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Using Multicriteria Decision Making to Evaluate the Risk of Hydrogen Energy Storage and Transportation in Cities

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Abstract: Hydrogen is an environmentally friendly source of renewable energy. Energy generation from hydrogen has not yet been widely commercialized due to issues related to risk management in its storage and transportation. In this paper, the authors propose a hybrid multiple-criteria decision-making (MCDM)-based method to manage the risks involved in the storage and transportation of hydrogen (RSTH). First, we identified the key points of the RSTH by examining the relevant literature and soliciting the opinions of experts and used this to build a prototype of its decision structure. Second, we developed a hybrid MCDM approach, called the D-ANP, that combined the decision-making trial and evaluation laboratory (DEMENTEL) with the analytic network process (ANP) to obtain the weight of each point of risk. Third, we used fuzzy evaluation to assess the level of the RSTH for Beijing, China, where energy generation using hydrogen is rapidly advancing. The results showed that the skills of the personnel constituted the most important risk-related factor, and environmental volatility and the effectiveness of feedback were root factors. These three factors had an important impact on other factors influencing the risk of energy generation from hydrogen. Training and technical assistance can be used to mitigate the risks arising due to differences in the skills of personnel. An appropriate logistics network and segmented transportation for energy derived from hydrogen should be implemented to reduce environmental volatility, and integrated supply chain management can help make the relevant feedback more effective.

Keywords: risk point identification; risk assessment; multicriteria decision making; risk of storage and transportation of hydrogen

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1. Introduction

Hydrogen energy is expected to be an important part of the global energy system in the future. As an energy carrier, hydrogen has important applications in transportation, industry, construction, and other fields. It has the advantages of high power density, zero emission, good thermal conductivity, convenient transportation, etc. [1]. Developing the industry for hydrogen energy is conducive to energy security and industrial upgrade [2]. The International Hydrogen Energy Commission has claimed that hydrogen energy will satisfy 18% of the terminal global energy demand by 2050, with a market value of more than USD 2.5 trillion, and hydrogen fuel-cell vehicles will account for 20–25% of vehicles worldwide [3].

The industrial processes and supply chain for hydrogen energy have gradually improved in China due to the development of key technologies. However, the country's hydrogen energy industry currently relies heavily on government policies and subsidies. This is primarily because the risk involved in the storage and transportation of hydrogen (RSTH) has affected the commercialization of this form of energy. Hydrogen is a flammable gas that belongs to Class II of dangerous goods according to GB6944. It is more unstable than fossil-fuel-based energy and is gaseous at a normal temperature and pressure. Crucial to the commercialization of hydrogen energy is guaranteeing the safety of each link of the supply chain. Many countries have set up special research institutions to investigate the safety of hydrogen energy to expedite its industrialization. Examples include the Japan Hydrogen Supply and Hydrogen Application Technology Association, the US Hydrogen Safety Center, the European Union's Fuel Cell and Hydrogen Joint Association, and the International Hydrogen Safety Association. Prevalent research has focused on assessing the safety of hydrogen fuel-cell vehicles [4], methods to calculate a safe distance for fuel dispensers for such vehicles [5], comparing the risks posed by hydrogenated gasoline engines [6], and quantitatively assessing the risk to humans during the operation of hydrogen refueling stations [7]. While the safe application of technologies for energy generation from hydrogen and the operation of hydrogen refueling stations have received widespread attention, other safety-related issues in the hydrogen energy supply chain have been neglected. This supply chain includes production, storage, transportation, and use, and imposes varying safety-related demands on different links of the chain. Research has shown that there is a long distance between the upstream and downstream links of the supply chain for hydrogen energy, especially during its storage and transportation. These links are characterized by a long residence time, uncertain external conditions, and the execution of a large number of logistical activities under the supervision of nonprofessionals [8]. The RSTH is thus high and needs to be managed.

In this study, we sought answers to the following research questions: What risk factors should be considered in the storage and transportation of hydrogen? What are the critical risk factors? How do we evaluate the RSTHs in specific cities? How should we execute the closed-loop management and control of risks based on the results of such evaluations? Answering these questions can help provide useful suggestions for reducing the RSTHs and, thus, economic loss, and motivate the comprehensive development of the hydrogen energy industry.

Multicriteria decision-making (MCDM)-based methods are often used to solve problems that are characterized by incommensurate and conflicting criteria. The indicators used to assess the RSTH have different units and conflict with one another, where this makes managing the RSTH a classic MCDM problem. In this paper, the authors use the decision-making trial and evaluation laboratory (DEMATEL) to analyze the interaction between aspects and criteria and use the analytic network process (ANP) to obtain the weights of key factors. Following this, we use fuzzy evaluation in a case study to assess the RSTHs of Beijing, China, and use the empirical results as the basis for suggesting control measures.

The remainder of this paper is organized as follows: Section 2 reviews the literature on the identification and evaluation of the RSTHs, and Section 3 introduces the proposed method. Section 4 considers Beijing as an example to show how to establish a system of indicators for urban RSTHs, measure the weights of the key risk factors, and evaluate the RSTHs. Section 5 discusses the implications of the work here for risk management in the context of hydrogen energy, and Section 6 summarizes the conclusions of this study.

2. Literature Review

2.1. Risk Factors Influencing RSTH

Recent studies have focused on risk factors related to key links in the industrial chain for hydrogen energy, such as the risks involved in hydrogen production [9–11] and at hydrogen refueling stations [12–14]. However, accidents in the hydrogen supply chain are more likely to occur at the juncture of its links, especially when the environment changes. Therefore, more attention should be paid to risk factors involved in the storage and transportation of hydrogen energy.

Hydrogen belongs to the category of dangerous goods. The literature on the risks involved in the storage and transportation of hydrogen energy has examined the issue from multiple perspectives. Lam et al. proposed eight risk factors: (i) equipment cracking,

(ii) equipment failure, (iii) incorrect operation, (iv) aging material, (v) system failure, (vi) unclear instructions, (vii) vehicular collision, and (viii) weather [15]. Li et al. reviewed the literature and accident reports related to hydrogen energy to develop a hierarchical system of indices of the relevant risk factors that considered six aspects: (i) natural disasters, (ii) equipment failure, (iii) design-related deficiencies, (iv) detrimental process-related factors, (v) human failure, and (vi) management flaws [16]. Zhang et al. comprehensively analyzed the risk factors in the production, storage, and transportation of hydrogen [17], and Moradi et al. classified and accounted for material-related factors that can affect the reliability of storage and delivery systems for it [18]. Fabiano et al. used field data to analyze the risk factors in the transport of dangerous goods from the perspectives of the characteristics of the road, meteorological conditions, and particulars of the traffic [19]. They considered the impacts of inherent factors (such as tunnels, radii of bends, gradient of height, and slope), meteorological factors, and traffic-related factors (e.g., frequency of trucks) to plan actions in case of emergency [20]. Guo et al. analyzed the impact of third-party damage, corrosion-induced destruction, design flaws, and the misuse of factors during pipeline transportation [21].

The brief review above shows that while many studies have been devoted to examining the risk factors in the storage and transportation of dangerous goods, scant work has considered the risks involved in the storage and transportation of hydrogen energy.

2.2. Risk Management and Control

Risk assessment forms the largest category of issues that need to be addressed for the transportation of dangerous goods, accounting for about 47.43% of the total [22]. Hans et al. assessed the risks of different modes of hydrogen transport, and their results can be used to take preventive or protective measures to reduce these risks [23]. Camila et al. estimated the risk involved in storage systems for bulk liquid hydrogen [24], and Byung et al. compared and analyzed the risks posed by hydrogen energy in different states of storage [25]. Lee et al. assessed the risk of transportation of hydrogen using a pipeline [26], and Kim et al. determined the safety and implications of mobile hydrogen refueling stations based on certain scenarios [13]. Moradi et al. reviewed risk and reliability analyses for the storage and delivery of hydrogen [18], and Francisco et al. categorized sections of a hydrogen pipeline according to the levels of risk [27]. Lam et al. identified important factors and effects in the context of logistical accidents involving hydrogen energy [15].

Some researchers have proposed control measures according to the results of risk assessment. Kim et al. claimed that it is necessary to prevent leaks through the regular maintenance of safety devices, such as those to detect gas leaks, emergency shut-off devices, and safety valves. Moreover, periodic inspections are needed to identify faulty connections, and damage to and failure of the core facilities [13]. Moradi et al. claimed that the opportunities offered by advances in sensors, data collection, and prognostics need to be explored to ensure the safe production and transportation of hydrogen energy [18]. Lam et al. proposed specific control measures for different risk factors [15], and Zhang et al. claimed that safety monitoring and early warning should be carried out during the storage and transportation of hydrogen, while the safety of key facilities should be evaluated and adequate risk control should be implemented [17]. Castiglia et al. proposed the standardized management and effective training of operators [28], and Lee et al. proposed real-time monitoring and early warning based on sensing technology to reduce risks during transportation [29]. However, the emergence of risks is usually complex and network-like in practice, and many risks are intimately related and often occur together [15]. Few studies have been devoted to countermeasures and suggestions for risk prevention.

Due to the interdependence of and correlation among the risk factors, developing strategies according to the categories of risk is more conducive to ensuring the safe operation of the supply chain for hydrogen energy.

2.3. Method of Assessing RSTH

In early work on risk, methods of qualitative risk research (QLR) were used to evaluate the risks of transportation and form the premise of research on transporting dangerous goods. Lees, Davies et al., and Erkut et al. used QLR methods to examine the risk of transporting dangerous goods [30,31]. More accurate quantitative models of risk assessment were subsequently developed and have been widely used for the transportation of dangerous goods. Current et al. developed a multiobjective method of risk assessment for the transport of dangerous goods by road that considers such factors such as the balance and cost of transport [32]. Leonelli et al. proposed a model of risk assessment for road transportation by considering multiple factors, such as hazardous substances, meteorological conditions, and seasonal directions of wind [33].

Researchers have used various methods to assess the RSTH. Julien et al. conducted a quantitative assessment of the risks posed by distribution networks for hydrogen [34], and Hans et al. used Bayesian networks to assess this risk [23]. Camila et al. used the FMEA to identify failure scenarios [24], and Byung et al. proposed a QRA-based comparison between the GHRS and the LHRS to analyze risk [25]. Alencar et al. proposed an MCDM that incorporates the human, financial, and environmental dimensions to assess the risk of transporting hydrogen in a pipeline [35]. Lee et al. used a model to analyze delivery scenarios for hydrogen and an improved version of the QRA to help choose a suitable transportation infrastructure for it [26]. Kim et al. performed a QRA of hydrogen refueling stations [13], and Francisco et al. proposed a multidimensional model of risk based on utility theory and the ELECTRE TRI method [27]. Lam et al. used network analysis to analyze the significant effects of risks [15].

Assessing the RSTH is a classical MCDM problem [36]. Wu et al. conducted a risk assessment of wind–photovoltaic–hydrogen energy storage projects by using an improved fuzzy synthetic approach to evaluation based on a cloud model [37]. Yang proposed an information-based model of risk control assessment that can improve information security for the companies and organizations involved [36]. In this study, they proposed an MCDM-based model that combines VIKOR, DEMATEL, and ANP to solve the problem of conflicting criteria that are interdependent and provide feedback [14]. Zheng et al. used the G-DEMATEL-AHP method to investigate the risk of flooding in urban areas of megacities [17], and Wang et al. built a combined analytical hierarchy process–fuzzy comprehensive evaluation (AHP–FCE) model to assess the risk posed by hazard installations [38]. Mohammad et al. used the hybrid Fuzzy DEMATEL-ANP to identify and assess the main risks in oil and gas projects under sanctions and uncertain conditions [39]. Li et al. proposed a framework comprising the fuzzy DEMATEL implemented with TOPSIS to assess the comprehensive risk posed by hydrogen generation units [16].

The above review shows the diversity of the methods that have been applied to risk assessment in the context of the storage and transportation of hydrogen energy. Because factors influencing the RSTH have interdependent impacts, the DEMATAL-ANP method is suitable for evaluating this risk in cities.

2.4. Prototype Decision Structure

We chose and integrated the risk factors involved in the storage and transportation of hydrogen based on the above literature review and classified them into different categories. We then deleted factors that had the same meaning. We thus developed a prototype of a decision structure consisting of five categories: (i) the risk posed by people, (ii) storage-related risk, (iii) transportation-related risk, (iv) environmental risk, and (v) management-related risk. A detailed description of each category is provided in Table 1.

Table 1. The initial set of risk factors for hydrogen storage and transportation.

Risk Category	Risk Factor	Risk Description	Reference
People-related Risk	Incorrect Operation	Human error; incorrect usage; illegal operation.	[15,16]
	Carelessness	Not being careful leads to problems.	[16]
	Lack of Expertise	Lack of relevant operational experience leads to operation problems.	[16]
Storage Risk	Equipment Cracking	Damage to equipment; cracked equipment case; deformation of equipment; high pressure affects the equipment and leads to penetration of hydrogen.	[13,15]
	Equipment Failure	Equipment malfunction; equipment fails to work; equipment not working as expected.	[15]
	Material Fatigue	Material aging; the storage system requires repeated loading of hydrogen, which has stringent requirements on the fatigue life of the container, but the fatigue resistance of the metal tank is inadequate.	[17,18,21]
	Liner Corrosion and Hydrogen Embrittlement	Corrosion and hydrogen-induced embrittlement of materials or connection tube; once hydrogen-induced embrittlement occurs, the safety of the storage cylinder is compromised, leading to hydrogen leakage.	[15,17,18,21]
	Frequent Filling of Equipment	Repeated use of hydrogen storage tank produces subtle cracks or knock friction, causing it to easily explode.	[17]
	Combination of Gases	During hydrogen canning, impurities such as hydrogen with slightly higher oxygen content remain in the storage tank. If the residual gas is not checked in time, the purity of hydrogen in the storage tank decreases, resulting in the formation of flammable mixed gas.	[17]
Transportation Risk	Vehicular Collision	Transportation accidents.	[15]
Environmental Risk	Weather	Heavy rain; earthquake; thunder strike; flood; mudslide.	[15,16,19,20,33]
	Hyperbaric Environment	After long-term exposure to high-pressure hydrogen, the antihydrogen brittleness energy of high-strength steel decreases with increasing strength, resulting in a decrease in its local plasticity and the acceleration of crack propagation.	[17]
	Temperature	Once the surrounding insulation layer has been destroyed and the ambient temperature has increased, liquefied hydrogen inside the storage container is rapidly vaporized, creating an instant strong pressure and explosion.	[17]
	Road Conditions	Tunnels; radii of bending; height gradient; slope; frequency of trucks; dangerous goods' trucks.	[19,20]
	Depth of the Pipeline	In the process of hydrogen transportation in a pipeline, if the pipeline is shallow, it is easily damaged.	[21]
	Soil Movement	If the soil moves during the transportation of hydrogen in a pipeline, the pipeline is damaged.	[21,23]

Table 1. *Cont.*

Risk Category	Risk Factor	Risk Description	Reference
Management Risk	Unclear Instructions	Lack of safety instructions; warning labels missing.	[15]
	Insufficient Safety Training	The lack of safety training leads to poor safety awareness among operators.	[16]
	Incorrect Maintenance Schedule	Maintenance of equipment is not performed as required.	[16,21]
	Deficient Operational Duties	Unclear powers and responsibilities.	[16]
	Decision Errors	Incorrect commands by managers.	[16]

3. Materials and Methods

3.1. Materials

First, the D-ANP method was used to obtain the importance of the criteria, and important criteria were selected for in-depth analysis. Then, the RSTH was evaluated by using the fuzzy comprehensive evaluation method. In order to obtain data, we designed the D-ANP questionnaire and the risk assessment questionnaire, respectively.

In order to obtain the D-ANP questionnaire, we investigated five experts in related fields and asked them to rate the influence of 0–4 points on the pairwise rule. In this paper, 0 = no influence, 1 = slight influence, 2 = moderate influence, 3 = high influence, and 4 = significant influence. All diagonal elements were zero. See Appendix A Tables A1–A5 for the scoring results of 5 experts. Then, we took the average value scored by 5 experts as the initial direct influence matrix.

We used commonly used levels of risk for the storage and transportation of dangerous goods to divided the risks related to hydrogen energy into four levels: significant risk, larger risk, general risk, and less risk. We investigated the influence of each criterion on RSTH by issuing questionnaires, and the interviewees chose the appropriate level according to their own experience. For example, for personnel awareness (A1), among the 100 valid questionnaires, 10 chose significant risks, 10 chose larger risks, 30 chose general risks, and 50 chose less risks. We divided 10, 10, 30, and 50 by 100 to obtain 0.1, 0.1, 0.3, and 0.5. This questionnaire is convenient and practical and can fully absorb the opinions of relevant personnel.

3.2. DEMATEL-Based ANP

It is important to identify the key factors affecting the RSTH and calculate their weights. The commonly used subjective methods of determining their weights include the AHP, ANP, and DEMATEL. The ANP and AHP are similar in that both are founded on a pairwise-comparison-based decision matrix. However, the AHP does not consider the influence among the factors, their interdependence, and the dominance of one of many factors at the same level. The calculations of the pairwise-comparison-based decision for the ANP are also complicated. Ouyang et al. proposed a combination of DEMATEL and ANP to avoid the complex pairwise comparison of the latter by directly using the total influence matrix generated by the former as the unweighted supermatrix of the ANP [40].

The procedure of the D-ANP is as follows [41]:

Step 1: Build the direct influence matrix.

A is first constructed by using the degree of effect between each pair of factors taken from respondent questionnaires:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1j} \\ a_{21} & a_{22} & \cdots & a_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} \end{bmatrix} \quad (1)$$

where a_{ij} represents the extent to which factor i affects factors j, specified on a numerical scale.

Step 2: Generate the normalized direct influence matrix.

A is then normalized to generate the normalized direct influence matrix X:

$$\mathrm{X} = \lambda \mathrm{A} = \begin{bmatrix} \lambda a_{11} & \lambda a_{12} & \cdots & \lambda a_{1j} \\ \lambda a_{21} & \lambda a_{22} & \cdots & \lambda a_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ \lambda a_{i1} & \lambda a_{i2} & \cdots & \lambda a_{ij} \end{bmatrix} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} \\ x_{21} & x_{22} & \cdots & x_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} \end{bmatrix} \quad (2)$$

where $\lambda = \frac{1}{\max\limits_{ij}\left\{\max \sum\limits_{i=1}^{n} a_{ij}, \max \sum\limits_{j=1}^{n} a_{ij}\right\}}$

Step 3: Generate the total influence matrix.

The total influence matrix is generated by:

$$\mathrm{T} = \mathrm{X}(I - \mathrm{X})^{-1} = \begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1j} \\ t_{21} & t_{22} & \cdots & t_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ t_{i1} & t_{i2} & \cdots & t_{ij} \end{bmatrix} \quad (3)$$

Step 4: Determine the causal relationship between the criteria based on prominence and relation.

The causes and effects can be derived from T. Each row of the total influence matrix is summed to obtain the value denoted by D and each column to obtain the value denoted by C. $D + C$ represents prominence, which represents the relative importance of the corresponding factor. A higher prominence implies greater importance. $D - C$ is the relation, where a positive relation means that the corresponding factor tends to affect the other elements, referred to as a cause, and a negative relation means that the corresponding factor tends to be affected by the other elements, referred to as an effect.

Step 5: Obtain the relative weight of each criterion by using the limiting supermatrix

According to a previous study [41], the total influence matrix of DEMATEL can be treated as an unweighted supermatrix for the ANP. Therefore, a weighted matrix, W, can be obtained by normalizing T, and the global weight of each factor can be obtained by multiplying W by itself several times until a limiting supermatrix, W^*, is obtained.

Step 6: Identify the critical factors.

Because the relative weights can represent the importance of each criterion, we identify the key factors according to the relative weight obtained by the D-ANP:

$$Z = \begin{bmatrix} z_1 & z_2 & \cdots & z_n \end{bmatrix} \quad (4)$$

where z_n is the weight of factor n.

3.3. Fuzzy Evaluation

Fuzzy theory is an appropriate way to deal with the problems of uncertainty in and incommensurability among factors. The degree of membership in fuzzy theory can be used to transform a qualitative problem into a quantitative problem. We use fuzzy vagueness in this paper to evaluate the RSTH. The procedure is as follows:

Step 1: Determine the set of factors and their weights.

We construct the set of factors and calculate their weights. The former can be expressed as:

$$U = u_1, u_2, \cdots u_n \quad (5)$$

Step 2: Determine the set of evaluations.

By referring to the literature on the transportation and storage of dangerous goods, we divide the levels of risk and form the set of evaluations V:

$$V = v_1, v_2, \cdots v_m \tag{6}$$

Step 3: Construct a comprehensive evaluation matrix.

We used a questionnaire survey for each factor according to the set of comments and processed the survey data to form a comprehensive evaluation matrix R:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \tag{7}$$

where r_{nm} represents the result of evaluation of factor n with respect to comment m.

Step 4: Execute the matrix synthesis operation to obtain the set of comprehensive fuzzy evaluations.

The weighted average operator is an effective means of executing the synthesis operation [42]. We combine the weight matrix Z and the comprehensive evaluation matrix R according to it to obtain the comprehensive set of fuzzy evaluations B:

$$B = Z \circ R = (b_1, b_2, \cdots b_n) = \sum (z_i \cdot r_{ij})(j = 1, 2, \ldots m)$$

Step 5: Normalize the comprehensive set of fuzzy evaluations.

The comprehensive set of fuzzy evaluations B is normalized; if $B = (b_1, b_2, \cdots b_n)$, then $b'_k = \frac{b_k}{\sum_{j=1}^{m} b_j}, (\forall k \leq m)$ and $B' = (b'_1, b'_2, \cdots b'_n)$

Step 6: Perform a comprehensive evaluation.

We use the principle of the maximum degree of membership to choose the corresponding grade v_j of the largest b'_j in the comprehensive set of fuzzy evaluations $B' = (b'_1, b'_2, \cdots b'_n)$ as the result of the comprehensive evaluation.

The framework of our model is shown in Figure 1. Jiang [43] used the D-ANP to identify and analyze the key risk factors of an emergency logistics system and accurately calculate the weight of each. He et al. [44] proposed a quantitative method of risk assessment for high-temperature operations based on the AHP and fuzzy evaluation. We followed Jiang's method to identify the risk factors, distinguish them, calculate their weights, and assess them using fuzzy evaluation [43].

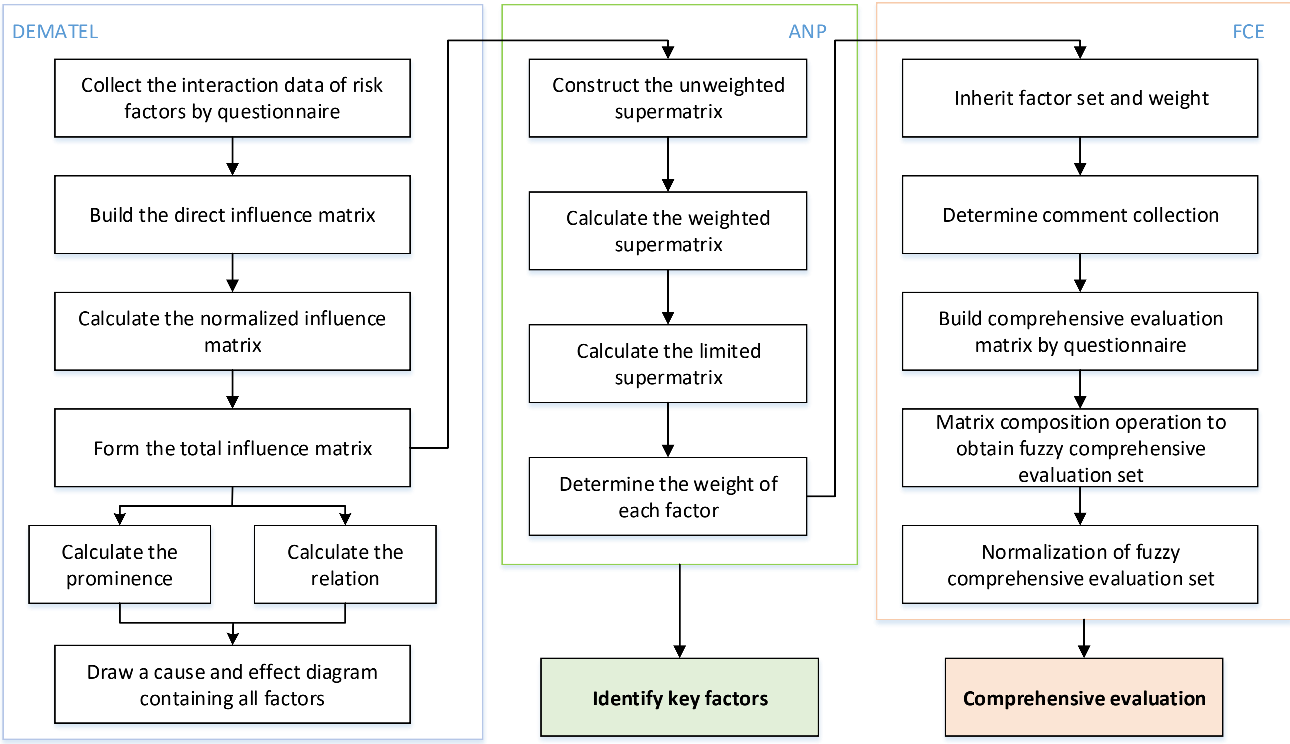

Figure 1. Framework of the proposed model for the RSTH.

4. Empirical Study

4.1. Introduction to the Case

Beijing has attached great importance to the development of its hydrogen energy industry in recent years. The city recently issued the Implementation Plan for the Development of Hydrogen Energy Industry (2021–2025), which is a blueprint for the development of the hydrogen energy industry. A number of policies and measures have also been formulated to support the development of the hydrogen energy industry along six aspects: scientific and technological R&D, the industrialization of technology and equipment, industrial innovation and development, infrastructure construction, demonstration and application, and the construction of a standard service system. A large number of hydrogen-related enterprises over the entire supply chain have emerged under these policies. They are engaged in hydrogen production, storage, transportation, hydrogenation, and application, and their number and scale are continually expanding. Hydrogen energy is classed as a dangerous good as serious losses of personnel and property may occur in case of an accident involving it. The hydrogen energy industry is both a development opportunity and a major challenge for Beijing. It is thus important to manage the risk posed by this industry, identify the key risk factors, evaluate the level of risk posed by them, and reduce it.

4.2. Determining the Formal Decision Structure

We sorted the risk factors in Table 1 and solicited industry experts for interviews. We considered the following issues: First, we needed to know more about the typical cases of accidents in links involved in the storage and transportation of hydrogen energy. Examining such cases revealed the causes of the accidents and the risk factors. Second, we needed to understand China's and Beijing's safety regulatory systems for the hydrogen energy industry, including the relevant laws, regulations, and industry norms. We used the explicit provisions of these regulatory systems to deduce the key factors and integrated them into our system of indicators. Third, we needed to define the entire process and key nodes in the storage and transportation of hydrogen energy and explore common risk factors. Finally, we needed to learn to apply risk management and control to hydrogen energy and to understand the main elements involved as a supplement to the system of indicators. We used a group composed of five experts (see Table 2 for details). We interviewed them and adopted several of their suggestions. For example, all experts agreed that it is reasonable to decompose the risk factors according to the five categories of personnel, storage, transportation, environment, and management. The risk factors related to personnel in Table 1 were further divided in terms of awareness, technology, quality, and health. Hydrogen-induced embrittlement is an important risk factor during its storage. The stability of the transportation process is a key constraint on the transportation of hydrogen energy. In terms of management, the industry is concerned about the standardized management of storage and transportation and uses technologies for real-time monitoring and feedback. The final system of indicators is shown in Table 3.

Table 2. Professional backgrounds of the selected five experts.

Expert	Organization	Position	Duties	Seniority (yr)
A	Traffic Detachment of Municipal Public Security Bureau	Division marshal	Handle safety accidents	21
B	City business bureau	Deputy director	Implement and investigate safety management laws and regulations	20
C	A hydrogen energy technology and equipment company	Technical director	Hydrogen energy storage and transportation technology management	18
D	A new energy technology research Institute	Senior Research Fellow	Risk assessment and safety assurance for hydrogen facilities	16
E	An international testing group	Technical director	Safety design and risk assessment in hazardous situations	10

Table 3. The formal decision structure.

Aspect	Criteria	Explanation
People-related Risk (A)	Personnel Awareness (A1)	Risk in operational activities is caused by a lack of awareness of personnel.
	Personnel Skills (A2)	Risk in operational activities is caused by limited technical competence of personnel.
	Personnel Emotions (A3)	Personnel are at risk in operational activities owing to psychological and emotional fluctuations.
	Personnel Health (A4)	Risk in operational activities is caused by the poor physical health of personnel.
Storage Risk (B)	Equipment Liner Corrosion and Hydrogen-induced Embrittlement (B1)	When the stored hydrogen contains impurities, corrosion is more serious. Once hydrogen-induced embrittlement occurs, the safety of the storage cylinder decreases, leading to leakage.
	Equipment Fatigue (B2)	The storage system requires repeated loading of hydrogen, which has stringent requirements on the fatigue life of the container, but the fatigue resistance of the metal tank is inadequate.
	Penetration (B3)	Hydrogen permeation is a problem in composite containers with metal tanks under high pressure.
	Frequent Filling of Equipment (B4)	Repeated use of the hydrogen storage tank produces subtle cracks or knock friction, making it easy to explode.

Table 3. *Cont.*

Aspect	Criteria	Explanation
	Combination of Gases (B5)	During the canning of hydrogen, such impurities as hydrogen with slightly higher oxygen content remain in the storage tank. If the residual gas is not checked in time, hydrogen in the storage tank becomes impure and this can lead to the formation of flammable mixed gas.
	Liquefaction Storage Stability (B6)	Once the surrounding insulation layer has been destroyed and the ambient temperature increased, liquefied hydrogen inside the storage container is vaporized rapidly to create an instant strong pressure and explosion.
Transportation Risk (C)	Deficiency of Transportation Equipment (C1)	Serious accidents may be caused due to design, manufacturing, installation and other reasons of transportation tools.
	Transport Equipment Failure (C2)	This is the risk of a sudden loss of a prescribed functioning condition of a conveyance.
	Stability of Transportation (C3)	Inevitable movements occur in in the normal operation of the transportation vehicle that must be controlled.
Environmental Risk (D)	Accuracy of Environmental Information (D1)	Inaccurate information is obtained regarding storage and transportation due to problems with personnel, tools, and equipment.
	Environmental Volatility (D2)	This is uncertainty in the risk of hydrogen storage and transportation caused by environmental fluctuations and changes in the process.
	Hyperbaric Environment (D3)	After long-term exposure to high pressure hydrogen, the antihydrogen brittleness energy of high-strength steel decreases with increasing pressure, resulting in a decrease in its local plasticity and the acceleration of crack propagation.
Management Risk (E)	Standardized Management (E1)	The process of hydrogen storage and transportation is relatively standardized.
	Comprehensive Management (E2)	Comprehensively manage the plan, equipment, testing personnel, and tools for hydrogen storage and transportation process.
	Dynamic Monitoring (E3)	The personnel, vehicles, environment, and equipment are tested during storage and transportation.
	Effectiveness of Feedback (E4)	Timely feedback regarding problems identified by monitoring can prevent accidents during storage and transportation.

4.3. Identifying Key Risk Factors

We gave the questionnaire to the five experts and scored their responses according to Formula (1). We treated their results equally, calculated the average score, and formed an initial direct impact matrix for D-ANP, as shown in Table 4. Using Formula (2), we first summed each column and each row, respectively, and then found the maximum value. We took the reciprocal of the maximum value as λ, and multiplied λ by the initial direct influence matrix to obtain the normalized direct influence matrix. Using Formula (3), we first subtracted the normalized direct influence matrix from the unit matrix I, and then found its inverse matrix. Finally, we multiplied the normalized direct influence matrix to obtain the total impact matrix, as shown in Table 5.

Table 4. The initial direct influence matrix.

	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**	**C3**	**D1**	**D2**	**D3**	**E1**	**E2**	**E3**	**E4**
A1	0.0000	0.4000	0.0000	0.0000	0.0000	0.0000	1.2000	0.0000	1.4000	0.4000	0.0000	0.4000	1.4000	2.0000	0.0000	0.0000	1.0000	1.2000	1.2000	1.6000
A2	0.0000	0.0000	1.0000	0.0000	0.0000	0.4000	0.6000	0.6000	1.6000	0.0000	0.0000	1.6000	1.0000	1.6000	1.0000	0.0000	1.0000	1.0000	1.0000	1.0000
A3	0.6000	0.8000	0.0000	2.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	1.2000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000
A4	1.6000	1.2000	0.0000	0.0000	0.0000	0.0000	0.0000	2.0000	1.0000	0.0000	0.0000	1.0000	1.6000	1.2000	0.0000	0.0000	1.0000	1.0000	1.6000	0.0000
B1	0.0000	0.0000	0.0000	2.0000	0.0000	0.0000	2.0000	0.0000	0.0000	1.6000	0.0000	1.0000	2.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000
B2	0.0000	0.0000	0.0000	1.0000	1.0000	0.0000	0.0000	1.2000	2.0000	1.0000	0.0000	1.0000	2.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
B3	0.0000	0.0000	0.0000	1.6000	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	0.0000	0.0000	2.0000	0.0000	1.6000	1.0000	0.0000	0.0000	1.6000	1.0000
B4	0.0000	0.0000	0.0000	2.0000	1.0000	2.0000	1.0000	0.0000	2.0000	1.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000
B5	0.0000	0.0000	0.0000	1.2000	2.0000	1.0000	2.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.6000	0.0000	1.0000	0.0000	0.0000	0.0000	1.0000	1.0000
B6	0.0000	0.0000	0.0000	1.6000	1.0000	2.4000	2.4000	1.4000	0.0000	0.0000	0.0000	0.0000	1.0000	1.4000	0.0000	2.4000	1.6000	1.6000	1.0000	1.0000
C1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.8000	0.0000	0.0000	0.0000
C2	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.4000	0.0000	0.0000	0.0000	0.0000	0.0000	1.6000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000
C3	0.0000	0.0000	0.0000	0.6000	0.0000	1.0000	1.6000	0.4000	0.4000	0.6000	0.0000	1.4000	0.0000	1.4000	1.8000	0.0000	2.6000	2.2000	2.6000	1.4000
D1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	1.6000	1.6000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
D2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	2.4000	1.0000	1.0000	2.0000	0.0000	0.0000	3.6000	1.0000	0.0000	0.0000	3.2000	1.8000	1.4000	1.4000
D3	0.0000	0.0000	0.0000	0.0000	1.2000	0.0000	0.0000	0.0000	1.0000	2.0000	0.0000	0.0000	0.0000	1.0000	1.0000	0.0000	0.0000	0.0000	1.0000	1.0000
E1	1.2000	1.0000	0.0000	0.0000	0.0000	2.0000	2.0000	1.0000	1.6000	2.0000	1.6000	1.0000	1.6000	2.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000
E2	2.0000	1.0000	1.0000	0.0000	0.0000	2.0000	2.0000	1.0000	2.0000	2.0000	2.0000	1.0000	2.0000	1.6000	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000
E3	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	2.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000	3.0000	0.0000	0.0000	2.6000	1.0000	0.0000	0.0000
E4	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	3.0000	3.6000	0.0000	1.0000	3.6000	1.0000	0.0000	0.0000	2.0000	3.0000	1.0000	0.0000

Table 5. The total influence matrix.

	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	C1	C2	C3	D1	D2	D3	E1	E2	E3	E4
A1	0.0069	0.0176	0.0026	0.0137	0.0114	0.0190	0.0730	0.0094	0.0692	0.0432	0.0090	0.0326	0.0852	0.0903	0.0162	0.0068	0.0560	0.0605	0.0635	0.0684
A2	0.0073	0.0053	0.0346	0.0171	0.0116	0.0314	0.0550	0.0296	0.0752	0.0295	0.0084	0.0695	0.0754	0.0777	0.0486	0.0064	0.0575	0.0533	0.0575	0.0495
A3	0.0289	0.0328	0.0028	0.0722	0.0062	0.0141	0.0243	0.0114	0.0213	0.0210	0.0078	0.0182	0.0628	0.0634	0.0099	0.0030	0.0528	0.0513	0.0530	0.0446
A4	0.0588	0.0442	0.0031	0.0153	0.0110	0.0218	0.0353	0.0745	0.0581	0.0246	0.0089	0.0519	0.0876	0.0683	0.0169	0.0048	0.0579	0.0517	0.0772	0.0174
B1	0.0079	0.0058	0.0009	0.0802	0.0075	0.0166	0.0914	0.0137	0.0203	0.0733	0.0052	0.0473	0.0980	0.0232	0.0145	0.0103	0.0557	0.0223	0.0270	0.0476
B2	0.0045	0.0033	0.0006	0.0499	0.0441	0.0170	0.0289	0.0484	0.0797	0.0503	0.0040	0.0453	0.0922	0.0191	0.0135	0.0064	0.0224	0.0158	0.0538	0.0133
B3	0.0062	0.0045	0.0010	0.0638	0.0121	0.0168	0.0320	0.0129	0.0536	0.0588	0.0059	0.0155	0.0999	0.0270	0.0648	0.0388	0.0317	0.0250	0.0785	0.0490
B4	0.0080	0.0060	0.0008	0.0842	0.0465	0.0835	0.0657	0.0166	0.0882	0.0584	0.0064	0.0174	0.0737	0.0239	0.0457	0.0073	0.0585	0.0199	0.0608	0.0174
B5	0.0057	0.0041	0.0009	0.0579	0.0746	0.0473	0.0959	0.0128	0.0222	0.0597	0.0049	0.0170	0.0919	0.0227	0.0459	0.0084	0.0292	0.0225	0.0592	0.0497
B6	0.0121	0.0083	0.0027	0.0757	0.0496	0.1028	0.1169	0.0638	0.0397	0.0436	0.0115	0.0257	0.0869	0.0783	0.0211	0.0865	0.0809	0.0757	0.0698	0.0547
C1	0.0018	0.0014	0.0002	0.0033	0.0011	0.0046	0.0082	0.0025	0.0043	0.0052	0.0022	0.0369	0.0399	0.0069	0.0045	0.0019	0.0315	0.0053	0.0063	0.0041
C2	0.0035	0.0025	0.0005	0.0398	0.0040	0.0067	0.0607	0.0069	0.0112	0.0148	0.0022	0.0094	0.0721	0.0452	0.0437	0.0361	0.0156	0.0122	0.0173	0.0106
C3	0.0135	0.0091	0.0036	0.0394	0.0152	0.0621	0.1035	0.0318	0.0522	0.0650	0.0168	0.0716	0.0635	0.0869	0.0765	0.0108	0.1205	0.1011	0.1190	0.0686
D1	0.0019	0.0013	0.0004	0.0096	0.0036	0.0088	0.0505	0.0062	0.0087	0.0439	0.0021	0.0588	0.0713	0.0129	0.0426	0.0070	0.0155	0.0123	0.0150	0.0100
D2	0.0134	0.0092	0.0034	0.0263	0.0174	0.0392	0.1348	0.0523	0.0729	0.1124	0.0168	0.0293	0.1766	0.0766	0.0258	0.0142	0.1453	0.0958	0.0912	0.0755
D3	0.0025	0.0017	0.0006	0.0128	0.0490	0.0136	0.0269	0.0082	0.0455	0.0855	0.0037	0.0108	0.0289	0.0489	0.0398	0.0079	0.0205	0.0160	0.0471	0.0442
E1	0.0459	0.0374	0.0032	0.0260	0.0181	0.0917	0.1101	0.0486	0.0860	0.1006	0.0602	0.0589	0.1083	0.0981	0.0233	0.0134	0.0339	0.0600	0.0692	0.0562
E2	0.0711	0.0379	0.0349	0.0290	0.0191	0.0910	0.1112	0.0481	0.0993	0.1003	0.0717	0.0593	0.1233	0.0880	0.0244	0.0134	0.0380	0.0310	0.0725	0.0590
E3	0.0084	0.0060	0.0018	0.0196	0.0424	0.0538	0.1019	0.0130	0.0551	0.0628	0.0423	0.0547	0.0772	0.1215	0.0184	0.0100	0.1043	0.0500	0.0264	0.0190
E4	0.0144	0.0093	0.0046	0.0307	0.0529	0.0423	0.0971	0.0221	0.1312	0.1610	0.0167	0.0615	0.1772	0.0769	0.0259	0.0178	0.1051	0.1320	0.0777	0.0333

We obtained the significance and correlation of each risk factor and used them to determine their causal types. The results are shown in Table 6.

Table 6. Prominence and relation of each risk factor in RSTH.

Factor	D	C	D + C	D − C	Type
A1	0.7544	0.3227	1.0771	0.4317	Driving factors
A2	0.8005	0.2476	1.0482	0.5529	Driving factors
A3	0.6017	0.1033	0.7050	0.4984	Driving factors
A4	0.7894	0.7664	1.5557	0.0230	Driving factors
B1	0.6686	0.4976	1.1662	0.1710	Driving factors
B2	0.6124	0.7843	1.3967	−0.1718	Outcome factors
B3	0.6979	1.4235	2.1213	−0.7256	Outcome factors
B4	0.7888	0.5329	1.3217	0.2559	Driving factors
B5	0.7325	1.0941	1.8266	−0.3616	Outcome factors
B6	1.1063	1.2138	2.3202	−0.1075	Outcome factors
C1	0.1721	0.3066	0.4787	−0.1345	Outcome factors
C2	0.4151	0.7914	1.2065	−0.3764	Outcome factors
C3	1.1306	1.7919	2.9225	−0.6613	Outcome factors
D1	0.3825	1.1557	1.5382	−0.7731	Outcome factors
D2	1.2284	0.6221	1.8505	0.6063	Driving factors
D3	0.5143	0.3114	0.8257	0.2029	Driving factors
E1	1.1492	1.1327	2.2819	0.0165	Driving factors
E2	1.2225	0.9137	2.1362	0.3088	Driving factors
E3	0.8886	1.1420	2.0307	−0.2534	Outcome factors
E4	1.2898	0.7919	2.0818	0.4979	Driving factors

The results showed that the RSTH-related factors can be divided into two categories. The driving factors included personnel awareness (A1), personnel skills (A2), personnel emotions (A3), personnel health (A4), liner corrosion and hydrogen-induced embrittlement of the equipment (B1), frequent filling of the equipment (B4), environmental volatility (D2), hyperbaric environment (D3), standardized management (E1), comprehensive management (E2), and the effectiveness of feedback (E4). These factors formed a direct source of risk for the RSTH. The outcome-related factors included equipment fatigue (B2), penetration (B3), combination of gases (B5), stability of liquefaction storage (B6), deficiencies in the transportation equipment (C1), failure of the transport equipment (C2), stability of transportation (C3), accuracy of environmental information (D1), and dynamic monitoring (E3). These factors formed indirect sources of risk for the RSTH. The higher the value of the degree of a relationship was, the greater was the influence of the relevant factors on the other factors. The panel of experts believed that D2, A2, and E4 could be used as the root factors affecting the RSTH for further analysis.

The total influence matrix shown in Table 5 was treated as part of the unweighted supermatrix-based ANP model. In the total influence matrix, each number was divided by the sum of each column to normalize the total influence matrix, and the matrix obtained was used as the weighted supermatrix. By multiplying the weighted supermatrix by itself three times, the numbers in each row of the matrix tended to be the same, and the limit supermatrix could be obtained, as shown in Table 7.

Table 7. The limiting supermatrix derived by the weighted supermatrix.

	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**	**C3**	**D1**	**D2**	**D3**	**E1**	**E2**	**E3**	**E4**	**Rank**
A1	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	0.0449	13
A2	0.0588	0.0588	0.0589	0.0588	0.0588	0.0588	0.0588	0.0588	0.0588	0.0588	0.0588	0.0588	0.0588	0.0588	0.0588	0.0588	0.0588	0.0588	0.0588	0.0588	7
A3	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	14
A4	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	0.0571	8
B1	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	15
B2	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	16
B3	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	0.0455	11
B4	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	0.0471	9
B5	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	12
B6	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	0.0704	5
C1	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	20
C2	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	0.0255	18
C3	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	0.0702	6
D1	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	0.0216	19
D2	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	0.0726	3
D3	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	0.0318	17
E1	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	4
E2	0.0880	0.0880	0.0880	0.0880	0.0879	0.0880	0.0880	0.0880	0.0880	0.0880	0.0880	0.0880	0.0880	0.0880	0.0880	0.0879	0.0880	0.0880	0.0880	0.0880	1
E3	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	0.0467	10
E4	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	0.0757	2

The data in each row in Table 7 are the limit values, representing the weight of each criterion. The weight can be ranked according to the value. The rankings showed that the eight most influential factors were also key factors of the RSTH, including comprehensive management (E2), effectiveness of feedback (E4), environmental volatility (D2), standardized management (E1), stability of liquefaction storage (B6), stability of transportation (C3), personnel skills (A2), and personnel health (A4).

4.4. Assessment of Urban RSTH

We distributed 120 copies of it to the expert group and officials of important hydrogen-related enterprises in Beijing. A total of 106 responses were collected and 100 were valid. In the process of questionnaire data statistics, we divided the number of different risk evaluation questionnaires by the number of valid questionnaires for statistical processing, as shown in Table 8.

Table 8. Evaluation matrix.

Criterion	Significant Risk	Larger Risk	General Risk	Less Risk
A1	0.1	0.1	0.3	0.5
A2	0.1	0.2	0.3	0.4
A3	0.08	0.21	0.23	0.48
A4	0	0.17	0.3	0.53
B1	0.2	0.2	0.3	0.3
B2	0.11	0.23	0.35	0.31
B3	0.1	0.14	0.33	0.43
B4	0.1	0.1	0.5	0.3
B5	0.2	0.1	0.3	0.4
B6	0.05	0.11	0.46	0.38
C1	0	0.02	0.42	0.56
C2	0	0.12	0.32	0.56
C3	0.09	0.14	0.67	0.1
D1	0	0.42	0.33	0.25
D2	0.04	0.16	0.57	0.23
D3	0.03	0.12	0.34	0.51
E1	0.13	0.22	0.34	0.31
E2	0.11	0.21	0.41	0.27
E3	0.04	0.22	0.39	0.35
E4	0.09	0.34	0.27	0.3

The weights of the factor calculated in Table 6 can be expressed as a set of weights:

$$Z = \begin{pmatrix} 0.0449, 0.0588, 0.0440, 0.0571, 0.0394, 0.0352, 0.0455, 0.0471, 0.0452, 0.0704, \\ 0.0090, 0.0255, 0.0702, 0.0216, 0.0726, 0.0318, 0.0713, 0.0880, 0.0467, 0.0757 \end{pmatrix}$$

According to Formula (4), the synthetic calculation for each risk is as follows:

$$\begin{aligned} Significant\ risk = {} & 0.1 \times 0.0449 + 0.1 \times 0.0588 + 0.08 \times 0.0440 + 0 \times 0.0571 + 0.2 \times 0.0394 + 0.11 \times 0.0352 \\ & + 0.1 \times 0.0455 + 0.1 \times 0.0471 + 0.2 \times 0.0452 + 0.05 \times 0.0704 + 0 \times 0.0090 + 0 \times 0.0255 \\ & + 0.09 \times 0.0702 + 0 \times 0.0216 + 0.04 \times 0.0726 + 0.03 \times 0.0318 + 0.13 \times 0.0713 + 0.11 \times 0.0880 \\ & + 0.04 \times 0.0467 + 0.09 \times 0.0757 = 0.0853 \end{aligned}$$

By analogy, the fuzzy set of evaluations can be obtained as follows:

$$B = (0.0853, 0.1823, 0.3843, 0.3482)$$

According to the principle of the maximum degree of membership, we can conclude that Beijing can be classed as incurring a general risk with regard to the storage and transportation of hydrogen energy. This also shows that if Beijing does not strengthen its risk management in this context, this may lead to more accidents and, possibly, casualties.

5. Discussion

5.1. Causality between Critical Factors

A causal diagram of the critical factors based on the total influence matrix is shown in Figure 2. Table 5 shows that A2, D2, and E4 were suitable as the sources of risk because of their maximal relations. Improving the performance of "personnel skills" (A2) can help improve the other criteria. A2 is fundamental to the risk management and control of the storage and transportation of hydrogen energy and can guarantee the stability of the enterprise while reducing the overall risk. Improving A2 can promote improvements in D2, which in turn can promote E1 and E4. The improvement in E4 can further help improve A4 and E2.

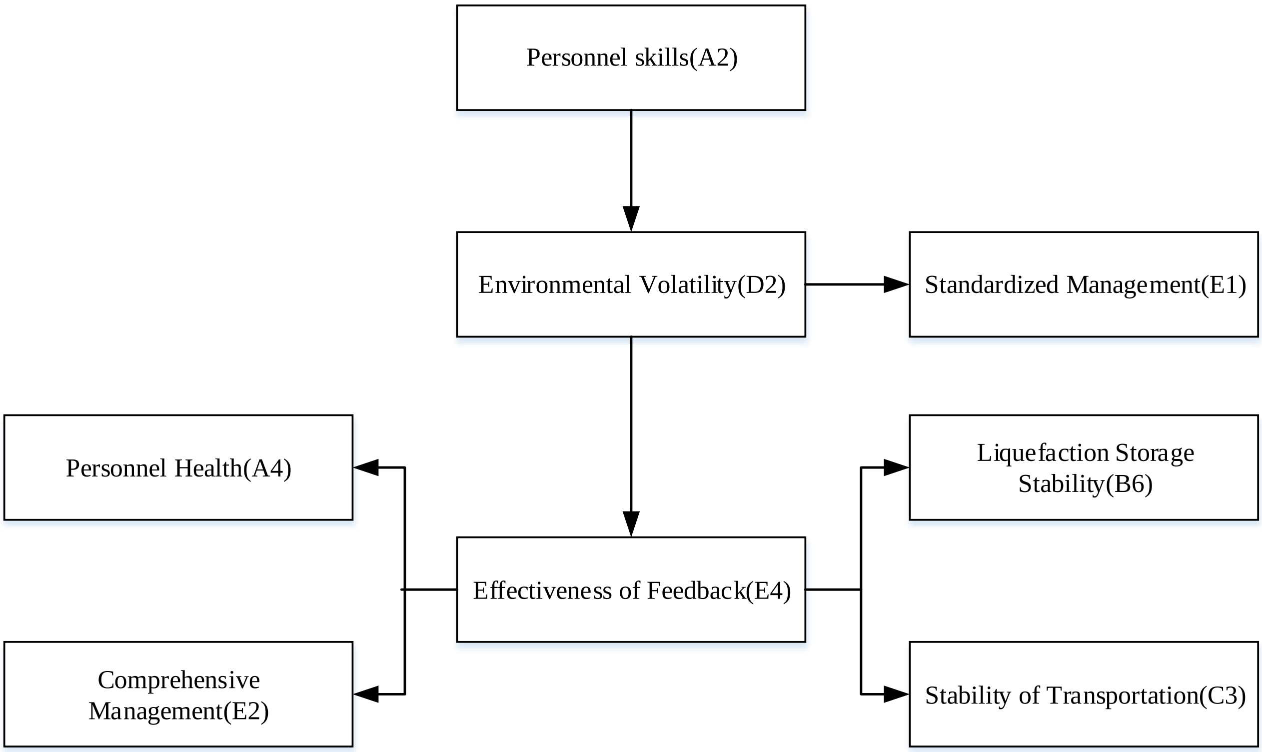

Figure 2. Causal diagram involving the critical factors.

5.2. Managerial Implications

In this paper, we proposed a hybrid MCDM-based method to identify the key RSTHs by analyzing the supply chain for hydrogen energy in Beijing. As we concluded that the risk level of Beijing in context is general, we focus on addressing the main risk factors for it. The RSTH usually does not emerge alone in practice, and is often accompanied by highly correlated risks [16]. Therefore, based on the results shown in Figure 2, we propose countermeasures according to the types of risks to ensure systematic risk management.

(1) The risk weight of personnel skills (A2) was 0.0880, the rank of A2 was first, and was a root driving factor. A2 was part of people-related risks and formed the most important risk factor. This is because the human operators involved in the supply chain for hydrogen energy are sometimes not trained appropriately, are unfamiliar with the characteristics of hydrogen energy, and cannot deal with emergencies. This result is consistent with that of Zheng et al., who evaluated risk factors for typical hydrogen storage processes in China [45]. Le et al. reached a similar conclusion when studying integrated technical frameworks for safety information of hydrogen energy storage [46]. Furthermore, our study explicitly demonstrates that AI and big data technology can be integrated into the process to assist in decision making in case

of emergencies [47]. This can reduce the risks caused by differences in the quality of operators.

(2) Environmental volatility (D2) is part of environmental risk, the risk weight of D2 is 0.0726, the rank of D2 is third, and it is also a driving factor for E4 and E1. The results here showed that the security of the storage and transportation of hydrogen energy depend on the stability of the environment and the process. Kim [13] and Zhang [17], respectively, proved the impact of external temperature and pressure on RSTHs, and Lam et al. [15] proved that the performance of the complicated environmental volatility is a critical risk factor. However, the solution to the D2 is generally based on the control of static storage environment volatility, and few studies have been conducted to deal with dynamic environment volatility. In practice, with the development of hydrogen energy commercialization, more and more hydrogen energy will be in a dynamic transportation environment. This paper proposes that the logistics network for hydrogen energy needs to be redesigned and segmented transportation should be used to reduce the risk due to D2. Large-scale centralized transportation is needed between cities, and small-scale and high frequency distribution is needed within them.

(3) Effectiveness of feedback (E4) is part of management-related risk. The risk weight of E4 is 0.0757, the rank of E4 is second, and it is also a driving factor for A4, B6, E2, C3. Most previous studies focused on the breakthrough of feedback technologies [48,49]. Dynamic path scheduling in combination with the GIS, GPS, and AI; and site selection based on the characteristics of hydrogen energy storage; and monitoring and providing an early warning of surrounding hazardous sources by using IOT-based sensing equipment were proved to be crucial for reducing the risk of E4 [50]. However, ignoring the guiding role of the RSTH management will lead to the role of the technology being greatly reduced. Enterprises are used to attending to safety issues rather than the supply chain [51]. Supply chain management for hydrogen energy is invariably fragmented owing to the large number of personnel and conversion of equipment during storage and transportation [52]. Therefore, risk control measures are needed from the perspective of integrating the supply chain, including improving safety standards for urban hydrogen energy, using information technology to ensure that the responsibility for charging stations in the supply chain is clear and the RSTHs can be traced, and unifying the online management of the equipment and sites used for the storage and transportation of hydrogen energy [17].

(4) Some risk factors are related to key technologies and are not easy to address in a short time. this finding is consistent with that of Mufachi [53] and Pugazhendhi [54]. Furthermore, it is proved that the technology and the mode of operation used must match each other in RSTH management; otherwise, the short board effect occurs [17]. This paper clarifies the responsibilities of the subjects in the hydrogen energy supply chain and designs the strategies to strengthen management cooperation. One effective solution is for technology suppliers to undertake liability for operational management because their professional knowledge of hydrogen energy is conducive to addressing vulnerabilities in management. At the same time, an incentive mechanism should be designed to ensure the enthusiasm of the technicians involved in supply chain management.

6. Conclusions

The safety concern of the storage and transportation of hydrogen energy is a hindrance to its commercialization. This paper proposed a framework to manage the RSTH according to the logistical chain of "risk identification-risk assessment–risk control".

We used a hybrid MCDM-based method to identify and evaluate the RSTHs. The weighted importance of each risk factor was calculated by combining its importance score obtained from DEMATEL with its weight obtained by the ANP model. The results showed that personnel skills, environmental volatility, and the effectiveness of feedback during the storage and transportation of hydrogen energy are factors driving the RSTHs and have an important impact on the other factors. The general risk grade for the storage and transportation of hydrogen energy in Beijing was calculated by using the FE model. The key to RSTH management is to trace risks upstream and downstream of the supply chain and to design strategies to deal with complex risk chains.

The conclusion drawn from the results are quite different from previous studies. Most previous studies mainly systematically identified the safety status and technical challenges of hydrogen energy infrastructure in the fields of preparation, storage, transportation, and supply [55–57]. The research results of this paper proved that the integrated management of hydrogen energy supply chain was more important than the technologies. Based on the identification of the critical RSTHs, an early warning mechanism, emergency response mechanism, and post-traceability control mechanism can be established. In this process, advanced technologies can accelerate the construction of risk management systems and rapidly improve the personnel skills. Therefore, the risk control system integrated with advanced technology established in this paper plays an important role in accelerating the commercial development of hydrogen energy.

Because the RSTHs are influenced by traffic conditions, the layout of the equipment used for hydrogen energy, the number of items of mobile equipment, and the system of indicators for the RSTH should be adjusted with the commercialization of hydrogen energy. In addition, the cost of the short-distance distribution of hydrogen energy in cities is high, and increases by USD 60 for every additional kilometer traveled by a hydrogen vehicle with a capacity of four tons [58]. The costs and risks of transportation and storage are contrary to each other in the commercialization of hydrogen energy, and balancing them is a key problem. We proposed a static risk management system here that is suitable for the promotion and development of the hydrogen energy industry. The early warning of risks can improve the resilience of the supply chain. Once the industry has entered the stage of large-scale commercialization, it should focus on developing dynamic risk management systems. Real-time risk supervision, emergency response, and the traceability of risks are the future directions of research in the area.

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Appendix A

Table A1. The score of Expert A.

	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	C1	C2	C3	D1	D2	D3	E1	E2	E3	E4
A1	0	1	0	0	0	0	0	0	2	1	0	1	2	2	0	0	1	1	0	1
A2	0	0	1	0	0	1	0	0	1	0	0	1	1	1	1	0	1	1	1	1
A3	0	0	0	2	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	1
A4	1	1	0	0	0	0	0	2	1	0	0	1	1	1	0	0	1	1	1	0
B1	0	0	0	2	0	0	2	0	0	2	0	1	2	0	0	0	1	0	0	1
B2	0	0	0	1	1	0	0	1	2	1	0	1	2	0	0	0	0	0	1	0
B3	0	0	0	2	0	0	0	0	1	1	0	0	2	0	2	1	0	0	2	1
B4	0	0	0	2	1	2	1	0	2	1	0	0	1	0	1	0	1	0	1	0
B5	0	0	0	1	2	1	2	0	0	1	0	0	1	0	1	0	0	0	1	1
B6	0	0	0	2	1	1	2	1	0	0	0	0	1	1	0	2	1	1	1	1
C1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
C2	0	0	0	1	0	0	1	0	0	0	0	0	2	1	1	1	0	0	0	0
C3	0	0	0	0	0	1	1	1	1	0	0	2	0	1	2	0	3	2	4	2
D1	0	0	0	0	0	0	1	0	0	1	0	1	2	0	1	0	0	0	0	0
D2	0	0	0	0	0	0	2	1	1	2	0	0	4	1	0	0	3	1	1	1
D3	0	0	0	0	1	0	0	0	1	2	0	0	0	1	1	0	0	0	1	1
E1	0	1	0	0	0	2	2	1	2	2	1	1	2	2	0	0	0	1	1	1
E2	2	1	1	0	0	2	2	1	2	2	2	1	2	2	0	0	0	0	1	1
E3	0	0	0	0	1	1	2	0	1	1	1	1	1	3	0	0	3	1	0	0
E4	0	0	0	0	1	0	1	0	3	4	0	1	4	1	0	0	2	3	1	0

Table A2. The score of Expert B.

	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	C1	C2	C3	D1	D2	D3	E1	E2	E3	E4
A1	0	0	0	0	0	0	2	0	1	0	0	0	1	2	0	0	1	1	2	2
A2	0	0	1	0	0	0	1	1	2	0	0	2	1	2	1	0	1	1	1	1
A3	1	1	0	2	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	1
A4	2	1	0	0	0	0	0	2	1	0	0	1	2	1	0	0	1	1	2	0
B1	0	0	0	2	0	0	2	0	0	1	0	1	2	0	0	0	1	0	0	1
B2	0	0	0	1	1	0	0	1	2	1	0	1	2	0	0	0	0	0	1	0
B3	0	0	0	1	0	0	0	0	1	1	0	0	2	0	1	1	0	0	1	1
B4	0	0	0	2	1	2	1	0	2	1	0	0	1	0	1	0	1	0	1	0
B5	0	0	0	1	2	1	2	0	0	1	0	0	2	0	1	0	0	0	1	1
B6	0	0	0	1	1	3	3	2	0	0	0	0	1	2	0	3	1	2	1	1
C1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0
C2	0	0	0	1	0	0	2	0	0	0	0	0	1	1	1	1	0	0	0	0
C3	0	0	0	1	0	1	2	0	0	1	0	1	0	2	3	0	3	3	3	1
D1	0	0	0	0	0	0	1	0	0	1	0	2	1	0	1	0	0	0	0	0
D2	0	0	0	0	0	0	3	1	1	2	0	0	3	1	0	0	3	2	2	2
D3	0	0	0	0	2	0	0	0	1	2	0	0	0	1	1	0	0	0	1	1
E1	2	1	0	0	0	2	2	1	1	2	2	1	1	2	0	0	0	1	1	1
E2	3	1	1	0	0	2	2	1	2	2	2	1	2	1	0	0	0	0	1	1
E3	0	0	0	0	1	1	2	0	1	1	1	1	1	3	0	0	2	1	0	0
E4	0	0	0	0	1	0	1	0	3	3	0	1	3	1	0	0	2	3	1	0

Table A3. The score of Expert C.

	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**	**C3**	**D1**	**D2**	**D3**	**E1**	**E2**	**E3**	**E4**
A1	0	0	0	0	0	0	2	0	1	0	0	0	1	2	0	0	1	2	2	2
A2	0	0	1	0	0	0	1	1	2	0	0	2	1	2	1	0	1	1	1	1
A3	0	1	0	2	0	0	0	0	0	0	0	0	1	2	0	0	1	1	1	1
A4	2	2	0	0	0	0	0	2	1	0	0	1	2	2	0	0	1	1	2	0
B1	0	0	0	2	0	0	2	0	0	2	0	1	2	0	0	0	1	0	0	1
B2	0	0	0	1	1	0	0	2	2	1	0	1	2	0	0	0	0	0	1	0
B3	0	0	0	2	0	0	0	0	1	1	0	0	2	0	2	1	0	0	2	1
B4	0	0	0	2	1	2	1	0	2	1	0	0	1	0	1	0	1	0	1	0
B5	0	0	0	2	2	1	2	0	0	1	0	0	2	0	1	0	0	0	1	1
B6	0	0	0	2	1	3	2	1	0	0	0	0	1	1	0	2	3	2	1	1
C1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2	0	0	0
C2	0	0	0	1	0	0	1	0	0	0	0	0	2	1	1	1	0	0	0	0
C3	0	0	0	1	0	1	2	0	0	1	0	1	0	1	0	0	2	2	1	1
D1	0	0	0	0	0	0	1	0	0	1	0	2	2	0	1	0	0	0	0	0
D2	0	0	0	0	0	0	2	1	1	2	0	0	4	1	0	0	4	3	1	1
D3	0	0	0	0	1	0	0	0	1	2	0	0	0	1	1	0	0	0	1	1
E1	2	1	0	0	0	2	2	1	2	2	2	1	2	2	0	0	0	1	1	1
E2	1	1	1	0	0	2	2	1	2	2	2	1	2	2	0	0	0	0	1	1
E3	0	0	0	0	1	1	2	0	1	1	1	1	1	3	0	0	3	1	0	0
E4	0	0	0	0	1	0	1	0	3	4	0	1	4	1	0	0	2	3	1	0

Table A4. The score of Expert D.

	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**C1**	**C2**	**C3**	**D1**	**D2**	**D3**	**E1**	**E2**	**E3**	**E4**
A1	0	1	0	0	0	0	0	0	2	1	0	1	2	2	0	0	1	1	0	1
A2	0	0	1	0	0	1	0	0	1	0	0	1	1	1	1	0	1	1	1	1
A3	1	1	0	2	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	1
A4	1	1	0	0	0	0	0	2	1	0	0	1	1	1	0	0	1	1	1	0
B1	0	0	0	2	0	0	2	0	0	2	0	1	2	0	0	0	1	0	0	1
B2	0	0	0	1	1	0	0	1	2	1	0	1	2	0	0	0	0	0	1	0
B3	0	0	0	2	0	0	0	0	1	1	0	0	2	0	2	1	0	0	2	1
B4	0	0	0	2	1	2	1	0	2	1	0	0	1	0	1	0	1	0	1	0
B5	0	0	0	1	2	1	2	0	0	1	0	0	1	0	1	0	0	0	1	1
B6	0	0	0	2	1	2	2	1	0	0	0	0	1	1	0	2	2	1	1	1
C1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
C2	0	0	0	1	0	0	1	0	0	0	0	0	2	1	1	1	0	0	0	0
C3	0	0	0	0	0	1	1	1	1	0	0	2	0	1	2	0	2	2	3	2
D1	0	0	0	0	0	0	1	0	0	1	0	1	2	0	1	0	0	0	0	0
D2	0	0	0	0	0	0	2	1	1	2	0	0	4	1	0	0	3	1	1	1
D3	0	0	0	0	1	0	0	0	1	2	0	0	0	1	1	0	0	0	1	1
E1	0	1	0	0	0	2	2	1	2	2	1	1	2	2	0	0	0	1	1	1
E2	2	1	1	0	0	1	3	1	2	2	2	1	2	2	0	0	0	0	1	1
E3	0	0	0	0	1	1	2	0	1	1	1	1	1	3	0	0	3	1	0	0
E4	0	0	0	0	1	0	1	0	3	4	0	1	4	1	0	0	2	3	1	0

Table A5. The score of Expert E.

	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	C1	C2	C3	D1	D2	D3	E1	E2	E3	E4
A1	0	0	0	0	0	0	2	0	1	0	0	0	1	2	0	0	1	1	2	2
A2	0	0	1	0	0	0	1	1	2	0	0	2	1	2	1	0	1	1	1	1
A3	1	1	0	2	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	1
A4	2	1	0	0	0	0	0	2	1	0	0	1	2	1	0	0	1	1	2	0
B1	0	0	0	2	0	0	2	0	0	1	0	1	2	0	0	0	1	0	0	1
B2	0	0	0	1	1	0	0	1	2	1	0	1	2	0	0	0	0	0	1	0
B3	0	0	0	1	0	0	0	0	1	1	0	0	2	0	1	1	0	0	1	1
B4	0	0	0	2	1	2	1	0	2	1	0	0	1	0	1	0	1	0	1	0
B5	0	0	0	1	2	1	2	0	0	1	0	0	2	0	1	0	0	0	1	1
B6	0	0	0	1	1	3	3	2	0	0	0	0	1	2	0	3	1	2	1	1
C1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0
C2	0	0	0	1	0	0	2	0	0	0	0	0	1	1	1	1	0	0	0	0
C3	0	0	0	1	0	1	2	0	0	1	0	1	0	2	2	0	3	2	2	1
D1	0	0	0	0	0	0	1	0	0	1	0	2	1	0	1	0	0	0	0	0
D2	0	0	0	0	0	0	3	1	1	2	0	0	3	1	0	0	3	2	2	2
D3	0	0	0	0	1	0	0	0	1	2	0	0	0	1	1	0	0	0	1	1
E1	2	1	0	0	0	2	2	1	1	2	2	1	1	2	0	0	0	1	1	1
E2	2	1	1	0	0	3	1	1	2	2	2	1	2	1	0	0	0	0	1	1
E3	0	0	0	0	1	1	2	0	1	1	1	1	1	3	0	0	2	1	0	0
E4	0	0	0	0	1	0	1	0	3	3	0	1	3	1	0	0	2	3	1	0

Table A6. The normalized direct influence matrix.

	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	C1	C2	C3	D1	D2	D3	E1	E2	E3	E4
A1	0.0000	0.0131	0.0000	0.0000	0.0000	0.0000	0.0392	0.0000	0.0458	0.0131	0.0000	0.0131	0.0458	0.0654	0.0000	0.0000	0.0327	0.0392	0.0392	0.0523
A2	0.0000	0.0000	0.0327	0.0000	0.0000	0.0131	0.0196	0.0196	0.0523	0.0000	0.0000	0.0523	0.0327	0.0523	0.0327	0.0000	0.0327	0.0327	0.0327	0.0327
A3	0.0196	0.0261	0.0000	0.0654	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0327	0.0392	0.0000	0.0000	0.0327	0.0327	0.0327	0.0327
A4	0.0523	0.0392	0.0000	0.0000	0.0000	0.0000	0.0000	0.0654	0.0327	0.0000	0.0000	0.0327	0.0523	0.0392	0.0000	0.0000	0.0327	0.0327	0.0523	0.0000
B1	0.0000	0.0000	0.0000	0.0654	0.0000	0.0000	0.0654	0.0000	0.0000	0.0523	0.0000	0.0327	0.0654	0.0000	0.0000	0.0000	0.0327	0.0000	0.0000	0.0327
B2	0.0000	0.0000	0.0000	0.0327	0.0327	0.0000	0.0000	0.0392	0.0654	0.0327	0.0000	0.0327	0.0654	0.0000	0.0000	0.0000	0.0000	0.0000	0.0327	0.0000
B3	0.0000	0.0000	0.0000	0.0523	0.0000	0.0000	0.0000	0.0000	0.0327	0.0327	0.0000	0.0000	0.0654	0.0000	0.0523	0.0327	0.0000	0.0000	0.0523	0.0327
B4	0.0000	0.0000	0.0000	0.0654	0.0327	0.0654	0.0327	0.0000	0.0654	0.0327	0.0000	0.0000	0.0327	0.0000	0.0327	0.0000	0.0327	0.0000	0.0327	0.0000
B5	0.0000	0.0000	0.0000	0.0392	0.0654	0.0327	0.0654	0.0000	0.0000	0.0327	0.0000	0.0000	0.0523	0.0000	0.0327	0.0000	0.0000	0.0000	0.0327	0.0327
B6	0.0000	0.0000	0.0000	0.0523	0.0327	0.0784	0.0784	0.0458	0.0000	0.0000	0.0000	0.0000	0.0327	0.0458	0.0000	0.0784	0.0523	0.0523	0.0327	0.0327
C1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0327	0.0327	0.0000	0.0000	0.0000	0.0261	0.0000	0.0000	0.0000
C2	0.0000	0.0000	0.0000	0.0327	0.0000	0.0000	0.0458	0.0000	0.0000	0.0000	0.0000	0.0000	0.0523	0.0327	0.0327	0.0327	0.0000	0.0000	0.0000	0.0000
C3	0.0000	0.0000	0.0000	0.0196	0.0000	0.0327	0.0523	0.0131	0.0131	0.0196	0.0000	0.0458	0.0000	0.0458	0.0588	0.0000	0.0850	0.0719	0.0850	0.0458
D1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0327	0.0000	0.0000	0.0327	0.0000	0.0523	0.0523	0.0000	0.0327	0.0000	0.0000	0.0000	0.0000	0.0000
D2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0784	0.0327	0.0327	0.0654	0.0000	0.0000	0.1176	0.0327	0.0000	0.0000	0.1046	0.0588	0.0458	0.0458
D3	0.0000	0.0000	0.0000	0.0000	0.0392	0.0000	0.0000	0.0000	0.0327	0.0654	0.0000	0.0000	0.0000	0.0327	0.0327	0.0000	0.0000	0.0000	0.0327	0.0327
E1	0.0392	0.0327	0.0000	0.0000	0.0000	0.0654	0.0654	0.0327	0.0523	0.0654	0.0523	0.0327	0.0523	0.0654	0.0000	0.0000	0.0000	0.0327	0.0327	0.0327
E2	0.0654	0.0327	0.0327	0.0000	0.0000	0.0654	0.0654	0.0327	0.0654	0.0654	0.0654	0.0327	0.0654	0.0523	0.0000	0.0000	0.0000	0.0000	0.0327	0.0327
E3	0.0000	0.0000	0.0000	0.0000	0.0327	0.0327	0.0654	0.0000	0.0327	0.0327	0.0327	0.0327	0.0327	0.0980	0.0000	0.0000	0.0850	0.0327	0.0000	0.0000
E4	0.0000	0.0000	0.0000	0.0000	0.0327	0.0000	0.0327	0.0000	0.0980	0.1176	0.0000	0.0327	0.1176	0.0327	0.0000	0.0000	0.0654	0.0980	0.0327	0.0000

Table A7. The weighted supermatrix obtained by normalizing the total influence matrix.

	A1	A2	A3	A4	B1	B2	B3	B4	B5	B6	C1	C2	C3	D1	D2	D3	E1	E2	E3	E4
A1	0.0214	0.0710	0.0247	0.0178	0.0230	0.0242	0.0513	0.0177	0.0633	0.0356	0.0292	0.0411	0.0475	0.0782	0.0261	0.0220	0.0494	0.0663	0.0556	0.0864
A2	0.0226	0.0214	0.3348	0.0223	0.0234	0.0401	0.0387	0.0556	0.0688	0.0243	0.0273	0.0878	0.0421	0.0673	0.0781	0.0205	0.0508	0.0583	0.0504	0.0625
A3	0.0894	0.1326	0.0266	0.0942	0.0125	0.0180	0.0171	0.0214	0.0195	0.0173	0.0256	0.0229	0.0350	0.0549	0.0159	0.0097	0.0466	0.0562	0.0464	0.0563
A4	0.1822	0.1787	0.0304	0.0200	0.0222	0.0278	0.0248	0.1398	0.0531	0.0203	0.0291	0.0655	0.0489	0.0591	0.0271	0.0154	0.0511	0.0566	0.0676	0.0219
B1	0.0243	0.0235	0.0089	0.1047	0.0152	0.0211	0.0642	0.0256	0.0185	0.0604	0.0171	0.0598	0.0547	0.0201	0.0233	0.0330	0.0492	0.0244	0.0236	0.0601
B2	0.0140	0.0132	0.0060	0.0651	0.0887	0.0217	0.0203	0.0908	0.0728	0.0414	0.0129	0.0573	0.0514	0.0165	0.0218	0.0205	0.0197	0.0173	0.0471	0.0168
B3	0.0193	0.0180	0.0093	0.0833	0.0243	0.0214	0.0225	0.0242	0.0490	0.0484	0.0191	0.0196	0.0558	0.0234	0.1042	0.1248	0.0279	0.0273	0.0688	0.0618
B4	0.0248	0.0242	0.0082	0.1099	0.0934	0.1065	0.0462	0.0311	0.0806	0.0481	0.0207	0.0219	0.0411	0.0207	0.0734	0.0234	0.0517	0.0218	0.0533	0.0219
B5	0.0175	0.0164	0.0084	0.0755	0.1499	0.0603	0.0674	0.0241	0.0203	0.0492	0.0161	0.0214	0.0513	0.0196	0.0739	0.0269	0.0258	0.0246	0.0519	0.0627
B6	0.0376	0.0336	0.0266	0.0988	0.0997	0.1311	0.0821	0.1198	0.0362	0.0359	0.0374	0.0324	0.0485	0.0677	0.0339	0.2778	0.0714	0.0828	0.0612	0.0691
C1	0.0054	0.0055	0.0021	0.0043	0.0022	0.0059	0.0058	0.0048	0.0039	0.0043	0.0072	0.0466	0.0223	0.0060	0.0073	0.0061	0.0278	0.0058	0.0055	0.0051
C2	0.0108	0.0102	0.0047	0.0519	0.0080	0.0086	0.0427	0.0129	0.0103	0.0122	0.0071	0.0119	0.0402	0.0391	0.0703	0.1160	0.0137	0.0133	0.0152	0.0134
C3	0.0417	0.0366	0.0349	0.0514	0.0305	0.0792	0.0727	0.0597	0.0477	0.0535	0.0548	0.0904	0.0354	0.0752	0.1230	0.0347	0.1064	0.1107	0.1042	0.0866
D1	0.0060	0.0053	0.0043	0.0125	0.0072	0.0112	0.0355	0.0117	0.0080	0.0361	0.0069	0.0743	0.0398	0.0111	0.0685	0.0225	0.0137	0.0135	0.0131	0.0126
D2	0.0415	0.0370	0.0332	0.0343	0.0350	0.0500	0.0947	0.0981	0.0666	0.0926	0.0549	0.0371	0.0986	0.0663	0.0414	0.0455	0.1282	0.1049	0.0798	0.0953
D3	0.0079	0.0070	0.0056	0.0167	0.0985	0.0174	0.0189	0.0154	0.0416	0.0704	0.0119	0.0136	0.0162	0.0423	0.0640	0.0255	0.0181	0.0175	0.0412	0.0559
E1	0.1422	0.1512	0.0308	0.0339	0.0364	0.1169	0.0773	0.0911	0.0786	0.0829	0.1965	0.0744	0.0604	0.0849	0.0375	0.0431	0.0299	0.0656	0.0606	0.0710
E2	0.2203	0.1531	0.3381	0.0378	0.0385	0.1161	0.0781	0.0903	0.0907	0.0826	0.2340	0.0749	0.0688	0.0761	0.0392	0.0432	0.0336	0.0340	0.0634	0.0745
E3	0.0261	0.0241	0.0177	0.0255	0.0852	0.0686	0.0716	0.0245	0.0504	0.0518	0.1378	0.0691	0.0431	0.1051	0.0295	0.0323	0.0921	0.0547	0.0231	0.0240
E4	0.0448	0.0374	0.0447	0.0401	0.1064	0.0539	0.0682	0.0415	0.1200	0.1326	0.0543	0.0777	0.0989	0.0665	0.0417	0.0572	0.0928	0.1444	0.0680	0.0420

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