/JIFS-222232
67. G. Büyüközkan, S. Güleryüz, An integrated DEMATEL-ANP approach for renewable energy resources selection in Turkey, *Int. J. Prod. Econ.*, **182** (2016), 435–448. https://doi.org/10.1016/j.ijpe.2016.09.015
68. I. Kazemian, S. A. Torabi, C. W. Zobel, Y. Li, M. Baghersad, A multi-attribute supply chain network resilience assessment framework based on SNA-inspired indicators, *Oper. Res. Int. J.*, **22** (2022), 1853–1883. https://doi.org/10.1007/s12351-021-00644-3
69. A. Padilla-Rivera, B. B. T. do Carmo, G. Arcese, N. Merveille, Social circular economy indicators: Selection through fuzzy delphi method, *Sustainable Prod. Consumption*, **26** (2021), 101–110. https://doi.org/10.1016/j.spc.2020.09.015
70. Y. W. Du, X. L. Shen, Group hierarchical DEMATEL method for reaching consensus, *Comput. Ind. Eng.*, **175** (2023), 108842. https://doi.org/10.1016/j.cie.2022.108842
71. T. L. Saaty, The modern science of multicriteria decision making and its practical applications: The AHP/ANP approach, *Oper. Res.*, **61** (2013), 1101–1118. https://doi.org/10.1287/opre.2013.1197
72. S. Daimi, S. Rebai, Sustainability performance assessment of Tunisian public transport companies: AHP and ANP approaches, *Socio-Econ. Planning Sci.*, **89** (2023), 101680. https://doi.org/10.1016/j.seps.2023.101680
73. Ü. Özdilek, The role of thermodynamic and informational entropy in improving real estate valuation methods, *Entropy*, **25** (2023), 907. https://doi.org/10.3390/e25060907
74. P. P. Dwivedi, D. K. Sharma, Evaluation and ranking of battery electric vehicles by Shannon's entropy and TOPSIS methods, *Math. Comput. Simul.*, **212** (2023), 457–474. https://doi.org/10.1016/j.matcom.2023.05.013
75. M. Shakerian, A. Choobineh, M. Jahangiri, M. Alimohammadlou, M. Nami, J. Hasanzadeh, Interactions among cognitive factors affecting unsafe behavior: integrative fuzzy DEMATEL ISM approach, *Math. Prob. Eng.*, **2020** (2020), 1–18. https://doi.org/10.1155/2020/8952624
76. I. Y. Wuni, Mapping the barriers to circular economy adoption in the construction industry: A systematic review, Pareto analysis, and mitigation strategy map, *Build. Environ.*, **223** (2022), 109453. https://doi.org/10.1016/j.buildenv.2022.109453
77. A. Ambituuni, J. M. Amezaga, D. Werner, Risk assessment of petroleum product transportation by road: A framework for regulatory improvement, *Saf. Sci.*, **79** (2015), 324–335. https://doi.org/10.1016/j.ssci.2015.06.022
78. E. Ayyildiz, A. T. Gumus, Pythagorean fuzzy AHP based risk assessment methodology for hazardous material transportation: An application in Istanbul, *Environ. Sci. Pollut. Res.*, **28** (2021), 35798–35810. https://doi.org/10.1007/s11356-021-13223-y
79. A. Belhadi, V. Mani, S. S. Kamble, S. A. R. Khan, S. Verma, Artificial intelligence-driven innovation for enhancing supply chain resilience and performance under the effect of supply chain dynamism: An empirical investigation, *Ann. Oper. Res.*, **2021** (2021), 1–26. https://doi.org/10.1007/s10479-021-03956-x

80. J. P. Ribeiro, A. Barbosa-Povoa, Supply Chain Resilience: Definitions and quantitative modelling approaches—a literature review, *Comput. Ind. Eng.*, **115** (2018), 109–122. https://doi.org/10.1016/j.cie.2017.11.006
81. A. Belhadi, S. S. Kamble, M. Venkatesh, C. J. C. Jabbour, I. Benkhati, Building supply chain resilience and efficiency through additive manufacturing: An ambidextrous perspective on the dynamic capability view, *Int. J. Prod. Econ.*, **249** (2022), 108516. https://doi.org/10.1016/j.ijpe.2022.108516
82. A. Akundi, D. Euresti, S. Luna, W. Ankobiah, A. Lopes, I. Edinbarough, State of Industry 5.0—analysis and identification of current research trends, *Appl. Syst. Innovation*, **5** (2022), 27. https://doi.org/10.3390/asi5010027
83. Y. Lu, H. Zheng, S. Chand, W. Xia, Z. Liu, X. Xu, et al., Outlook on human-centric manufacturing towards Industry 5.0, *J. Manuf. Syst.*, **62** (2022), 612–627. https://doi.org/10.1016/j.jmsy.2022.02.001
84. M. Kamalahmadi, M. Shekarian, M. M. Parast, The impact of flexibility and redundancy on improving supply chain resilience to disruptions, *Int. J. Prod. Res.*, **60** (2022), 1992–2020. https://doi.org/10.1080/00207543.2021.1883759
85. R. Lotfi, B. Kargar, M. Rajabzadeh, F. Hesabi, E. Özceylan, Hybrid fuzzy and data-driven robust optimization for resilience and sustainable health care supply chain with vendor-managed inventory approach, *Int. J. Fuzzy Syst.*, **24** (2022), 1216–1231. https://doi.org/10.1007/s40815-021-01209-4
86. K. E. K. Vimal, K. Churi, J. Kandasamy, Analysing the drivers for adoption of Industry 4.0 technologies in a functional paper-cement-sugar circular sharing network, *Sustainable Prod. Consumption*, **31** (2022), 459–477. https://doi.org/10.1016/j.spc.2022.03.006
87. C. Jandl, M. Wagner, T. Moser, S. Schlund, Reasons and strategies for privacy features in tracking and tracing systems—a systematic literature review, *Sensors*, **21** (2021), 4501. https://doi.org/10.3390/s21134501