mathematics

Article

An Evaluation System for COVID-19 Vaccine Transportation Quality Based on Fuzzy Analytic Hierarchy Process

Hung-Lung Lin [1,*], Yu-Yu Ma [2] and Chin-Tsai Lin [3]

[1] School of Economics and Management, Sanming University, No. 25, Ching-Tung Rd., Sanming 365004, China
[2] School of Education Science and Psychology, Minnan Normal University, No. 36, Shì Qian Zhi St., Zhangzhou 363000, China; misssuperyoyo@gmail.com
[3] Department of Business Administration, Ming Chuan University, 250 Zhong Shan North Road, Section 5, Taipei 111, Taiwan; ctlin@mail.mcu.edu.tw
* Correspondence: hsa8936.hsa8936@msa.hinet.net

Abstract: COVID-19 vaccines have become pivotal in combating the pandemic since 2019. However, risks stemming from human errors, equipment malfunctions, and emergencies during cold-chain transportation can jeopardize vaccine security without effective safety standards. To ensure COVID-19 vaccine transportation safety, efficiency, and quality while mitigating risks, this study employed the modified Delphi method (MDM) to create a cold-chain vaccine transportation quality evaluation system. With the fuzzy analytic hierarchy process (FAHP), it then ranked indicator importance. The system comprises 5 criteria and 26 sub-criteria, highlighting factors like local weather conditions, topography, road characteristics, cold-chain logistics standardization, and national economic development. These significantly impact vaccine transport quality and risk. Regional authorities are advised to address these high-priority indicators by enhancing equipment, refining operational procedures, strengthening monitoring, offering training, etc. This comprehensive approach could minimize potential transportation setbacks, ensuring vaccine safety and quality. Crucially, this system offers valuable insights for health policies, transportation bodies, and companies. It sets safety benchmarks for cold-chain vaccine transportation and can be extended to other vaccines or medicines. This contribution is pivotal for future vaccine transportation management.

Keywords: COVID-19 vaccines; cold-chain transportation; transportation safety and quality; modified Delphi method (MDM); fuzzy analytic hierarchy process (FAHP); fuzzy sensitivity

MSC: 90B50; 90Bxx; 15-11; 20F10; 03E72

Citation: Lin, H.-L.; Ma, Y.-Y.; Lin, C.-T. An Evaluation System for COVID-19 Vaccine Transportation Quality Based on Fuzzy Analytic Hierarchy Process. *Mathematics* **2023**, *11*, 3914. https://doi.org/10.3390/math11183914

Academic Editor: Hsien-Chung Wu

Received: 12 August 2023
Revised: 9 September 2023
Accepted: 12 September 2023
Published: 14 September 2023

1. Introduction

1.1. Background and Purpose

The outbreak of COVID-19 in late 2019 contributed to social and economic disruption globally, posing a serious threat to human life and health [1]. COVID-19 is an acute respiratory infectious disease arising from a newly emerged virus, and its suddenness and high infectiousness make emergency management a crucial part of prevention and control. The integration of emergency management and mathematical modeling for the prevention of unexpected epidemics has played a key role in the response to public health emergencies such as COVID-19 [1,2]. The reference basis for decision making in emergency management relies on scientifically supported mathematical modeling, such as the Hybrid Neural Network Prediction model proposed by Adedotun [2], which effectively predicts the number of infected individuals and provides an invaluable scientific reference for COVID-19 transmission emergency management plan. Consequently, effective emergency management, coupled with a scientific approach, makes it possible to take quick action, make scientific decisions, and respond effectively to minimize losses and risks, thereby protecting people and society.

Following the outbreak, many countries initiated an emergency management program involving the development, production, and distribution of vaccines. The implementation of a large-scale vaccination program for COVID-19 has become an important measure in the prevention and control of epidemics and is also an essential aspect of emergency management. The pharmaceutical cold chain mainly focuses on temperature-sensitive pharmaceutical products to maintain their proper quality and efficacy at every step of the distribution, transportation, marketing, and storage process, as well as to ensure that the products remain undamaged under different temperature conditions [3]. Guided by national policies, China has successively implemented a series of strategies and measures to immunize against various infectious diseases, including COVID-19. This reflects the high priority that the government attaches to public health. Despite the progress made by the government in the immunization strategy, the safety and efficacy of vaccines depend not only on their development process but are also closely linked to the transportation aspect of cold-chain logistics. Given this background, government departments and relevant organizations have jointly formulated the Technical Guidelines for the Road Transportation of COVID-19 Vaccines, an initiative that highlights the importance that the Government attaches to the safety of the cold-chain transportation of vaccines. In addition, the World Health Organization [4], aware of the major outbreaks, has promulgated good storage and distribution practices for medical products in the cold chain. The document noted that for the purpose of upholding the quality of pharmaceutical products in the complex economic activities involved in the distribution and transportation of medicines, any supplier associated with them should implement Good Manufacturing Practice (GMP), Good Storage Practice (GSP), and Good Distribution Practice (GDP) and require that receiving verification, product monitoring, and documenting processes be carried out in the storage area. In fact, notwithstanding the policy support and guidelines, the cold-chain transportation of vaccines still confronts many challenges, such as the complex and changeable natural environment, unstable transportation status, and the infrastructural condition of different regions, all of which may affect the quality and safe transportation of vaccines. In addition, ensuring strict compliance with transport technical guidelines in all aspects, implementing contingency plans, and being able to respond to emergencies in a timely manner are also issues that require continuous attention and improvement. These issues are, therefore, practical problems and challenges currently faced in the cold-chain transport of vaccines, although supported by policies and guidelines.

Given that the most significant issue in the transportation of vaccines is temperature, vaccines, as biological products, can be rendered ineffective due to high temperatures in every phase of the process, from the department where they are manufactured to the site where they are to be used. If effective transportation safety and quality standards are not established, human risks, equipment risks, and unexpected events may occur during transportation, ultimately resulting in vaccine failure. For this reason, China is still facing many challenges and problems in the cold-chain transportation of COVID-19 vaccines. There are four possible challenges and problems [5–8]. (1) Issues of temperature control: The inactivated vaccine used for COVID-19 is stored under extremely restrictive conditions, with a storage temperature range of 2 °C to 8 °C. The effectiveness of the vaccine is affected once the storage temperature range is exceeded. It is critical to uphold stable temperature control during cold-chain transportation, and any temperature fluctuations or temperature anomalies may result in loss of vaccine or loss of efficacy. (2) Risks in transit: COVID-19 vaccines require different transportation carriers to perform switching, loading and unloading, handling, and other operations during transit, and the risk of uncontrolled temperature exists in the transit process. (3) Inadequate cold-chain facilities in remote areas: With limited economic conditions in remote areas, the operation and maintenance of cold-chain equipment can require large amounts of investment, and the lack of financial support has led to inadequate cold-chain facilities. (4) Transportation difficulties due to complex terrain: The complexity and variability of the terrain in remote areas have greatly increased the challenges of vaccine transportation. For example, in mountainous areas or remote areas, a single form of transportation, such as road transport, water transport, and air transport, is not practicable. It is, therefore, necessary to transport vaccines with the help of multiplexes or special modes of transportation, which increases the risk and uncertainty of transportation.

For the aforementioned problems, the development of the cold-chain vaccine transportation industry in China is in the early stage; the transportation facilities are relatively outdated, and there are more quality risk problems in the cold-chain transportation process in the past, such as the condition of refrigerated trucks, outdoor temperature, route design, and road condition. This dynamically changing environment reduces the controllability of the cold-chain vaccine transportation process, and if the risk management of quality is not properly arranged, it is highly susceptible to cause deterioration in the quality of vaccines, which ultimately leads to vaccine failure or a reduction in the safety of their use [9]. Also, risk is a fundamental issue in logistics and supply-chain management and may present itself in many different forms, posing a threat to all parts of the supply chain. Risk management is a necessary and vital process to achieve safety and reliability in the transportation process. There are very few related studies and standards in the field of cold-chain transportation, especially concerning the safety of cold-chain vaccines, and there is a need for specialized transportation standards and initiatives to prevent risky events from occurring.

To ensure the safe and efficient transportation and quality safety of COVID-19 vaccines and to reduce the transportation risk, this study first adopts the MDM to build a quality evaluation index system for cold-chain vaccine transportation, then utilizes the fuzzy analytic hierarchy process (FAHP) to determine the priority of each indicator, and then puts forward important countermeasures based on the priority order. This study aims to establish a system of indicators that can provide an invaluable reference for decision makers in health policy, transportation management, and private transportation companies to determine safety standards for the cold-chain transportation of COVID-19 vaccines. Importantly, the indicator system constructed in this study also provides new ideas and references for the transportation safety of other vaccines or drugs and provides helpful experience and guidance for future safety management in the field of cold-chain vaccine transportation.

1.2. Research Innovations and Contributions

This study presents unique contributions to and innovations in the field of the cold-chain transport of COVID-19 vaccines in the following key areas of interest: (1) Constructing a comprehensive evaluation indicator system: Unlike previous studies, this study constructs and proposes a comprehensive and integrated evaluation index system for the quality of cold-chain COVID-19 vaccine transport from a global perspective. The system takes into account not only the technical aspects of infrastructure or equipment, such as temperature control and equipment safety, but also a combination of natural environmental conditions, the development of the social and economic environment, the management of security systems, and the quality and risk of the cold-chain transport of vaccines. This comprehensive indicator system makes up for the shortcomings of the previous studies and provides a practical solution for the thorough evaluation of cold-chain vaccine transportation. (2) Emphasizing the importance of risk assessment: Previous cold-chain research has tended to focus on technical indicators, and the importance of risk assessment has been ignored. This study can accurately identify possible risk events and propose corresponding countermeasures using risk assessment, thus enhancing the safety and stability of cold-chain transportation. (3) Filling gaps in existing research: This study highlights that comprehensive evaluation and risk assessment are often overlooked in former cold-chain studies. By addressing this shortcoming, this study provides a new research perspective and methodology for the field of cold-chain vaccine transportation and provides important guidance for the development of the field. (4) Providing references for other, similar fields: The evaluation indicator system and risk management methodology adopted in this study are not only applicable to the cold-chain transportation of COVID-19 vaccines but can also provide a reference for the study of the cold-chain transportation of other pharmaceuticals, biological products, and other fields. The promotion of this method could contribute new ideas and approaches to future research in similar fields.

2. Literature Review

2.1. Standards for Cold-Chain Logistics and Transportation Safety

Cold-chain logistics are strongly tied to human needs, such as the transportation of vaccines or food freshness, and there are temperature requirements and the need for cold-chain transportation in order to ensure quality. The significance of cold-chain logistics lies in the supply-chain activities that constantly maintain a low temperature from production to consumption and that may affect the safety of vaccines or food products when the temperature is not properly controlled. Although the air-conditioning system in transportation vehicles (e.g., trucks, ships, and airplanes) is set at the required temperature during actual transportation in cold-chain logistics, the actual temperature of the goods may vary due to factors such as the placement of the goods, fluctuations in the temperature caused by the opening and closing of the back door when the driver handles the goods, whether air conditioning in the refrigerator is operational or not, etc., which ultimately leads to poor quality of the transported goods. It is, therefore, worth emphasizing risk management to reduce the impact of any possible temperature fluctuations, to promote logistics development, to improve transport efficiency and quality, and to contribute to socio-economic development.

There have been different views among scholars on the definition of cold chain in recent years. Chen et al. [10] concluded that cold-chain systems are mainly applied to perishable food products to maintain their freshness during storage, transportation, and distribution. Thakur and Foras [11] emphasized that the key to the cold chain is to continuously maintain the temperature required for the product to ensure product quality and safety, while Kim et al. [12] stated that the cold chain includes production and product distribution control to meet the needs of the customers. Regardless of the definition, scholars are unanimous in emphasizing the importance of temperature control. This is because different commodities require different safe temperatures to maintain their quality, freshness, and safety. Cold-chain systems play a key role in modern logistics, especially in areas such as food and pharmaceuticals. In the case of pharmaceuticals, it is imperative that the successful development and administration of temperature-sensitive vaccines or medicines be carried out with the utmost care, especially under extreme temperature conditions. This makes cold-chain management an extremely important issue. Medicine or vaccines must be handled with care, or there may be detrimental impacts on public health. With cold-chain systems, food, medicine, and even vaccines are able to maintain proper temperatures at all times during transportation, storage, and distribution to ensure the quality and safety of the product while meeting the needs of the consumer [13]. However, there are a number of challenges associated with the cold-chain transport of both medicines and vaccines. Factors such as complex natural environments, unstable transportation conditions, regional differences in infrastructure, and human operations may affect the quality and safe transportation of medicine or vaccines. In terms of cold-chain logistics, it can be defined as the process with which pharmaceuticals, vaccines, or food products, for example, are maintained in a constant temperature-controlled environment during the various stages of their value-added activities, such as production, storage, and distribution, in order to protect them from temperature fluctuations that could lead to ineffective control, thus ensuring the quality and safety of the product. The goal of this process' system engineering is to maintain a constant temperature to prevent situations that could potentially adversely affect product quality [14].

The attention paid to the cold chain has been increasing internationally in recent years, and in 2003, the Cool Chain Association (CCA) was established in Europe; it is dedicated to the integration of the cold-chain industry and the establishment of the Cool Chain Quality Indicator (CCQI). This is a quality management system of reviews for risk assessment and management systems, with a particular focus on ensuring that perishable products in the cold chain maintain appropriate early warning measures in the presence of specific environmental factors [15]. The British Standards Institution (BSI) developed a standard called "Specification for the transport of chilled and frozen parcels" in 2017 that sets out specific standards for the safety of cold-chain transportation [16]. This standard contains temperature control requirements for the delivery of refrigerated or frozen packages by land transportation vehicles, as well as requirements for the resources, equipment, operations, and communications of distribution service providers. Furthermore, the standard defines the requirements and safety matters related to the handling of refrigerated parcels, the conditions of workplaces, refrigerated trucks, and cold-storage and cooling materials, as well as work instructions for operators, operation manuals, and employee training. The objective of this standard is to ensure that the quality and safety of refrigerated and frozen packages are effectively safeguarded during the cold-chain transportation process. It focuses in particular on all aspects of the transportation of such packages by land transport vehicles, including temperature control of the vehicles, appropriate facilities and equipment, and appropriate operation and training, to improve the efficiency and reliability of cold-chain transportation, to reduce damage to packages and quality problems, and to diminish the security risks that may arise during transportation.

For regulating the cold-chain market, China has also established many relevant laws and regulations for market supervision, such as the Technical Management Code for Food Cold-Chain Logistics, the Technical Code for Management of Cold-Chain Transportation of Livestock and Poultry Meat, and the Code of Practice for Cold-Chain Logistics Services for Aquatic Products. As a biological product, vaccines must be stored and transported under defined cold-chain conditions to ensure their quality. The National Medical Products Administration of China [17] has established "Requirements for the cold-chain transportation of Vaccines" for the transportation of COVID-19 vaccines. This document sets out the specific regulations and standards developed by the Chinese government and relevant authorities to ensure that the quality, safety, and efficacy of vaccines are guaranteed throughout the transportation process. These norms and requirements are all aimed at enhancing the safety and reliability of cold-chain transportation to safeguard the effectiveness of vaccines, and the health and safety of the people.

The quality and safety of cold-chain logistics are closely related to transportation in areas such as vaccines and food. The assurance of commodity quality and safety through supply-chain activities at constant low temperatures is critical. The establishment of standards and codes, such as the requirements of the International Cold-Chain Association and the British Standards Institution in Europe, as well as China's cold-chain transportation requirements for COVID-19 vaccines, has highlighted the importance of temperature control, supervision, and training. Adhering to these standards can effectively reduce temperature fluctuations and safety risks in transportation, improve the quality and reliability of cold-chain logistics, and ensure the quality of commodities and the safety of people's health. Countries should continue to prioritize cold-chain logistics and promote their development to meet people's demand for the quality and safety of goods.

2.2. Risk Management and Transportation Safety

Risk is a very fundamental issue that takes many different forms. These risks are as minor as delays or can be natural disasters, covering a very wide range of areas, and the impact of a risk can be short-lived, lasting only a few minutes, or can cause permanent damage. Risks may pose a threat to one part of the supply chain or may affect an industry's supply-chain system as a whole [18]. As a consequence, there is a need to pay close attention to risks in logistics and supply-chain management and to take measures to address and mitigate these risks in order to ensure the safety and reliability of the transportation process.

Risk management is a significant process in logistics and supply-chain management, which can be simply categorized into the following three categories [19–21]: (1) Risk identification: to identify the risk factors that may pose a threat or cause damage to the transportation process. (2) Risk assessment: to determine the possibility of a risk occurring and the extent of its impact. (3) Risk control and monitoring: to take measures to address and mitigate identified risks, to track changes in risks on an ongoing basis, and to implement control measures. In brief, risk management aims at identifying, assessing, and controlling risks that may adversely affect cold-chain transportation in order to ensure the safety and reliability of the transportation process. This involves the main steps of risk identification, assessment, control, and monitoring, to ensure an effective response to the risks to which different transport carriers may be exposed. The relationship between transportation security and risk management is that risk management is a systematic approach and measures are taken to achieve the goal of transportation security. Risk management methods are aimed at identifying, assessing, and mitigating the various potential risks associated with transportation in order to ensure the safety of people, goods, and the environment during transportation activities. Transportation safety requires effective risk management to improve the overall safety of the transportation system by preventing accidents, mitigating the effects of disasters, and so on. Thus, transportation safety and risk management are mutually reinforcing, and the safety and reliability of transportation activities can be promoted and maintained with a rational risk management approach [19–21]. In summary, this study integrates scholars' views on the relationship between transportation safety and risk management by drawing a mind map (Figure 1), which clearly demonstrates the interrelationship between transportation safety and risk management as well as the connotations of related concepts. (1) Relationship: The relationship between transportation safety and risk management is described. Risk management is emphasized as a way to achieve transport security by linking transport security objectives, risk management approaches, and cross-influencing impacts, while the interplay between the two is highlighted. (2) Transport safety objectives: The objectives of transport safety cover all aspects of transportation, including the reduction in the rate of traffic accidents, the protection of passengers and cargo, and environmental and social responsibility. These objectives are the core elements to be pursued in transportation activities. (3) Risk management methodology: Risk management is a series of strategies to achieve transportation safety objectives, including risk identification, risk assessment, risk mitigation, and contingency planning. (4) Cross-influence: The interplay between transportation safety and risk management is emphasized. Transportation safety can be enhanced by adopting effective risk management methods, while the achievement of transportation safety is one of the objectives of risk management.

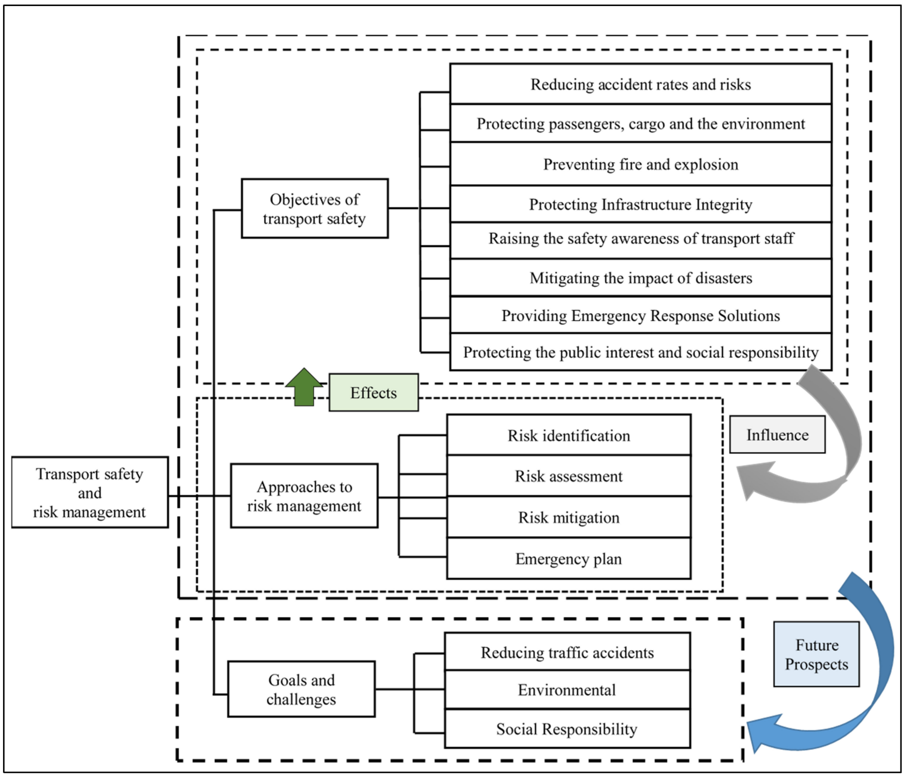

Figure 1. The relationship between transportation security and risk management.

In addition to the above 2.1 Standard Requirements for cold-chain Logistics and Transportation Security, the issue of transportation security and quality requirements is also a topic of concern for governments or scholars, and the scope of transportation security involves the security of transportation carriers, the security of the transportation process, the security of cargoes, the security of transportation documents and information, the security of transportation personnel, the security of transportation infrastructure, the security of the transportation network, and so on. For example, the characteristics (technical and structural) of truck tanks and carriers must comply with the requirements of international agreements when transporting hazardous materials and need to be regularly inspected and monitored to ensure the safety performance of transportation [22,23]. The safety of transport carriers is of paramount importance in the transportation industry, especially during transportation involving hazardous materials, because of the potential for serious damage to people and the environment in the event of an accident. In terms of truck characteristics (technical and structural) and the importance of technical vehicle inspections, there is a need to clarify their role in preventing human error and reducing the risk of accidents. According to the definition given by Ghaleh et al. [24], the improper functioning of vehicle equipment (which may be caused by technical and structural problems of the vehicle) can be considered a background condition for human error, which can increase the probability of driver error and thus increase the risk of accidents. These technical and structural problems may relate to the truck's handling performance, braking systems, airbags, etc. If these problems are not recognized and dealt with in a timely manner, they could have a significant impact on the driver's operation and the overall transportation process. Hence, to ensure safe transportation, vehicle technology must be regularly inspected to address potential problems and reduce the risk of accidents. Similarly, the focus may be different for different modes of transportation; e.g., quality and safety considerations and possible risk events involving sea, air, and land transportation may also vary. Nowadays, many scholars have proposed corresponding safety management measures; for example, for maritime transportation, Shang et al. [25] proposed transport quality and safety standards integrating safety and quality functions in Indonesian ferry services. Wu et al. [26] suggested the key factors for the assessment of the risk of liquefaction in maritime transport, and Ellis [27] analyzed the accidents and incidents that occurred during the maritime transport of packaged dangerous goods and pointed out the influencing factors that may occur when a risk event arises. For air transportation, Shen et al. [28] analyzed the impacts of lithium batteries on air transportation safety and also pointed out the factors that should be considered. Zhou et al. [29] introduced a Bayesian network-based model to reduce the safety risk of commercial air transportation systems, and Braude et al. [30] suggested the safety guidelines and preventive countermeasures for COVID-19 patients undergoing aeromedical transportation for air passenger transportation. For land transport, Sangiorgio et al. [15] put forward new safety standards for the infrastructure of the railroad transport system and train equipment, while Kozhukhovskaya et al. [31] carried out an analysis of the factors that contribute to the process of transporting goods by vehicle and the safety of vehicular traffic, as well as specific countermeasures for the risk of possible incidents. Epifanov et al. [32] conducted a quantitative evaluation of the passenger motor transport system with respect to indicators of transport quality and safety level and proposed to improve the efficiency and safety of the passenger motor transport system. Torres-Rubira et al. [33] evaluated the safety and quality of the passenger motor transportation system and presented a series of enhancements, including continuous improvements in risk management, employee health, environmental protection, emergency preparedness and response, equipment inspections, and ensuring that all operations are safe and fulfill customers' needs.

The studies summarized above show that risk is a fundamental issue in logistics and supply-chain management that may present itself in many different forms and pose a threat to all parts of the supply chain. Risk management is a necessary and important process to ensure the safety and reliability of the transportation process. The safety of the cold chain is often distinguished from general transportation safety in past governmental or organizational standards and norms, as well as in research by scholars, and if there are aspects of the cold chain that are addressed, they are often not comprehensive enough [34]. There has been little research, especially in areas involving the safety of cold-chain vaccine transportation. Risk management is a major concern in the transportation of vaccines. There is relatively little relevant research in the area of cold-chain transportation, particularly relating to the safe transportation of cold-chain vaccines; therefore, specialized transportation standards and measures are needed to prevent risky events.

3. Research Methodology

In this study, the modified Delphi method (MDM) and FAHP were used as the main methods. First, the MDM was utilized to collect expert opinions in order to reach consensus. Next, these expert opinions were used to construct a quality and safety standard for cold-chain transportation and form a quality and safety indicator system for the cold-chain transportation of COVID-19 vaccines. Third, the FAHP decision model was used to generate the triangular fuzzy number of each indicator, and the comprehensive weight and priority of each indicator were calculated. Finally, based on the results of the analysis, this study proposes specific countermeasures for the development of safety and quality standards for the cold-chain transportation of vaccines. The methodology of this study is detailed below. The research process of this study is illustrated in Figure 2.

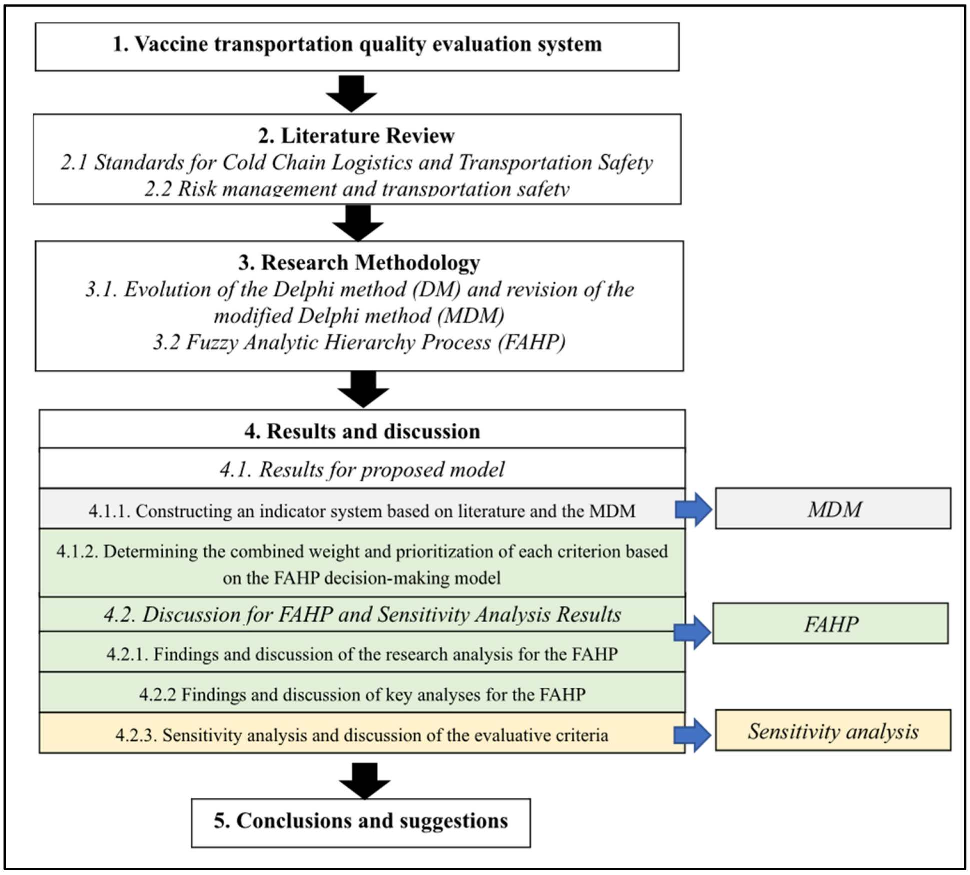

Figure 2. Qualitative and quantitative research process of this study.

3.1. *Evolution of the Delphi Method (DM) and Revision of the Modified Delphi Method (MDM)*

The Delphi method (DM) is a systematic, anonymous expert consultation technique designed to achieve consensus among experts through multiple rounds of opinion solicitation and feedback. This methodology is often used to deal with complex problems or future projections where expert opinion and experience are critical to solving the problem but cannot be agreed upon through traditional meetings or discussions.

The steps for implementing the DM are as follows [35]: (1) Establishment of an evaluation team: The main tasks are to develop project evaluation themes, to establish expert panels, to draft an expert consultation form, and to collect a series of analyses and statistical data on the opinions and conclusions of the experts. (2) Establishment of an expert group: Participants should have specialized knowledge; there is no fixed criterion for the number of participants, and there are advantages and disadvantages to having too many or too few, so the minimum number of experts should be selected under the premise of sufficient personnel. The number of experts in an actual study is generally 10 to 30 people. (3) Preparation of the questionnaire: The evaluation team conducts a systematic literature search on the issue under study and sets up the questionnaire entries based on the search results, and the time required to complete the questionnaire should not exceed 30 min. (4) Consultation in rounds: The first round of correspondence provides questionnaires, letters from experts, reference documents, and self-assessment forms for experts. The first round of the questionnaire is in principle open-ended, with qualitative questions, and experts are free to express their views.

The DM is generally applicable in the following situations [35]. With the purpose of ensuring the validity of the research findings, before deciding to apply the Modified Formal DM to a research study, it is important to consider whether it is really applicable to the research topic. (1) The research question itself provides less information and more uncertainty, and while it does not provide precise analytical techniques, it can be informed by the collection of subjective judgments. (2) Complex and multidisciplinary issues require the use of diverse expertise and experience to communicate and interact, and communication among individuals and groups needs to be efficient and interactive without being influenced by the group. (3) If face-to-face communication is adopted, it may lead to difficulties in determining the time and place of the meeting, and the communication process may easily lead to unhappiness or even conflict due to different opinions and positions, so it is necessary to ensure the anonymity of the participating experts. (4) Attention must be paid to preserving the independence of participation in expert judgment and avoiding social pressures, individual personality traits, etc., caused by the majority opinion, which may affect the results of the study.

Lin and Cho [36] argue that the DM has the following limitations: (1) The findings of the DM are susceptible to interference by subjective judgments of experts. (2) The process of implementing the DM is susceptible to the influence of the questionnaire distributor. (3) The DM is a time-consuming and labor-intensive process that is difficult to control. The MDM is an improved version of the traditional DM designed to reach expert consensus more efficiently. Compared with the traditional DM, the MDM has significant innovations with respect to the following points: (1) Diversified selection of experts: The MDM emphasizes a clear definition of the objectives and scope of the study and ensures that the experts selected have the knowledge and experience in the relevant fields. Moreover, the MDM advocates the participation of experts from multiple fields and backgrounds, covering a wide range of fields, such as academia, industry, and government sectors, in order to obtain more comprehensive and specialized opinions, thus enhancing the reliability of the consensus [36]. (2) The use of structured questionnaires: The MDM introduces structured questionnaires as an alternative to the traditional open-ended questionnaires. This type of questionnaire is designed to make the questions and options clearer, and the experts are able to express their views more precisely. The usefulness of structured questionnaires not only improves the effectiveness of expert responses but also helps to speed up the process of questionnaire collection and data analysis [37]. (3) The optimization mechanism of round-by-round surveys: The MDM also employs multiple rounds of surveys, but the goal is to progressively optimize expert opinions to reach consensus or near consensus. At the end of each round, the researcher assesses the consistency of expert opinions using methods such as interquartile deviation [37]. By analyzing these indicators, differences in opinion can be identified more efficiently, and targeted adjustments can be made, leading to a gradual convergence of expert opinions. (4) Efficient achievement of consistent results: The MDM interquartile assessment methodology plays an important role in achieving consistency of expert opinions. By identifying the variations and differences in the distribution of opinions, researchers can more accurately measure the degree of consistency of expert opinions. Such quantitative indicators help to quickly determine the formation of expert consensus and thus finalize the opinion more quickly [37]. This study organized the main implementation processes and differences between the DM and MDM, as shown in Figure 3.

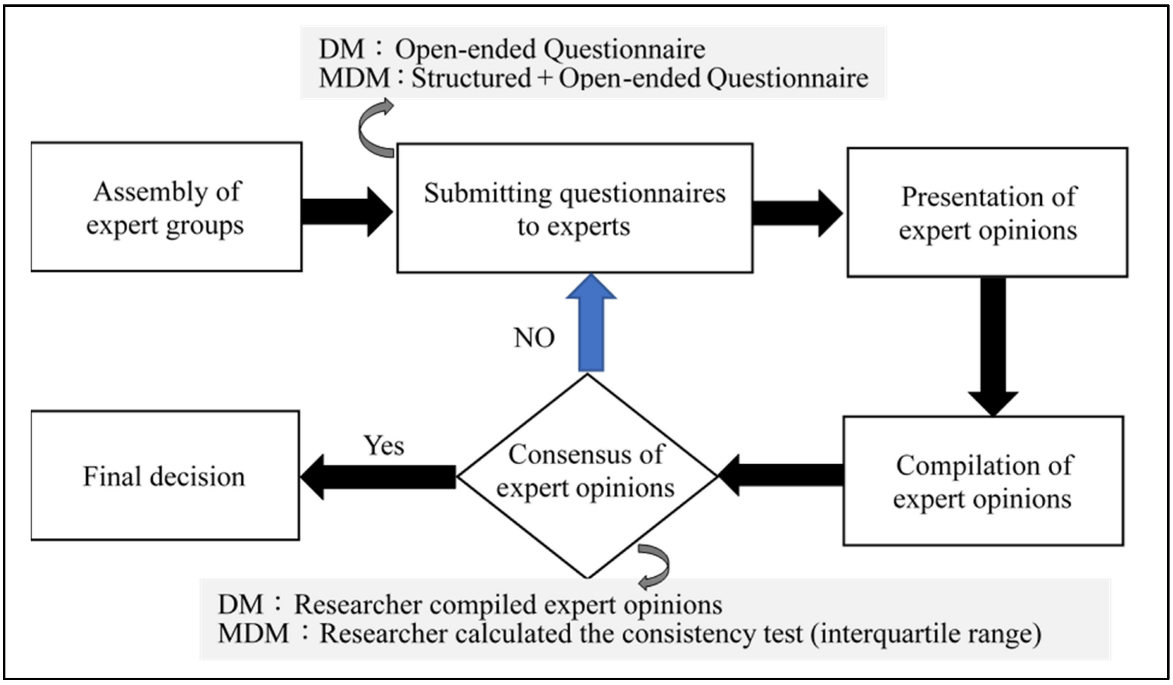

Figure 3. The main implementation process of DM and MDM.

On that basis, this study designed the evaluation index system using the MDM based on the initial evaluation index system decided in the previous section. Lin and Ma [37] noted that the MDM can be applied using a structured questionnaire with specific steps for the DM. This study utilized the MDM, in which the first step was to form an expert panel involving experts and scholars from logistics- and healthcare-related industries. The experts were selected among professionals in each of the following fields: First, professional managers of logistics companies. (1) Six professional managers working in logistics companies in the departments of general logistics or cold-chain logistics, transportation management, and quality management were chosen by us. Second, health professionals. We also selected (2) two pharmacists working as drug administrators in healthcare units and one specialist physician licensed in infection control. Third, faculty members of the university program. Similarly, we chose (3) faculty members of the Department of Logistics Engineering and Management, and the Department of Public Health Management of the university, six in total. These experts had extensive expertise and practical experience in the fields of general logistics, cold-chain logistics, transportation and distribution, warehouse management, public health and pharmaceutical management, and risk management. The second step was to collect the literature to develop the questionnaire. This study collected the relevant standard documents and literature on the quality and safety of cold-chain transportation and vaccine transportation and summarized the indicators to form a modified Delphi questionnaire. The third step was to distribute and collect the questionnaires. The questionnaire was solicited from the experts based on the questionnaire developed in the second step. The recovered questionnaires were used to obtain consensus results from the experts in terms of interquartile differences. Firstly, the average value of each indicator was calculated. If the average value was less than 4, the indicator was deleted; if the average value was greater than 4, then the quartile difference was used to make a judgment; if the quartile difference was less than 0.6, it meant that this indicator had a high degree of consistency of opinion in the expert group, and the indicator was retained. If it was greater than 1.0, then the group of experts had not reached agreement on the indicator, and the indicator was removed. The fourth step was to obtain expert consensus and construct the indicator system. If the results of expert consistency (quartile results) are not obtained, the third step (correction of the questionnaire solicitation form) is to be repeated until all the indicators are in line with the results of consistency, and finally, the indicator system can be constructed.

3.2. Fuzzy Analytic Hierarchy Process (FAHP)

Real-life decision-making activities involve selection, evaluation, and review, and a multi-criteria decision-making approach aims to help decision makers effectively evaluate and prioritize the advantages and disadvantages of various options from a wide range of evaluative attributes [38]. As a result, theoretical approaches have been successfully and widely applied to solve various problems in managerial decision making [36]. In Multi-Criteria Decision Making (MCDM), the analytic hierarchy process (AHP) is a widely used method [36]. The AHP was developed by Saaty in 1971, when he was working on strain planning issues for the U.S. Department of Defense, and the theory was published in a book in 1980 [34]. The AHP has been effectively adopted in policy planning, forecasting, judgment, resource allocation, and investment portfolios, providing a systematic and clearly structured hierarchy and assigning weights to each element in the hierarchy to provide decision makers with a basis for making choices and judgments on which to base optimal decisions [36].

Despite the fact that the AHP is widely used, it cannot adequately address the concepts of thinking, semantic expressions, and sensory judgments of experts or decision makers in the decision-making process with uncertainty and imprecision. In the AHP formula, human judgments are represented as accurate numbers [38]. Thus, the modal FAHP is a theory that has been developed to address the imprecision that arises when experts assess the relative importance of guidelines and alternatives. Inaccuracies can be caused by a variety of reasons, such as unquantifiable information, incomplete information, unavailable information, and part of the message being unknown. The traditional AHP method cannot effectively manage this type of imprecise information problem [38]. In light of this, this paper used the FAHP method to evaluate the decision-making options and provide decision makers with a better value measurement using the concept of interval scale, which can help them to decide the best options for different attributes.

The AHP by Saaty [39] uses only a judgment matrix to assess the degree of fuzziness in a decision problem, as shown in Equation (1). Assuming that the decision maker has n different independent criteria, like $C_1, C_2, \ldots, C_n$, which have weights $W_1, W_2, \ldots, W_n$, the decision maker does not know the value of W_i, $i = 1, 2, \ldots, n$ in advance, but they are able to make a two-by-two comparison between different criteria. Furthermore, assuming that the decision maker evaluates (C_i, C_j) based on a two-by-two comparison judgment scale, he or she can obtain a judgment matrix $n \times n$ as follows:

$$A = [a_{ij}] = \begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{pmatrix} \quad (1)$$

presenting $a_{ij} = 1$ and $a_{ji} = \frac{1}{a_{ij}}$, $i, j = 1, 2, \ldots, n$.

This study applied the concept by Lin et al. [38] to reach consensus among experts and analyze the data to build a decision-making model. The process of applying the FAHP consists of the following five main steps.

Step 1: Constructing the Problem and Model

This study constructed a decision-making model based on fuzzy hierarchical analysis based on the results of the expert questionnaire. First, using the initial guidelines decided in the first stage, this paper adopted the specific steps proposed by Murry and Hammons [34] to form a panel of experts to discuss and determine the upper and lower hierarchical relationships of the criteria, as well as the relevance of each criterion. Lastly, the FAHP assessment model was designed on the basis of the results of the discussion.

Step 2: Constructing the triangular fuzzy number

The fuzzy set theory proposed by Zadeh [40] is used to deal with uncertainty problems caused by imprecision and vagueness. The biggest difference between fuzzy sets and explicit sets is that Zadeh proposes to replace the characteristic function of explicit sets with a membership function. The dependency function extends the value of the characteristic function, which is either 0 or 1, to a real number in the range of 0 and 1.

Each decision maker performs a comparison of the relative importance level of criteria i and j, which result in a different level of difference, and the triangular fuzzy numbers need to be extracted from it using three numbers, which are L, M, and U, respectively. They indicate the minimum, the geometric mean, and the maximum of all decision-maker evaluation scores, respectively. The geometric mean accurately represents the consensus of experts and is the most widely used in practical applications [39]. Here, the geometric mean is used in the modeling of triangular fuzzy numbers. The TFN equations are as shown in (2) to (5).

$$\tilde{u}_{ij} = (L_{ij},\ M_{ij},\ U_{ij}) \tag{2}$$

$$L_{ij} \le M_{ij} \le U_{ij} \text{ and } L_{ij},\ M_{ij},\ U_{ij} \in [1/9, 9] \tag{3}$$

$$L_{ij} = \min(B_{ijk}) \tag{4}$$

$$M_{ij} = \sqrt[n]{\prod_{k=1}^{n} B_{ijk}}$$

and

$$U_{ij} = \max(B_{ijk}) \tag{5}$$

where B_{ijk} stands for the relative importance evaluation scores of expert k for the two criteria $C_i - C_j$.

Step 3: Construction of fuzzy pairwise comparison matrix and inverse fuzzification

$$A = [a_{ij}] = \begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{pmatrix} \tag{6}$$

where a_{12} is determined in the TFN, which refers to the relative importance of the two criteria C_1 and C_2. Meanwhile, $[a_{ij}]$ indicates that the TFN can be determined using Equations (2) to (5). In this study, defuzzification is based on Equations (7) and (8), and the method can clearly express the fuzzy perception.

$$g_{\alpha,\ \beta}(\tilde{a}_{ij}) = \left[\beta \cdot f_\alpha(L_{ijk}) + (1-\beta) \cdot f_\alpha(U_{ijk})\right],\ 0 \le \beta \le 1,\ 0 \le \alpha \le 1 \tag{7}$$

$$f_\alpha(L_{ijk}) = (M_{ij} - L_{ijk}) \cdot \alpha + L_{ijk}$$

and

$$f_\alpha(U_{ijk}) = U_{ijk} - (U_{ijk} - M_{ij}) \cdot \alpha$$

$$g_{\alpha,\ \beta}(\tilde{a}_{ji}) = 1/g_{\alpha,\ \beta}(\tilde{a}_{ij}),\ 0 \le \beta \le 1,\ 0 \le \alpha \le 1,\ i > j \tag{8}$$

where α indicates the decision maker's preferences and β indicates the decision maker's risk taking; decision makers can get a more complete picture of the risks they face in different situations. The values of α and β can be taken as a sensitivity analysis for evaluating decision options, where the decision maker is able to determine α based on the uncertainty about the future investment environment, where a larger value of α indicates higher uncertainty about the future environment, meaning that the future investment environment faces a higher degree of risk. Conversely, a smaller α value represents a more stable future environment, whereby the future investment environment is less exposed to a lower degree of risk. α can be any number between 0 and 1, but for analytical convenience, it is usually given a value of 0.1, 0.2, ..., 1 for simulations with uncertainty. $\alpha = 0$ stands for the upper and lower bounds, U_{ij} and L_{ij}, of the triangular fuzzy number, while $\alpha = 1$ stands for the geometric mean, M_{ij}, of the triangular fuzzy number.

The value can also be any number between 0 and 1, but usually, 0.1, 0.3, 0.5, 0.7, 0.9 are used to simulate the decision maker's psychological state. Thus, the judgment matrix can be represented as in Equation (9).

$$g_{\alpha,\,\beta}\left(\widetilde{A}\right) = g_{\alpha,\,\beta}\left(\left[\widetilde{a}_{ij}\right]\right) = \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} \begin{bmatrix} 1 & g_{\alpha,\,\beta}(\widetilde{a}_{12}) & \cdots & g_{\alpha,\,\beta}(\widetilde{a}_{1n}) \\ 1/g_{\alpha,\,\beta}(\widetilde{a}_{12}) & 1 & \cdots & g_{\alpha,\,\beta}(\widetilde{a}_{2n}) \\ \vdots & \vdots & \vdots & \vdots \\ 1/g_{\alpha,\,\beta}(\widetilde{a}_{1n}) & 1/g_{\alpha,\,\beta}(\widetilde{a}_{2n}) & \cdots & 1 \end{bmatrix} \tag{9}$$

Step 4: Determining the eigenvectors

In $g_{\alpha,\,\beta}\left(\widetilde{A}\right)$, denoted by value $\widetilde{a}_{ij}$, $W_1,\ W_2,\ \ldots,\ W_n$ are utilized to denote the values of the n elements, $C_1,\ C_2,\ \ldots,\ C_n$, thus reflecting the value of the recorded judgment. The relationship between weights W_i and judgment $\widetilde{a}_{ij}$ can be simply expressed in terms of $W_i/W_j = \widetilde{a}_{ij}(i,\ j = 1,\ 2,\ \ldots,\ n)$. Namely, $g_{\alpha,\,\beta}\left(\widetilde{A}\right)$, multiplied by weight vector x of the elements, is equal to nx, so $\left[\left(g_{\alpha,\,\beta}\left(\widetilde{A}\right) - nx\right] = 0$, where x is the eigenvector with respect to eigenvalue n. When decision makers make pairwise comparisons, their subjective judgment assigns a value, and $\widetilde{a}_{ij}$, which is this value, differs from the true value of W_i/W_j by a relative degree, so that g fails to hold. Saaty [39] suggested replacing n with maximum eigenvalue $\lambda_{\max}$ of the matrix.

$$g_{\alpha,\,\beta}\left(\widetilde{A}\right)\cdot W = \lambda_{\max} W \tag{10}$$

and

$$\left[\left(g_{\alpha,\,\beta}\left(\widetilde{A}\right) - \lambda_{\max} I\right]\cdot W = 0 \tag{11}$$

where W is the eigenvector; $0 \le \beta \le 1$, $0 \le \alpha \le 1$ in $g_{\alpha,\,\beta}\left(\widetilde{A}\right)$. Comparing Equations (1) and (9), we can see that the traditional AHP or FAHP uses only a specific quantity (geometric mean) to represent the expert opinion of the pairwise comparison matrix, while fuzzy opinions and expert consensus are represented by triangular fuzzy numbers. Both of them are used to calculate the weights of the fuzzy opinions and expert consensus.

The consistency indicator, CI, and the consistency ratio, CR, are used to determine the consistency of the matrix and to modify implausible estimates [39]. Here are the definitions of CI and CR:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{12}$$

$$CR = \frac{CI}{RI} \tag{13}$$

where RI is called *Random Index* and is the random index value of the order positive inverse matrix, which can be obtained from the RI. If $CR < 0.1$, the estimate is acceptable; otherwise, the matrix must be re-established for judgment until $CR < 0.1$ [39].

After calculating the weights among the elements of each level, the weights of the overall level are calculated. Finally, the weights and priorities of the options or elements are determined to provide decision makers with an important reference point for making decisions or plans.

4. Results and Discussion

The results and discussion of this study are presented in two parts. The first part includes the results of the proposed model and discusses the results of the analysis of the proposed model, MDM with FAHP. A discussion of the results of the analysis of the FAHP and sensitivity are presented in Part II, as detailed below.

4.1. Results of Proposed Model

4.1.1. Constructing an Indicator System Based on the Literature and the MDM

In this phase, the literature collection was the main focus, and the technical standards of the government and international organizations on transport quality and safety, vaccine transport, cold-chain transport, and other related literature were compiled and summarized. In total, 6 primary indicators, 29 secondary indicators, and 173 tertiary indicators were determined. After three rounds of screening, the COVID-19 vaccine transport quality and safety indicators were finalized into 5 primary indicators (criteria) and 26 secondary indicators (sub-criteria). The indicator system is shown in Figure 4, and the definitions of the sub-criteria are described below.

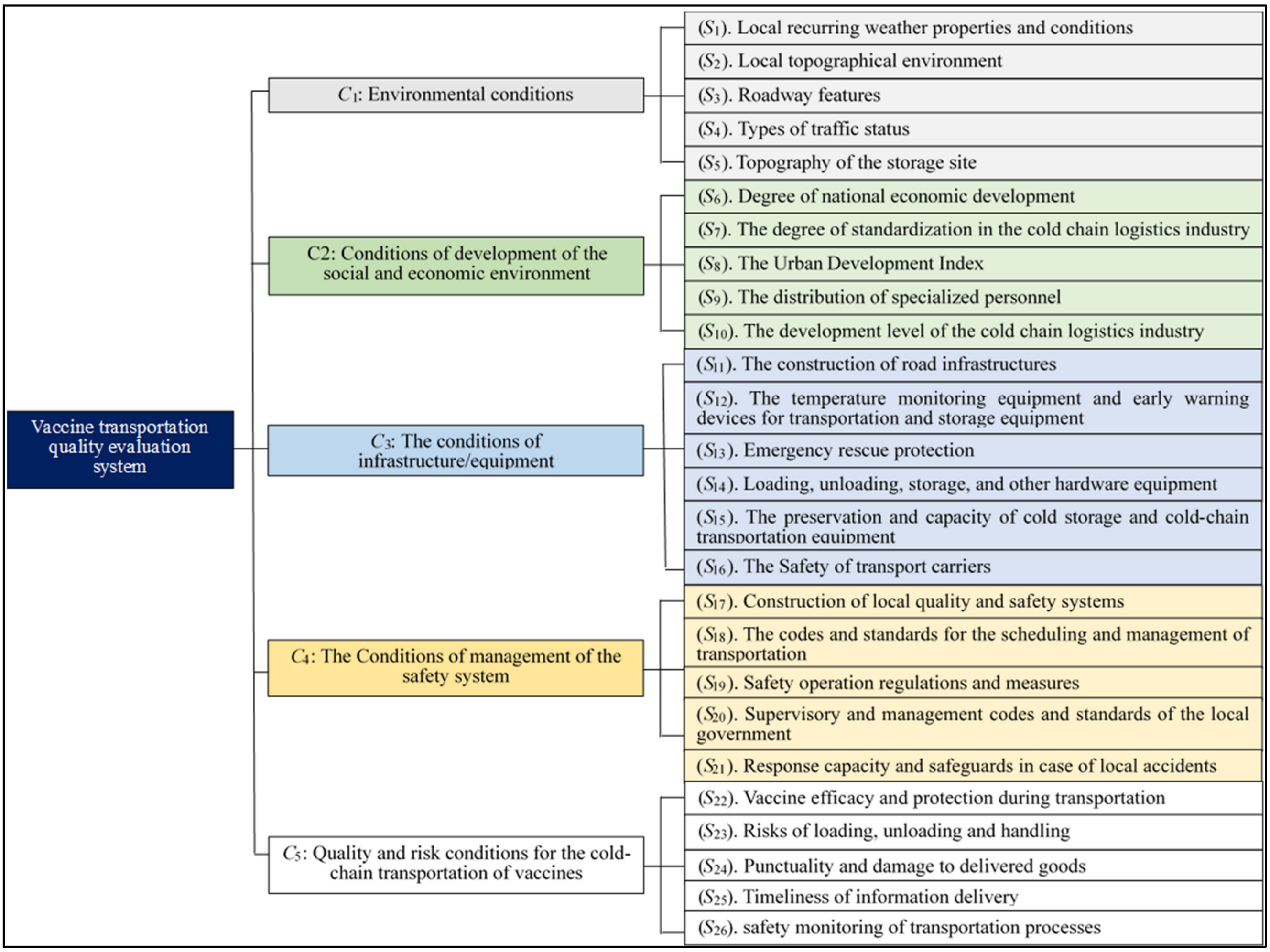

Figure 4. Hierarchy model for vaccine transportation quality.

1. C_1: Environmental conditions

(S_1) Local recurring weather properties and conditions: Weather conditions mainly include fog, frost, clouds, rain, wind, lightning, thunder, snow, haze, hail, and so on. Adverse weather causes the road surface to be slippery, the land to be muddy, the driver's field of vision to be not clear, the barometric pressure and airflow to change, and so on. Frequent inclement weather, such as strong winds, heavy snow, and rain, can increase the frequency of transportation accidents.

(S_2) Local topographical environment: China is a vast area with a lot of mountains, and diverse and complex landscapes; the southwestern region has a lot of mountains and plateaus, slopes, and curves, and traffic accidents occur frequently. For example, on the Tibetan Plateau and in other high-altitude areas, a driver can very easily suffer from physical problems, which has a certain impact on the driver's driving safety. Compared with low-altitude areas, the frequency of tire wear and even flat tires is higher. The transportation process should select different transportation carriers according to the local terrain environment. The use of transportation carriers that do not match the local terrain produces a greater threat to cold-chain vaccine transportation work, which affects the quality of vaccines.

(S_3) Roadway features: Roadway features mainly include changes in pavement conditions (sharp curves/steep slopes/tunnels, floods, cliffs/landslides, earthquakes, etc.), the poor condition of roads, and the routes being irrationally planned. Roads with these features are transportation accident-prone roads and should be taken seriously.

(S_4) Types of traffic status: Traffic conditions can be categorized into obstructed, congested, and smooth conditions. Of these, obstruction of the flow is the most common one. ① Obstructed flow: This refers to a higher average density of vehicles on a given segment of a trip, longer stop-and-wait times during the trip, and average trip speeds of less than 20 km/h. ② Congested flow: It indicates that the density of the roadway is high and that frequent passive acceleration and deceleration occur during the trip, resulting in an average speed of less than 45 km/h and more than 20 km/h. ③ Smooth flow: In a section of a road with smooth flow, the average density of vehicles is relatively low; they are free to maneuver while traveling, and the average travel speed is higher than 45 km/h. The frequency of accidents varies according to the type of the traffic status.

(S_5) Topography of the storage site: Topography is an important factor that affects the temperature, which is an important factor that affects the quality of vaccines. The topography of vaccine storage sites is, therefore, an important influence on the quality and safety of vaccines.

2. C_2: Conditions of development of the social and economic environment

(S_6) Degree of national economic development: Since the outbreak, people's health has been greatly threatened, and a safe and effective COVID-19 vaccine is the most powerful weapon to prevent the transmission of the virus. The transportation of vaccines requires significant financial support; thus, the level of national economic development is closely related to the safety of vaccine transportation.

(S_7) Degree of standardization in the cold-chain logistics industry: The standardization of cold-chain logistics is of great significance in supporting the healthy and sustainable development of the cold-chain logistics industry, better coordinating the development of the industry, improving the technical level of the cold-chain industry, increasing the efficiency of refrigerated transportation, reducing the damage rate, the quality and safety of vaccines, and protecting the safety of people and property.

(S_8) Urban development index: The urban development index (UDI) is a comprehensive indicator for determining the competitiveness of a city, the quality of urban life, the level of urban development, and the economic strength of a city. The safety of vaccine transportation depends on the level of urban development, the quality of urban life, the economic strength of a city, and the competitiveness of a city, as these factors provide its foundation.

(S_9) Distribution of specialized personnel: With the rapid development of cold-chain logistics, the lack of personnel in this field is a bottleneck, an obstacle that restricts the development of cold-chain logistics. Cold-chain logistics personnel are professionals engaged in work, management, and research related to the cold-chain logistics process, such as packaging, handling, storage, loading and unloading, distribution and processing, information processing, transportation and distribution, etc., in order to ensure the quality and safety of cold-chain items and to reduce the loss of cold-chain items. The improvement in cold-chain logistics technology needs the support of talents, but the lack of cold-chain logistics professionals has a far-reaching impact on the development of the cold-chain logistics industry.

(S_{10}) Development level of the cold-chain logistics industry: The cold-chain logistics industry has become one of the most important industries concerning the quality of people's living standards since the outbreak of COVID-19 epidemic. Its high-quality development can, to a large extent, influence the government's governing level, because the level of development of the cold-chain logistics industry has a major influence on the safety of vaccine transportation, which is closely related to people's health.

3. C_3: Conditions of infrastructure/equipment

(S_{11}) Construction of road infrastructures: The development of road infrastructure is a basic prerequisite for ensuring the normal functioning of the transportation industry. And transportation infrastructure is a basic necessity for economic and social development. It saves energy for the development of the transportation industry, and lagging construction can be a stumbling block to transportation development.

(S_{12}) Temperature monitoring equipment and early warning devices for transportation and storage equipment: Due to the special nature of cold-chain vaccine supply, temperature control plays the most prominent role in the whole risk evaluation, so the temperature monitoring system must be sound when the cold-chain vaccine transportation system is sound. The installation of temperature alarm settings on vaccine storage equipment allows for real-time warnings and timely adjustments in the event of changes in the temperature conditions during cold storage and during vaccine circulation. In addition, the temperature alarm system should be maintained and serviced in a timely manner, so as to ensure the efficient operation of the temperature monitoring system. Temperature alarm equipment plays a very important role from the production of vaccines to their storage and transportation. Should an abnormal temperature condition occur, an emergency program is activated. Temperature monitoring equipment and early warning devices in transportation and storage facilities are a safety guarantee for the quality of vaccines.

(S_{13}) Emergency rescue protection: Transportation accidents happen all the time, and emergency rescue protective gear plays an integral role in emergency rescue efforts. It is not only the material foundation of rescue work but also an important cornerstone to ensure the smooth implementation of rescue work. To ensure the efficiency of the emergency rescue operation and to have access to the various types of rescue equipment required for the accident, it is crucial to standardize, and scientifically and systematically manage emergency protective devices.

(S_{14}) Loading, unloading, storage, and other hardware equipment: Hardware equipment such as loading, unloading, and storage equipment can simplify the operation process of transportation personnel and reduce labor, which is an essential foundation for the improvement in transportation efficiency.

(S_{15}) Preservation and capacity of cold-storage and cold-chain transportation equipment: Cold-chain logistics and transportation require supporting facilities and equipment to carry out logistics and transportation, so the availability and capacity of cold-storage and cold-chain transportation equipment are essential in infrastructure construction.

(S_{16}) Safety of transport carriers: With regard to transportation carriers, consideration should be given to their safety and operational status, which have a significant impact on transportation safety.

4. C_4: Conditions of management of safety systems

(S_{17}) Construction of local quality and safety systems: Currently, there is a lack of special standards for national cold-chain logistics systems for pharmaceuticals and a lack of enforcement power of the pharmaceutical quality management department and its monitoring, and the technical problems of cold-chain logistics involve a number of disciplines, such as pharmacy, mechanics, and refrigeration technology. It is, therefore, necessary to involve complex talents to ensure the perfection and specialization of cold-chain technology, which is the current challenge faced by the industry. Existing problems such as poor risk awareness among practitioners and the need to improve the professionalism of technicians require the construction of a quality system and a regulatory system to avoid their risks. "Chain breaks" in the cold-chain supply of vaccines represent the most lethal risk, and with the exception of natural force majeure, all other types of risk can be avoided and minimized using effective quality and regulatory systems.

(S_{18}) Codes and standards for the scheduling and management of transportation: Codes and standards for the scheduling and management of transportation are indicators of the monitoring of the cold-chain transportation process. Monitoring the entire transportation process can effectively prevent accidents.

(S_{19}) Safety operation regulations and measures: The process of cold-chain transportation of vaccines involves a series of complex operational procedures and also places high demands on the temperature conditions of vaccines, so their institutional management must take into account the safety of society and the environment. A series of strict management systems and emergency plans must be established and implemented during the transportation of vaccines to secure safety and effectiveness of transportation.

(S_{20}) Supervisory and management codes and standards of the local government: Supervisory and management codes and standards of the local government not only provide a clear direction and guarantee for the development of local cold-chain logistics but also perform a supervisory role in the process of their development to ensure their successful operation.

(S_{21}) Response capacity and safeguards in case of local accidents: When confronted with emergencies, it is particularly important to refine an emergency management system, and the mechanism and construction of a legal system to strengthen the safeguards and to enhance the capacity to deal with emergencies.

5. C_5: Quality and risk conditions for cold-chain transportation of vaccines

(S_{22}) Vaccine efficacy and protection during transportation: Vaccine efficacy refers to the disease-preventive effect of a vaccine on the vaccinated individual as demonstrated in clinical trials. The protective effect of a vaccine is the performance of the vaccine in preventing infection by a virus under real conditions outside of clinical trials. It is because of the effectiveness of vaccines and their protective effects that people's lives and health are guaranteed.

(S_{23}) Risks of loading, unloading, and handling: In the cold-chain transportation of vaccines, different modes of transportation require different transport carriers; thus, loading and unloading handling operations are indispensable. Vaccine quality is the most vulnerable in this operation, and risk prevention in loading and unloading is extremely important.

(S_{24}) Punctuality and damage to delivered goods: The cold-chain transportation of vaccines requires the transporter to deliver vaccines accurately and in good condition to the designated location, so punctuality and damage in cargo delivery are key evaluation indexes.

(S_{25}) Timeliness of information delivery: Vaccines require traceability of information during transportation, and this information has a direct impact on the performance of cold-chain logistics.

(S_{26}) The safety monitoring of transportation processes: The safety monitoring of transportation processes allows for a quantitative evaluation of the safety of infrastructure equipment and a scientific evaluation of the operational effectiveness of facilities and equipment. This allows for the timely maintenance of facilities and equipment with poor operational effectiveness, ensuring transportation safety and effectively controlling any adverse effects on both transportation safety and vaccine quality.

4.1.2. Determining the Combined Weight and Prioritization of Each Criterion Based on the FAHP Decision-Making Model

1. Establishment of a hierarchical structure

This study determined a safety index evaluation system based on the MDM. Then, it constructed a hierarchical structure in accordance with the basic assumptions of the fuzzy hierarchical analysis method, and the hierarchical structure can be categorized into 5 criteria and 26 sub-criteria, as shown in Figure 4.

2. Establishment of TFNs

A total of 15 FAHP expert questionnaires based on the hierarchical structure constructed in step 1 were distributed in this study. The expert group consisted of representatives from industry, government, and academia, and there were five representatives from the industry. They worked in the industry as managers or general managers of logistics-related departments and were proficient in transportation safety management, international logistics and transportation, and cold-chain transportation management. Four experts from governmental units were engaged in emergency management, and disease prevention and control in governmental departments and were well versed in the coordination and management of the development of contingency plans, the adoption of emergency measures, and the prevention and control of major epidemics. In addition, there were six representatives from the academic community who taught in logistics-related programs at undergraduate universities and were proficient in logistics and transportation management, logistics cost management, logistics information technology, warehouse management, etc. The questionnaire of this study was administered during the period of 29 March 2023 to 5 April 2023. Based on the above questionnaires given to 15 experts, this study used Equations (2) to (5) to establish the triangular fuzzy numbers. Each expert conducted a two-by-two comparison of the criteria based on the 9-point scale proposed by Saaty [39]. Once each expert finished filling in the answers, a consistency check was carried out to ensure that the CI and CR values were <0.1%. In case the standard was not met, the experts were required to complete the questionnaire again until the standard was reached. This study organized the scores of each question given by 15 persons; statistically calculated the maximum value, minimum value, and geometric mean of each question; and constructed a pairwise comparative triangular fuzzy number matrix based on the questions. For example, as shown in Table 1, C_1 was compared to C_2 for the first question of the first questionnaire, where 0.166 (C_1:C_2 = 1:6) represents the minimum value given by the 15 experts for the question, 1.055 represents the geometric mean given by the 15 experts for the question, and 7 (C_1:C_2 = 7:1) represents the maximum value given by the 15 experts for the question. Table 1 shows the triangular fuzzy number matrix constructed for all the questions in this study.

3. Construction of fuzzy pairwise comparison matrix and defuzzification

In accordance with pairwise comparisons among criteria, a fuzzy pairwise comparison matrix was constructed with the evaluation results of the 15 experts, and a fuzzy pairwise comparison matrix with defuzzification was constructed in accordance with Equations (7) and (8). For example, for the 5 × 5 matrix in Table 2, the matrix is divided into upper and lower triangles from the lower-left corner to the upper-right corner. It is enough to consult an expert about the upper triangle of the matrix, where the lower triangle is the inverse of the upper triangle, to find the inverse. For example, the first term in the matrix is a_{12}. After each of the 15 experts answered the question, there were 15 ratios with a minimum value of 0.142, a geometric mean of 1.338, and a maximum value of 4. When the values of α and β are 0.5, the decision maker considers the uncertainty of the future environment to be stable and has a neutral attitude towards the future; therefore, the triangular fuzzy matrices of each criterion are defuzzified by simulating the stability condition of α and β.

Table 1. Triangular fuzzy number matrix for each criterion and sub-criterion.

	C_1	C_2	C_3	C_4		C_5
C_1	1, 1, 1	0.166, 1.055, 7	0.125, 1.835, 7	0.143, 1.395, 4		0.166, 2.370, 8
C_2	—	1, 1, 1	0.25, 1.486, 4	0.25, 0.882, 5		0.2, 1.544, 7
C_3	—	—	1, 1, 1	0.166, 0.661, 4		0.333, 1.668, 4
C_4	—	—	—	1, 1, 1		2, 2.642, 6
C_5	—	—	—	—		1, 1, 1
C_1	S_1	S_2	S_3	S_4		S_5
S_1	1, 1, 1	0.142, 1.338, 4	0.166, 1.389, 5	0.25, 1.794, 6		0.5, 3.316, 7
S_2	—	1, 1, 1	0.333, 1, 3	0.25, 1.219, 4		0.5, 2.456, 5
S_3	—	—	1, 1, 1	0.25, 2, 4		2, 3.825, 6
S_4	—	—	—	1, 1, 1		0.5, 2.112, 5
S_5	—	—	—	—		1, 1, 1
C_2	S_6	S_7	S_8	S_9		S_{10}
S_6	1, 1, 1	0.125, 2.627, 4	0.2, 1.333, 2	0.2, 1.251, 4		0.125, 1.919, 6
S_7	—	1, 1, 1	0.25, 2.119, 4	0.25, 1.219, 5		0.5, 1.560, 5
S_8	—	—	1, 1, 1	0.166, 1.625, 3		0.25, 1.169, 4
S_9	—	—	—	1, 1, 1		0.333, 1.693, 5
S_{10}	—	—	—	—		1, 1, 1
C_3	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}
S_{11}	1, 1, 1	0.125, 1.291, 4	0.166, 1.161, 7	0.142, 1.544, 4	0.125, 1.764, 4	0.142, 1.176, 6
S_{12}	—	1, 1, 1	0.333, 1.738, 6	0.2, 1.291, 5	0.5, 1.104, 2	0.5, 1.45, 3
S_{13}	—	—	1, 1, 1	0.142, 1.195, 4	0.25, 1.768, 4	0.2, 1.389, 6
S_{14}	—	—	—	1, 1, 1	0.25, 1.169, 4	0.2, 1.016, 5
S_{15}	—	—	—	—	1, 1, 1	0.333, 1.345, 6
S_{16}	—	—	—	—	—	1, 1, 1
C_4	S_{17}	S_{18}	S_{19}	S_{20}	S_{21}	
S_{17}	1, 1, 1	2, 2.521, 3	0.25, 1.169, 4	0.25, 1.303, 5	0.2, 1.150, 5	
S_{18}	—	1, 1, 1	0.125, 1.951, 3	0.166, 2.155, 4	0.25, 1.235, 2	
S_{19}	—	—	1, 1, 1	0.25, 1.42, 7	0.25, 1.794, 5	
S_{20}	—	—	—	1, 1, 1	0.25, 1.15, 8	
S_{21}	—	—	—	—	1, 1, 1	
C_5	S_{22}	S_{23}	S_{24}	S_{25}	S_{26}	
S_{22}	1, 1, 1	0.2, 2.379, 6	0.25, 1.653, 5	0.2, 1.133, 4	0.333, 2.559, 6	
S_{23}	—	1, 1, 1	0.25, 1.402, 6	0.25, 1.366, 4	0.142, 1.239, 7	
S_{24}	—	—	1, 1, 1	0.25, 1, 4	0.5, 1.919, 4	
S_{25}	—	—	—	1, 1, 1	0.333, 1.071, 5	
S_{26}	—	—	—	—	1, 1, 1	

Table 2. Triangular fuzzy matrix for the natural environmental conditions.

C_1	S_1	S_2	S_3	S_4	S_5
S_1	1, 1, 1	0.142, 1.338, 4	0.166, 1.389, 5	0.25, 1.794, 6	0.5, 3.316, 7
S_2	—	1, 1, 1	0.333, 1, 3	0.25, 1.219, 4	0.5, 2.456, 5
S_3	—	—	1, 1, 1	0.25, 2, 4	2, 3.825, 6
S_4	—	—	—	1, 1, 1	0.5, 2.112, 5
S_5	—	—	—	—	1, 1, 1

When $a_{13}, a_{14}, a_{15}, a_{23}$, and so on, in the sequence are also counted, a new comparison matrix is constructed, as shown in Table 3. The other criteria and sub-criteria are presented similarly. Table 4 shows the fuzzy pairwise comparisons and relative weights of the criteria, and Tables 5–9 show the fuzzy pairwise comparisons and relative weights of the sub-criteria.

Table 3. Fuzzy pairwise comparison matrix and relative weights for the example in Table 2.

C_1	S_1	S_2	S_3	S_4	S_5	*Eigenvectors*
S_1	1.000	1.705	1.986	2.460	3.533	0.346
S_2	0.587	1.000	1.333	1.672	2.603	0.224
S_3	0.504	0.750	1.000	2.063	3.913	0.222
S_4	0.407	0.598	0.485	1.000	2.431	0.136
S_5	0.283	0.384	0.256	0.411	1.000	0.073

Table 4. Fuzzy pairwise comparison matrix and relative weights of the criteria of the evaluation system (α and β = 0.5).

	C_1	C_2	C_3	C_4	C_5	*Eigenvectors*
C_1	1.000	2.319	2.699	1.733	3.227	0.362
C_2	0.431	1.000	1.806	1.754	2.572	0.228
C_3	0.371	0.554	1.000	1.372	1.917	0.156
C_4	0.577	0.570	0.729	1.000	3.321	0.173
C_5	0.310	0.389	0.522	0.301	1.000	0.080

Table 5. Fuzzy pairwise comparison matrix and relative weights for the natural environmental conditions (α and β = 0.5).

C_1	S_1	S_2	S_3	S_4	S_5	*Eigenvectors*
S_1	1.000	1.705	1.986	2.460	3.533	0.346
S_2	0.587	1.000	1.333	1.672	2.603	0.224
S_3	0.504	0.750	1.000	2.063	3.913	0.222
S_4	0.407	0.598	0.485	1.000	2.431	0.136
S_5	0.283	0.384	0.256	0.411	1.000	0.073

Table 6. Fuzzy pairwise comparison matrix and relative weights for the development conditions of the social and economic environment (α and β = 0.5).

C_2	S_6	S_7	S_8	S_9	S_{10}	*Eigenvectors*
S_6	1.000	1.226	0.916	1.462	1.885	0.252
S_7	0.816	1.000	2.143	1.922	2.155	0.284
S_8	1.092	0.467	1.000	1.099	1.490	0.173
S_9	0.684	0.520	0.910	1.000	2.180	0.177
S_{10}	0.531	0.464	0.671	0.459	1.000	0.113

Table 7. Fuzzy pairwise comparison matrix and relative weights for the infrastructure/equipment conditions (α and β = 0.5).

C_3	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	*Eigenvectors*
S_{11}	1.000	1.418	2.222	1.359	1.314	1.819	0.233
S_{12}	0.705	1.000	2.452	1.946	1.177	1.600	0.220
S_{13}	0.450	0.408	1.000	1.454	1.345	1.910	0.152
S_{14}	0.736	0.514	0.688	1.000	1.490	1.792	0.149
S_{15}	0.761	0.850	0.743	0.671	1.000	2.256	0.151
S_{16}	0.550	0.625	0.524	0.558	0.443	1.000	0.095

Table 8. Fuzzy pairwise comparison matrix and relative weights for the conditions of the management of the security system (α and β = 0.5).

C_4	S_{17}	S_{18}	S_{19}	S_{20}	S_{21}	*Eigenvectors*
S_{17}	1.000	2.511	1.490	1.696	1.735	0.299
S_{18}	0.398	1.000	0.995	1.273	0.934	0.204
S_{19}	0.671	1.005	1.000	2.523	2.210	0.220
S_{20}	0.590	0.786	0.396	1.000	2.638	0.164
S_{21}	0.577	1.071	0.453	0.379	1.000	0.113

Table 9. Fuzzy pairwise comparison matrix and relative weights for the quality and risk conditions of cold-chain vaccine transportation (α and β = 0.5).

C_5	S_{22}	S_{23}	S_{24}	S_{25}	S_{26}	*Eigenvectors*
S_{22}	1.000	2.740	2.139	1.617	2.863	0.358
S_{23}	0.365	1.000	1.940	1.428	2.189	0.216
S_{24}	0.468	0.516	1.000	1.563	2.085	0.174
S_{25}	0.619	0.700	0.640	1.000	1.800	0.157
S_{26}	0.349	0.457	0.480	0.556	1.000	0.095

4. Determining the weighting and prioritization of the criteria

At first, the weight prioritization of individual criteria and sub-criteria was decided based on the eigenvector values in Table 10. Later, each sub-criterion was weighted to arrive at a combined weight for the overall sub-criteria, the results of which can be seen in Table 10. The results and discussion of the research analysis are discussed in Section 4.2.2.

Table 10. Results of fuzzy evaluation of the indicator system.

Criterion	Criterion Weights	Subcriterion	Subcriterion Weights	Overall Combined Weighting	Overall Rank
C_1	0.362	S_1	0.346	0.125	1
		S_2	0.224	0.081	2
		S_3	0.222	0.080	3
		S_4	0.136	0.049	7
		S_5	0.073	0.026	16
C_2	0.228	S_6	0.252	0.057	5
		S_7	0.284	0.065	4
		S_8	0.173	0.039	9
		S_9	0.177	0.040	8
		S_{10}	0.113	0.026	16
C_3	0.156	S_{11}	0.233	0.036	11
		S_{12}	0.220	0.034	13
		S_{13}	0.152	0.024	18
		S_{14}	0.149	0.023	20
		S_{15}	0.151	0.024	18
		S_{16}	0.095	0.015	23
C_4	0.173	S_{17}	0.299	0.052	6
		S_{18}	0.204	0.035	12
		S_{19}	0.220	0.038	10
		S_{20}	0.164	0.028	15
		S_{21}	0.113	0.020	21
C_5	0.080	S_{22}	0.358	0.029	14
		S_{23}	0.216	0.017	22
		S_{24}	0.174	0.014	24
		S_{25}	0.157	0.013	25
		S_{26}	0.095	0.008	26

4.2. Discussion of FAHP and Sensitivity Analysis Results

4.2.1. Findings and Discussion of the Research Analysis of the FAHP

The results are discussed in two parts in this study. The first part presents the results and discussion of the main analysis; this part illustrates and discusses the combined results of Table 10 (α and β = 0.5). The second part is a discussion of the sensitivity analysis of the evaluation criteria; this part simulates α and β separately and discusses the results of the simulation. The details are as follows.

4.2.2. Findings and Discussion of Key Analyses of the FAHP

1. The results of the levels of the criteria

The results show that the importance of the criterion levels, in descending order, is natural environmental conditions (C_1), conditions of development of the social and economic environment (C_2), conditions of management of the security system (C_4), conditions of infrastructure/equipment (C_3), and quality and risk conditions for cold-chain transportation of vaccines (C_5). Among them, the sum of the weights of the two criteria C_1 and C_2 is 0.59, which is higher than 50%, revealing the significant influence of the natural environmental conditions and the development conditions of the social and economic environment in the process of cold-chain transportation of COVID-19 vaccines. The natural environment is a force majeure factor that is difficult for people to fight against, so transportation operators should always pay attention to changes in the surroundings. When an unusual situation occurs, it is necessary to take emergency measures in a timely manner and report the situation to seek help from various parties. In the event of an unusual situation, it is necessary to take emergency measures in good time and to report the situation in order to obtain assistance from various parties. The development conditions of the social and economic environment are an important basis for vaccine transport. When the social and economic environment lags behind, the transport of vaccines may be difficult and the safety of people's lives may not be guaranteed. The condition of safety system management (C_4) is in the middle of the five guidelines. The management of safety systems in the process of cold-chain transportation of COVID-19 vaccines includes the management of the safety of the personnel, the transportation carrier, and the operation process, as well as vaccine quality. The conditions of infrastructure/equipment (C_3) were given higher criterion weights than the quality and risk conditions for cold-chain transportation of vaccines (C_5). Infrastructure equipment belongs to the hardware conditions, including cold-storage and cold-chain transportation equipment, road infrastructure, temperature control equipment, rescue materials, transportation carriers, etc., and is the most basic material support. Without infrastructure, there would be no place to store vaccines, not to mention transportation. This makes infrastructure equipment and its operation and maintenance extremely important. The quality and risk conditions for the cold-chain transportation of vaccines (C_5) is at the end of the five criteria, suggesting that the first four are prerequisites for the last. When the first four criteria are properly implemented, the fifth criterion will be naturally achieved.

2. Level of analysis of the sub-criteria

The overall comprehensive weights of the sub-criteria are ranked in descending order, and the top 10 are listed in descending order as follows: local recurring weather properties and conditions (S_1), local topographical environment (S_2), roadway features (S_3), degree of standardization in the cold-chain logistics industry (S_7), degree of national economic development (S_6), construction of local quality and safety systems (S_{17}), types of traffic status (S_4), distribution of specialized personnel (S_9), urban development index (S_8), and safety operation regulations and measures (S_{19}). Local recurring weather properties and conditions (S_1) are very critical, as severe weather greatly increases the probability of transportation accidents, a threat to the safety of vaccine transportation. The local topographical environment (S_2) is an important factor in temperature changes. When the temperature of the natural environment changes, greater attention should be paid to the changes in the temperature of the environment in which vaccines are stored, otherwise the effectiveness of the vaccines and their protective effect are affected. Roadway features (S_3), including sharp turns, steep slopes, and tunnels, characterize transportation accident-prone roadways, and vaccine transportation drivers should drive carefully. The degree of standardization of the cold-chain logistics industry (S_7) is a reflection of the level of development of the cold-chain logistics industry; the higher the degree of its standardization, the more advanced the level of development, and vice versa. The degree of national economic development (S_6), as a key driver of stable social and economic development, leads to the possibility of losing control of an outbreak in the event of a major epidemic and the inability to stabilize and safely transport vaccines. This highlights the importance of stable transportation of vaccines in effectively containing epidemics. The construction of local quality and safety systems (S_{17}) has a major influence on the overall transportation process of vaccines, and the degree of local quality and safety systems affects the safety and quality of vaccine transportation. Vaccine quality is affected by different types of traffic status (S_4) and different levels of complexity of road conditions, with a low probability of accidents if the road is unobstructed and a high probability of accidents if the traffic is congested. The distribution of specialized personnel (S_9) is an important part in the development of the cold-chain industry, and the shortage of cold-chain logistics personnel has become a bottleneck and a short coming restricting the development of cold-chain logistics. The urban development index (S_8) includes aspects such as the level of urban development, economic strength, etc. The material infrastructure of vaccine transportation is guaranteed to come from sustained economic development. Safety operation regulations and measures (S_{19}) in the vaccine transportation process are critical, and this includes the operator's operating specifications, operating process specifications, etc. Only standardized operations can guarantee the quality of vaccines, and the risk of losing the effectiveness of vaccines is caused by the slightest irregularity.

4.2.3. Sensitivity Analysis and Discussion of the Evaluation Criteria

In this study, a sensitivity analysis of the evaluation criteria was conducted using the values of α and β. Decision makers can determine α based on the uncertainty of the future environment. The higher the value of α, the higher the uncertainty of the future environment, which means that there is a higher degree of risk of the future environment. Conversely, the smaller the value of α, the more stable the future environment, meaning that the future environment is expected to be less risky. In addition, the decision maker can determine the value of β based on his or her own judgment, and $\beta = 0$ indicates that the decision maker has an optimistic view of the future environment. Conversely, a different value signifies that the decision maker is pessimistic about the future environment. In the analysis that follows, conditions $\alpha = 0.5$ and $\beta = 0$–1, and conditions $\beta = 0.5$ and $\alpha = 0$–1 were simulated.

As illustrated in Figure 5, decision makers perceive the future environment as more stable when $\alpha = 0.5$ and $\beta = 0$–1. When the risk level is the lowest ($\beta = 0$), the first five evaluation criteria are vaccine efficacy and protection during transportation (S_{22}), local recurring weather properties and conditions (S_1), degree of national economic development (S_6), construction of local quality and safety systems (S_{17}), and construction of road infrastructures (S_{11}). They grow steadily until $\beta = 0.3$, when the ranking of the importance of the indicators changes. As decision makers become more pessimistic about the future environment, the top five indicators when $\beta = 0$ continue to have the highest importance when $\beta = 1$, and their order of importance is consistent with that at the lowest level of environmental risk ($\beta = 0$). The results demonstrate that unless a major event occurs (e.g., a rapidly spreading epidemic or war), the importance ranking results for the criteria remain stable in future environments, which is consistent with the results for $\alpha = 0.5$ and $\beta = 0.5$. As such, the five indicators of vaccine efficacy and protection (S_{22}), local recurrent weather attributes and conditions (S_1), degree of national economic development (S_6), construction of local quality and safety systems (S_{17}), and construction of road infrastructures (S_{11}) need to be focused on regardless of future environmental stability.

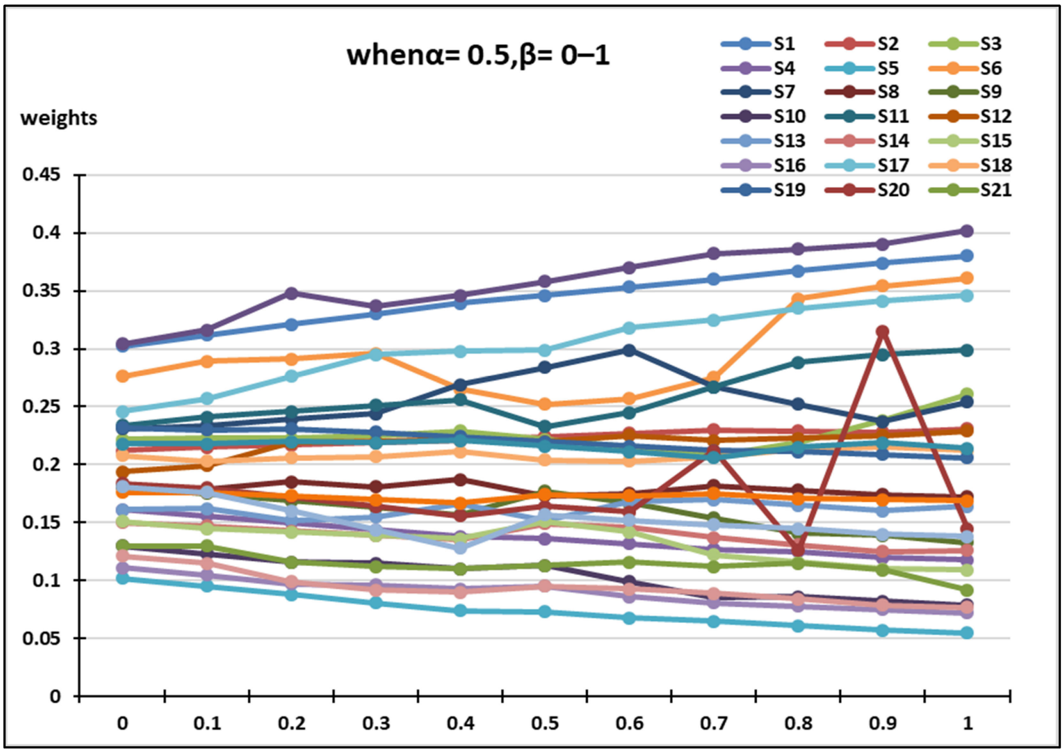

Figure 5. Simulation of α = 0.5, β = 0–1.

The reason for vaccinating with COVID-19 vaccines is that vaccine efficacy and the protective effect (S_{22}) can safeguard people's lives and health, and in the post-pandemic era, if vaccines lose their efficacy, our lives are threatened. Local recurring weather properties and conditions (S_1), such as heavy rains and other inclement weather, result in reduced road capacity and affect the safety of vaccine transportation. The national economy is the material guarantee for the transportation of vaccines, which is why the degree of national economic development (S_6) affects the efficiency of vaccine transportation. The construction of local quality and safety systems (S_{17}) plays a supervisory and standardizing role in the operation process of vaccine transportation. If the local quality and safety standards are very strict, then all the work of vaccine transportation can be carried out in a well-organized manner; otherwise, it is disorganized, and the quality and safety of vaccines cannot be guaranteed, which would threaten the lives and health of the people. The construction of road infrastructures (S_{11}) is the cornerstone of economic and social development and is an important impetus to promote the vigorous development of the transportation industry. If construction lags behind, it poses constraints on the development of vaccine transportation work, making it more difficult.

Figure 6 indicates that when $\beta = 0.5$ and $\alpha = 0$–1 and when the future environment is the most stable ($\alpha = 0$), the first five evaluation criteria are vaccine efficacy and protection during transportation (S_{22}), local recurring weather properties and conditions (S_1), construction of local quality and safety systems (S_{17}), degree of national economic development (S_6), and degree of standardization in the cold-chain logistics industry (S_7). With the increasingly unstable environment in the future, the weights of the top five ranked indicators gradually descend when the environment is stable, and the weights of the lower-ranked indicators gradually ascend. The indicators having steadily ascending weights are the safety monitoring of transportation processes (S_{26}), response capacity and safeguards in case of local accidents (S_{21}), types of traffic status (S_4), distribution of specialized personnel (S_9), and rate of timeliness of information delivery (S_{25}). This suggests that transportation safety monitoring, emergency response capabilities, traffic status, cold-chain technical talent, and information transfer become increasingly critical as the future environment becomes more uncertain.

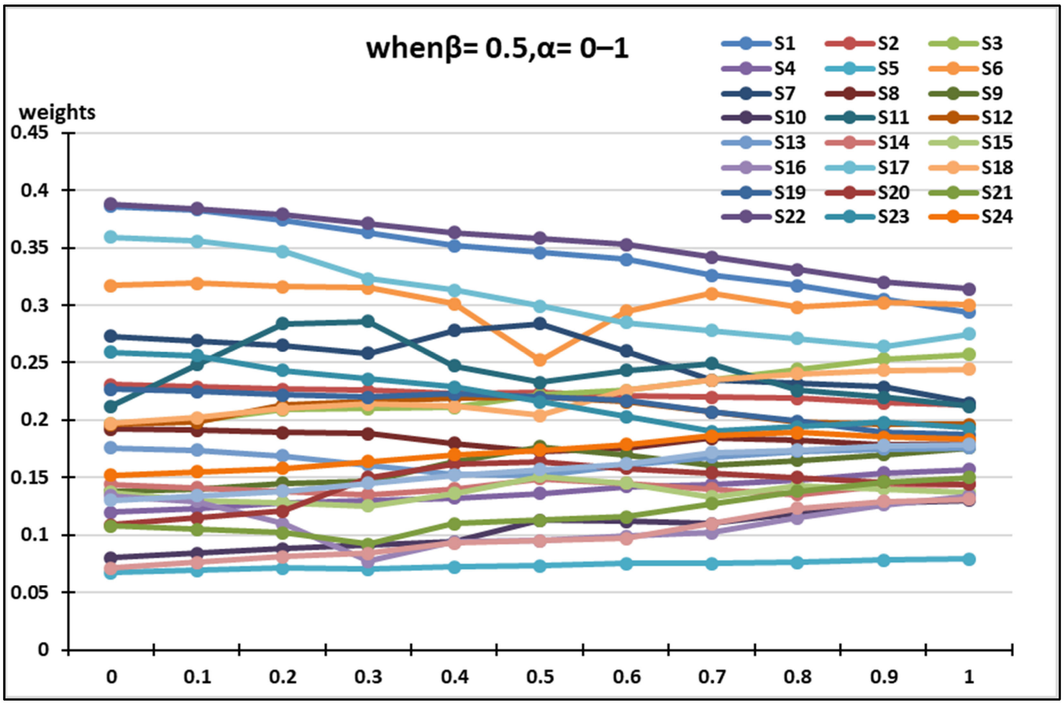

Figure 6. Simulation of β = 0.5, α = 0–1.

The safety monitoring of transportation processes can quantitatively evaluate the safety of facilities and equipment and scientifically assess their operational effectiveness, so that broken facilities and equipment can be detected and maintained in a timely manner to ensure transportation safety. Human beings are not yet sensitive enough to perceive environmental uncertainty; thus, the safety monitoring of transportation processes (S_{26}) is becoming increasingly important as environmental risks increase. While future environmental risks, such as floods, mudslides, and other natural disasters, will increase, they can be mitigated if the emergency response capacity of transport personnel is strong, and transport safeguards are put in place. On the contrary, the quality of vaccines is at stake. Consequently, the importance of the response capacity and safeguards in case of local accidents (S_{21}) for accident occurrence has gradually gained in significance.

The types of traffic status (S_4) are obstructed flow, congested flow, and smooth flow. When there is increased uncertainty about the future environment, such as when ground collapse occurs, the transportation status category may change or increase, and this is an element that affects vaccine transportation efforts in a timely manner. The shortage of cold-chain logistics personnel has become a bottleneck and a weakness in the development of cold-chain logistics in this stage, and cold-chain personnel play a crucial role in enhancing cold-chain logistics technology. With future environmental risks becoming higher, the training of specialized personnel is becoming more urgent because of their technical expertise and ability to cope with changes in the environment. The distribution of specialized personnel (S_9) steadily increases in weight. The timeliness of information delivery (S_{25}) requires that information be conveyed within a defined period of time, and environmental instability may result in poor information being delivered by the staff who do not convey the relevant information within the required period of time, which in turn affects the timeliness of vaccine transportation.

With $\beta = 0.5$ and $\alpha = 0$–1, when the environment is the most stable in the future ($\alpha = 0$), the first five evaluation criteria are vaccine efficacy and protection during transportation (S_{22}), local recurring weather properties and conditions (S_1), construction of local quality and safety systems (S_{17}), degree of national economic development (S_6), and degree of standardization in the cold-chain logistics industry (S_7). With an increasingly unstable future environment, the weight of the top five ranked indicators gradually drops as the environment stabilizes, and the lower-ranked indicators gradually rise. Among those with steadily increasing weights are the safety monitoring of transportation processes (S_{26}), response capacity and safeguards in case of local accidents (S_{21}), types of traffic status (S_4), distribution of specialized personnel (S_9), and rate of timeliness of information delivery (S_{25}). This suggests that the safety monitoring of transportation, emergency response capabilities, traffic status, cold-chain talent, and information delivery become increasingly important as the uncertainties of future environments become elevated.

5. Conclusions and Suggestions

The MDM and FAHP were applied as the main methods in this study; consensus among experts was successfully achieved through several rounds of consultation and feedback; finally, a quality and safety indicator system for cold-chain transportation of COVID-19 vaccines was constructed. The cold-chain transportation of vaccines involves a wide and varied range of risk factors that are critical to ensuring safety of transportation and the quality of vaccines. This study fully utilized the strengths of the MDM and FAHP in expert consensus building and quantitative analysis. The methods used can be discussed and summarized in the following two ways: (1) Providing a solid foundation: The MDM excelled at building expert consensus, and multiple rounds of feedback and revisions provided insights into the quality and safety of cold-chain vaccine transport. The process of repeated expert consultation helps to eliminate individual subjective biases, leading to more objective and accurate conclusions in defining the problem and developing evaluation criteria. (2) Providing objectivity and scientific methodology: Special attention was paid to the use of the MDM and FAHP in conjunction with each other in this study. As a tool for expert opinion collection, the MDM acquired a wealth of expertise and experience for this study, while the FAHP provided a scientific basis for the determination of opinion weights in the quantitative analysis stage. The combination of these two methods allowed us to integrate different perspectives and opinions more systematically in the process of reaching expert consensus, while maintaining a certain degree of objectivity and scientificity in the assessment phase. By integrating the MDM and FAHP, this study emphasized the balance of professionalism and objectivity in the methodology. This methodological combination not only allowed a better understanding and assessment of the quality and safety of cold-chain vaccine transportation but also provided a solid basis for subsequent decisions and measures.

In general, the choice and use of methodology played a crucial role in this study. The integral combination of the MDM and FAHP allowed for a greater understanding and assessment of the quality and safety of cold-chain vaccine transportation, providing a firm foundation for subsequent decisions and measures. With the efforts of this study, a significant step has been made in the field of quality and safety of cold-chain vaccine transportation, which could support the protection of public health and social security.

In light of the results of the evaluation, we can better understand the important criteria for the safety of potential cold-chain vaccine transportation. The occurrence of risk events is evaluated against key criteria, and responses are taken accordingly. For example, we found that environmental conditions (C_1) have a high influence on the quality and safety of cold-chain transportation in the results of the evaluation of the levels of criteria. As a result of risk assessment, we can further analyze risk situations under different environmental conditions, such as traffic congestion and temperature changes that may be caused by inclement weather, with a view to preparing contingency plans and measures. In the analysis at the sub-criteria level, the criterion of risks of loading, unloading, and handling (S_{23}) was identified as one of the important sub-criteria affecting the quality and safety of cold-chain vaccine transportation. By means of risk assessment, we can identify the key factors that may lead to vaccine damage during loading, unloading, and handling, such as irregular operation and equipment failure, and take training and supervisory measures to reduce the likelihood of risk occurrence. Concurrently, risk assessment can also help decision makers to prioritize the allocation and investment of resources. With limited resources, decision makers can minimize potential transportation risks by prioritizing high-risk factors based on the severity of different risks.

To summarize, risk assessment has an important role to play in research on and the practice of quality and safety in cold-chain transportation. By taking into account the assessment results at the levels of criteria and sub-criteria, we can better understand the challenges and opportunities for the quality and safety of cold-chain transportation and adopt corresponding measures and strategies to ensure that the cold-chain transportation process of COVID-19 vaccines is safe and reliable, so as to safeguard the lives and health of the people. Thereby, it is recommended that risk assessment be treated as an important reference in the quality and safety management of cold-chain vaccine transportation in the future and that the risk management system be continuously improved, so as to better cope with potential transportation risks and ensure the successful implementation of vaccine transportation. In addition, the indicator system and analytical methods constructed in this study can also be applied to other areas of vaccine or drug transportation safety, providing useful experience and guidance for safety management in related industries.

Author Contributions: Conceptualization, H.-L.L. and C.-T.L.; Methodology, H.-L.L. and C.-T.L.; Resources, Y.-Y.M.; Writing—review & editing, Y.-Y.M.; Supervision, H.-L.L. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the financial support from Social Science Foundation of Fujian Province, China (grant number FJ2022T006), and Sanming University (grant numbers 23YG03S, 19YG06S).

Data Availability Statement: Not applicable.

Acknowledgments: The authors gratefully acknowledge Social Science Foundation of Fujian Province, China, and Sanming University for financial support. Also, heartfelt thanks go to the group of experts who participated in the survey, with special thanks to those who were mentioned in the MDM and FAHP. We are grateful for your valuable comments and in-depth participation, which provided rich insights and helpful guidance for this study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wang, W.; Xia, Z. Study of COVID-19 Epidemic control capability and emergency management strategy based on optimized SEIR model. *Mathematics* **2023**, *11*, 323. [CrossRef]
2. Adedotun, A.F. Hybrid neural network prediction for time series analysis of COVID-19 cases in Nigeria. *Int. J. Manag. Decis. Mak.* **2022**, *1*, 46–55. [CrossRef]
3. Bishara, R.H. Cold-chain management–an essential component of the global pharmaceutical supply chain. *Am. Pharm. Rev.* **2006**, *9*, 105–109.
4. World Health Organization. *Guidelines for the International Packaging and Shipping of Vaccines*; World Health Organization: Geneva, Switzerland, 2020.
5. Yu, Y.B.; Briggs, K.T.; Taraban, M.B.; Brinson, R.G.; Marino, J.P. Grand challenges in pharmaceutical research series: Ridding the cold-chain for biologics. *Pharm. Res.* **2021**, *38*, 3–7. [CrossRef] [PubMed]
6. Lin, Q.; Zhao, Q.; Lev, B. Cold-chain transportation decision in the vaccine supply chain. *Eur. J. Oper. Res.* **2020**, *283*, 182–195. [CrossRef]
7. Rashid, M. *Identify Constraints of Vaccine Supply Chain: A Case Study of Finnish Red Cross*; The Humanitarian Logistics and Supply Chain Research Institute Hanken School of Economics Helsinki: Helsinki, Finland, 2020.
8. Fahrni, M.L.; Ismail, I.A.N.; Refi, D.M.; Almeman, A.; Yaakob, N.C.; Saman, K.M.; Babar, Z.U.D. Management of COVID-19 vaccines cold-chain logistics: A scoping review. *J. Pharm. Policy Pract.* **2022**, *15*, 16. [CrossRef]
9. Feng, J.; Qin, L.I. How to ensure vaccine safety: An evaluation of China's vaccine regulation system. *Vaccine* **2021**, *39*, 5285–5294. [CrossRef]
10. Chen, Y.Y.; Wang, Y.J.; Jan, J.K. A novel deployment of smart cold-chain system using 2G-RFID-Sys. *J. Food Eng.* **2014**, *141*, 113–121. [CrossRef]
11. Thakur, M.; Forås, E. EPCIS based online temperature monitoring and traceability in a cold meat chain. *Comput. Electron. Agric.* **2015**, *117*, 22–30. [CrossRef]
12. Kim, K.; Kim, H.; Kim, S.K.; Jung, J.Y. i-RM: An intelligent risk management framework for context-aware ubiquitous cold-chain logistics. *Expert Syst. Appl.* **2016**, *46*, 463–473. [CrossRef]

13. Defraeye, T.; Cronjé, P.; Berry, T.; Opara, U.L.; East, A.; Hertog, M.; Nicolai, B. Towards integrated performance evaluation of future packaging for fresh produce in the cold-chain. *Trends Food Sci. Technol.* **2015**, *44*, 201–225. [CrossRef]
14. Xiao, X.; He, Q.; Fu, Z.; Xu, M.; Zhang, X. Applying CS and WSN methods for improving efficiency of frozen and chilled aquatic products monitoring system in cold-chain logistics. *Food Control* **2016**, *60*, 656–666. [CrossRef]
15. Sangiorgio, V.; Mangini, A.M.; Precchiazzi, I. A new index to evaluate the safety performance level of railway transportation systems. *Saf. Sci.* **2020**, *131*, 104921. [CrossRef]
16. British Standard Institute. PAS 1018:2017 Indirect, Temperature-Controlled Refrigerated Delivery Services–Land Transport of Refrigerated Parcels with Intermediate Transfer. 2017. Available online: www.bsigroup.com/en-GB/about-bsi/media-centre/press-releases/2017/march/Specification-for-the-transport-of-chilled-and-frozen-parcels-launched (accessed on 18 March 2023).
17. The National Medical Products Administration of China. *Provisions on Administration of Vaccine Manufacturing and Distribution*; The National Medical Products Administration of China: Beijing, China, 2022.
18. Fan, Y.; Stevenson, M. A review of supply chain risk management: Definition, theory, and research agenda. *Int. J. Phys. Distrib. Logist. Manag.* **2018**, *48*, 205–230. [CrossRef]
19. De Oliveira, U.R.; Marins, F.A.S.; Rocha, H.M.; Salomon, V.A.P. The ISO 31000 standard in supply chain risk management. *J. Clean. Prod.* **2017**, *151*, 616–633. [CrossRef]
20. DuHadway, S.; Carnovale, S.; Hazen, B. Understanding risk management for intentional supply chain disruptions: Risk detection, risk mitigation, and risk recovery. *Ann. Oper. Res.* **2019**, *283*, 179–198. [CrossRef]
21. Lei, X.; MacKenzie, C.A. Assessing risk in different types of supply chains with a dynamic fault tree. *Comput. Ind. Eng.* **2019**, *137*, 106061. [CrossRef]
22. Ambituuni, A.; Amezaga, J.M.; Werner, D. Risk assessment of petroleum product transportation by road: A framework for regulatory improvement. *Saf. Sci.* **2015**, *79*, 324–335. [CrossRef]
23. Conca, A.; Ridella, C.; Sapori, E. A risk assessment for road transportation of dangerous goods: A routing solution. *Transp. Res. Procedia* **2016**, *14*, 2890–2899. [CrossRef]
24. Ghaleh, S.; Omidvari, M.; Nassiri, P.; Momeni, M.; Lavasani, S.M.M. Pattern of safety risk assessment in road fleet transportation of hazardous materials (oil materials). *Saf. Sci.* **2019**, *116*, 1–12. [CrossRef]
25. Shang, K.C.; Huang, S.T.; Buchari, E.; Lirn, T.C.; Della, R.H. Integration of safety quality function deployment in ferry services: Empirical study of Indonesia. *Res. Transp. Bus. Manag.* **2023**, *47*, 100938. [CrossRef]
26. Wu, W.; Li, Y.; Zhao, Z.; Zheng, Q.; Zhang, C.; Ji, H.; Yu, S. Quantitative analysis of liquefaction risk of liquefiable solid bulk cargoes during sea transport. *Ocean Eng.* **2022**, *258*, 111751. [CrossRef]
27. Ellis, J. Analysis of accidents and incidents occurring during transport of packaged dangerous goods by sea. *Saf. Sci.* **2011**, *49*, 1231–1237. [CrossRef]
28. Shen, H.; Zhang, Y.; Wu, Y. A comparative study on air transport safety of lithium-ion batteries with different SOCs. *Appl. Therm. Eng.* **2020**, *179*, 115679. [CrossRef]
29. Zhou, Z.; Yu, X.; Zhu, Z.; Zhou, D.; Qi, H. Development and application of a Bayesian network-based model for systematically reducing safety risks in the commercial air transportation system. *Saf. Sci.* **2023**, *157*, 105942. [CrossRef]
30. Braude, D.; Lauria, M.; Humpheries, A.; O'Donnell, M.; Shelly, J.; Berve, M.; Dixon, D. Safety of Air Medical Transport of Patients With COVID-19 by Personnel Utilizing Routine Personal Protective Equipment. *Air Med. J.* **2022**, *41*, 25–26. [CrossRef]
31. Kozhukhovskaya, L.; Baskov, V.; Ignatov, A. Modular management of indicators of efficiency and safety of transportation processes. *Transp. Res. Procedia* **2017**, *20*, 361–366. [CrossRef]
32. Epifanov, V.; Obshivalкin, M.; Lukonkina, K. Management of quality and security level of transportation in the system of regular passenger motor transport. *Transp. Res. Procedia* **2018**, *36*, 141–148. [CrossRef]
33. Torres-Rubira, J.L.; Escrig-Tena, A.B.; López-Navarro, M.A. Internalization of the 'Safety & Quality Assessment for Sustainability'System Motivations and performance in Spanish road transport firms. *Res. Transp. Bus. Manag.* **2023**, *49*, 100990.
34. Ding, J.F.; Weng, J.H.; Chou, C.C. Assessment of key risk factors in the cold-chain logistics operations of container carriers using best worst method. *Int. J. Refrig.* **2023**, *in press*. [CrossRef]
35. Murry, J.W., Jr.; Hammons, J.O. Delphi: A versatile methodology for conducting qualitative research. *Rev. High. Educ.* **1995**, *18*, 423–436. [CrossRef]
36. Lin, H.L.; Cho, C.C. An ideal model for a merger and acquisition strategy in the information technology industry: A case study for investment in the Taiwanese industrial personal computer sector. *J. Test. Eval.* **2020**, *48*, 775–794. [CrossRef]
37. Lin, H.L.; Ma, Y.Y. A new method of storage management based on ABC classification: A case study in Chinese supermarkets' distribution center. *SAGE Open* **2021**, *11*, 21582440211023193. [CrossRef]
38. Lin, H.L.; Ma, Y.Y.; Lin, C.T. Evaluating Pallet Investment Strategy Using Fuzzy Analytic Network Process: A Case in Chinese Chain Supermarkets. *Mathematics* **2021**, *9*, 3210. [CrossRef]
39. Saaty, T.L. *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*; McGraw: New York, NY, USA, 1980.
40. Zadeh, L.A. Fuzzy sets. *Inf. Control* **1965**, *8*, 338–353. [CrossRef]