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Evaluating Critical Factors Influencing the Reliability of Emergency Logistics Systems Using Multiple-Attribute Decision Making

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Abstract: The infectious disease COVID-19 has swept across the world in 2020, and it continues to cause massive losses of life and severe economic problems in all countries. Providing emergency supplies such as protective medical equipment and materials required to secure people's livelihood is thus currently prioritized by governments. Establishing a reliable emergency logistics system is critical in this regard. This paper used the Delphi method to design a formal decision structure to assess emergency logistics system reliability (ELSR) by obtaining a consensus from a panel of experts. Assessing ELSR is a typical multiple-attribute decision making (MADM) problem, and the related MADM methods are usually on the basis of symmetry principles. A hybrid MADM model, called the Decision Making Trial and Evaluation Laboratory (DEMATEL)-based Analytical Network Process (D-ANP), was developed to identify the critical factors influencing ELSR. An analysis of empirical evidence showed that the emergency logistics command and coordination system and the emergency material supply system play important roles in ELSR, while the emergency logistics transportation and distribution system and the emergency information system are not so important. This conclusion is different from previous research about traditional disaster emergency logistics. Moreover, the cause–effect relationships among the key factors indicated that the system of command and coordination for emergency logistics and the supply system for emergency materials should be improved. Accordingly, effective suggestions for emergency logistics services for epidemic prevention are provided in this paper. The main contributions of this paper are (1) establishing a comprehensive and systematic evaluating index of ELSR for epidemic prevention; (2) employing a kind of structured, namely D-ANP, to identify the critical factors with non-commensurable and conflicting (competing) characteristics; and (3) comparing the differences of reliable criteria between the emergency logistics of epidemic prevention and the traditional disaster emergency logistics.

Keywords: COVID-19; emergency logistics system reliability; critical factors; Delphi method; multiple-attribute decision making

1. Introduction

The disease COVID-19 has swept across the globe in recent months and poses a serious threat to life. According to the World Health Organization (WHO), as of 17 June 2020, there have been 8,061,550 people infected with COVID-19 worldwide, 440,290 of who have died [1]. To make matters worse, epidemic experts believe that the number will continue to rise until a vaccine is available.

Many countries have taken strong control measures to deal with the spread of the virus, including sealing off cities, stopping citizens from going to work and class, suspending indoor recreational activities and large gatherings, and forbidding eating in restaurants. Though all governments have responded to the epidemic, shortages of supplies has led to a series of problems. Medical resources, such as N95-type masks, isolation gowns, life-support machines, and extracorporeal Membrane Oxygenation (ECMO), are in short supply in many countries, and the shortage of materials for medical protection has increased the risk of infection among medical staff. The shortage of materials needed for everyday living, such as clean water and toilet paper, has caused panic in the public. It is thus clear that in case of an emergency, an adequate supply of such materials is vital for maintaining social stability. Reliable emergency logistics systems play an important role in this regard.

Emergency logistics refers to special logistics activities aimed at quickly providing necessary materials in case of natural disasters, public health and social security emergencies, and large-scale accidents, with the aim of maximizing efficiency to minimize the loss of life and property [2]. For example, after an earthquake, the first priority of rescue is to save people's lives, so the role of emergency logistics is to send large-scale rescue equipment and necessities to the disaster area immediately; after an epidemic outbreak, the first problem to be solved is to block the source of infection, so the role of emergency logistics is to send a large number of protective materials to the epidemic center.

Increasing attention has been paid to emergency logistics in recent years, and most relevant studies have focused on optimizing the path for the transportation of emergency logistics and constructing distribution networks. Moreno et al. [3] proposed a transportation problem involving the reuse of vehicles in emergency logistics, and they developed two stochastic mixed-integer programming models to integrate and coordinate the location of facilities and decisions related to transportation and fleet sizes in a multi-period, multi-commodity, and multi-modal context under uncertainty. Vanvactor [4] conducted a quasi-case study to discuss the role of emergency healthcare supply chain management in disaster mitigation and management. To avoid shortages in inventory, Yang et al. [5] proposed a two-stage approach to tackle the sub-problems of vehicle routing and relief allocation in the context of emergency logistics. Liu and Ji [6] proposed an efficient online path planning algorithm for emergency logistics based on double ant colony optimization, and Chen et al. [7] introduced the reliability of a transportation network using random link capacity to explore factors that affect the reliability of logistics networks. They claimed that an effective measure to improve the reliability of a logistics system is to reduce redundancy in logistical capacity. The main purpose of transportation network optimization is to deliver emergency materials to the demand place as fast as possible. However, because the emergency logistics transportation and distribution system is just the tip of the iceberg of the whole emergency logistics system, only focusing on this point is not enough for emergency logistics system reliability (ELSR). Due to COVID-19, the world is facing an acute shortage of medical devices and protective equipment such as face masks, protective clothing, and respirators, which shows that ELSR has been inadequate. The unreliability of any link in the emergency supply chain causes serious problems [8]. For example, as far as the shortage of face masks is concerned, it is clear that the sudden outbreak of the epidemic has resulted in a serious shortage of inventory and affected production capacity. Therefore, a comprehensive and systematic assessment of ELSR is needed.

In this paper, we explore the answers to the following research questions: What factors should be included in the evaluation index of ELSR, and which of them are the critical factors, and is there causal relationship between key factors? Answering these questions can be beneficial for providing effective suggestions for emergency logistics services. Moreover, doing so will contribute to understanding the difference between the emergency logistics of epidemic prevention and the traditional disaster emergency logistics. Specifically, we built a formal decision structure by achieving an experts' consensus through the Delphi method. Furthermore, evaluating ELSR is a typical multiple-attribute decision making (MADM) problem. Because a decision matrix usually has symmetrical or asymmetrical relationships, MADM can be categorized in to the field of symmetry. A hybrid MADM model, called

Decision Making Trial and Evaluation Laboratory (DEMATEL)-based Analytical Network Process (ANP) (D-ANP) [9], was used to solve a such problem.

This paper adds to previous research with the following new contributions. First, it establishes a comprehensive and systematic evaluating index of ELSR for epidemic prevention. Second, because the problem of ELSR is characterized by several non-commensurable and conflicting (competing) criteria where there may be no solution that simultaneously satisfies all criteria [10], some traditional methods—such as the analytic hierarchy process (AHP) [11], the weighted average method, entropy weight, and even the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [12]—are not suitable for solving such problems, so we employed a kind of structured methodology, namely the D-ANP, to obtain the relative weight of each criterion so as to find critical factors. Moreover, the causal relationships between critical factors were identified. Third, this paper aimed to compare the differences of reliable criteria between the emergency logistics of epidemic prevention and the traditional disaster emergency logistics.

The remainder of this paper is organized as follows: Section 2 reviews related literature on the factors influencing ELSR and establishes the prototype of a decision structure, and Section 3 introduces the procedure of the Delphi method and the D-ANP model. Section 4 uses the Delphi method to establish the formal research structure and applies the D-ANP method to evaluate ELSR. Section 5 discusses the various outcomes and provides the conclusions of this study.

2. Related Works

Such emergencies as natural disasters, viral outbreaks, and safety accidents frequently occur all over the world, and they pose a significant threat to social stability the safety of people [13]. Handling these emergencies requires resources, and so ELSR is important.

2.1. Factors Influencing ELSR

A number of studies have been conducted on the evaluating criteria of ELSR. From the perspective of supply chain management, Luton [14] agreed that supply chain reliability mainly refers to the reliability of inventory. Tamrat and Marijn [15] used a stochastic simulation to discuss the reliability of delivery and inventory in supply chain systems. Lin and Chang [16] focused on assessing the performance of a manufacturing system with multiple production lines from the perspective of network analysis, and they measured the probability that the manufacturing network could satisfy customers' orders. This probability was measured as the system's reliability. Huang [17] claimed that in addition to considering suppliers (sources) and markets (sink), the inventory of distribution centers should be considered when studying the reliability of systems with random distribution networks.

In addition to research from the perspective of supply chains, some scholars have argued that factors that affect ELSR should be discussed from the perspective of logistics service providers. Shen [18] proposed that the reliability of third- and fourth-party logistics affects the reliability of a logistics system. Yao and Tian [19] claimed that trans-routing flexibility significantly contributes to improving the reliability of logistics systems, and this contribution is greater when demand changes. Tao et al. [20] classified the reliability of logistics machinery into research on the reliability of logistics service providers, and they claimed that this is important for the success of emergency logistics activities. Li et al. [21] claimed that when logistics enterprises provide emergency material distribution services, drivers, route optimization, and vehicles are the three most important evaluation indicators. He et al. [22] studied the ability of logistics service providers to reliably coordinate supply chains, and they analyzed the influence of changes in their optimal capacity and expected profit on reliability and penalties.

In general, the evaluation of emergency logistics is a systematic problem, and, as such, it has also been considered in the context of literature on system theory. Based on the idea of systematization, Wang et al. [23] established a model to evaluate an emergency logistics system for colliery floods. Combined with the organization, management, decision making, quality of personnel, rescue technology, and geological environment of rescue activities, the emergency logistics system was divided into an information processing system, a material supply system, an emergency engineering system, and other parts for organization, coordination, and management. Gong et al. [24] constructed an operation model and an index system to assess emergency logistics systems that considered four perspectives: the emergency logistics information system, the emergency transportation and distribution system, the emergency logistics command and coordination system, and the emergency logistics financing system. They used the entropy method to determine weights of the reliability index of emergency logistics systems. Based on the theory of reliability engineering, Guo [25] conducted an exploratory study on the reliability of the emergency logistics materials system, the emergency logistics facilities and equipment system, and the emergency logistics distribution system. She also proposed that the reliability of internal coordination be added to the traditional understanding of ELSR. This argument was also supported by Acimovic and Goentzel [26], who claimed that internal objectives such as procurement and warehousing costs, as well as organizational objectives, were necessary to respond quickly to the demand for humanitarian aid.

In addition, some scholars have studied the index of emergency logistics. Han et al. [27] claimed that reliability is the most important factor in assessing emergency logistics, and a comprehensive evaluation index should include timeliness, economy, and flexibility. Chen et al. [28] established an index to assess the reliability of emergency logistics supply chains, including material availability, correctness, arrival time, and node management and information. Cai et al. [29] claimed that timeliness and reliability are the main indices for the selection of transportation routes for emergency logistics in case of earthquakes. It is easy to see from the above research that timeliness is an important factor that affects ELSR, and it is closely related to the efficiency of emergency transportation networks [30]. Wang et al. [31] established an emergency logistics path selection model based on cumulative prospect theory to improve the reliability of the transportation of emergency materials after fully considering subjective factors and the attitude of the decision makers to risk. Edrissi et al. [32] discussed the role of the transportation network in ELSR. The reliability of stations is important for the entire network stations because they constitute important nodes in the emergency logistics transportation network [33].

The above literature review shows that ELSR is mostly based on reliability engineering theory combined with the specific function of a given supply chain, or according to the measured reliability of a node. On the one hand, research in the area has considered the reliability of the supply chain and the logistics system; on the other, it has only discussed the reliability of a single emergency logistics function and not that of the system as a whole. It is well known that the evaluation of ELSR involves not only the suppliers and carriers of emergency materials but also the coordination and command capabilities of public service departments of the government. Additionally, the differences of reliable criteria between the emergency logistics of epidemic prevention and the traditional disaster emergency logistics should be compared. Therefore, it is necessary to establish a comprehensive and systematic evaluating index of ELSR for epidemic prevention.

2.2. Assessing Methods for ELSR

Some methods are used to assess the emergency logistics. Based on the Choquet Interval intuitionistic fuzzy sets—Technique for Order Preference by Similarity to an Ideal Solution (CI-TOPSIS) fuzzy multi-criterion group strategy, Zhu et al. [34] proposed a method to identify cascading failure in and assess the invulnerability of emergency logistics networks. Gao and Tan [35] applied grey entropy theory to assess emergency logistics suppliers. Wang and Yang [36] proposed a method of set pair analysis, and they constructed an ideal index system for the evaluation of emergency logistics suppliers. Caunhye et al. [37] used content analysis to review optimization models deployed in emergency logistics. Liu et al. [38] used meta-graphs in research on the reliability of supply chains to develop an algorithm to calculate the reliability of a structure and comprehensive capabilities of a supply chain system, and they conducted a numerical example to study the applicability of the algorithm to supply chain management. Thomas [39] developed a method to quantify the reliability of the supply chain of emergency logistics systems based on reliability interference theory, where the reliability of the supply chain was defined as the ability of its main transfer point to provide the required supply under a specified time and conditions. Philippe and Lionel [40] proposed a method to assess supply chain reliability based on a Bayesian network that used multi-state nodes to describe the polymorphism of a system and its members' business to solve for the special phenomenon between shared enterprises. Yao [41] established a performance evaluation index and used the back-propagation (BP) neural network to evaluate the performance of emergency logistics. However, evaluating ELSR is a typical MADM problem. The relevant methods are often used to solve problems characterized by several non-commensurable and conflicting (competing) criteria where there may be no solution that simultaneously satisfies all criteria [10]. Because factors influencing ELSR have interdependent impacts [42], the D-ANP method is suitable for solving such problems.

2.3. Prototype Decision Structure

Based on the aforementioned literature, the criteria influencing ELSR were selected and integrated. Next, these criteria were classified into different aspects according to their definitions and functions. Then, according to the meaning of each criterion, the criteria with the same meaning were deleted. Following these steps, this paper is able to propose a prototype of a decision structure consisting of seven perspectives: the emergency logistics information system, the emergency transportation and distribution system, the emergency logistics command and coordination system, the response capabilities of the production system, the reserve system, the procurement system, and emergency logistics personnel. Table 1 shows these perspectives and the criteria used to assess them.

Table 1. Prototype decision structure.

Aspect	Criteria	References
Emergency logistics information system	Accuracy of the information transfer	[23,24,28,41]
	Timely feedback	[23,24,28,41]
	Real-time information dissemination and sharing degree	[23,24,28,41]
	Security and confidentiality	[23,24,41]
	Disaster monitoring and early warning	[23,24,41]
	Information collection and analysis	[23,24,28,41]
	Integrated database	[23,24,41]
	Emergency report and information release	[23,24,28,41]
Emergency logistics transportation and distribution system	Mode and path selection of rationality	[3,5,18–21,25,27,29–32]
	In time of transport arrived	[3,5,15,18–21,25,27–30]
	Safety of emergency materials	[3,18,21,25,29]
	Reasonable choice of means of transport	[3,5,18,19,21,25,29–32]
	Reasonable setting of a distribution center	[20,25,28,29,32,33]
	Reasonable traffic arrangement	[3,15,19,21,25,27,29,31,32]
Emergency logistics command and coordination system	Quick response ability	[18,22,24,41]
	Coordination control capability	[22–25,41]
	Process standardization	[23–25,41]
	Support of advanced technology	[23,24,41]
	Emergency plan	[23,24,41]
	Expert consultant decision team	[22,41]
	National mobilization capacity	[23,24,41]
	Reasonable organizational structure	[23–25,41]
	Legal protection	[24,41]
Production system response ability	Emergency supply capacity of raw materials	[14,16,17,24,25,28]
	Ability to quickly produce emergency supplies	[15,16,24,25,36]
	Ability to quickly finished packing	[15,16,25,36]
	Flexibility of production system	[16,17,25,27,36]
	Production system maintenance and operation ability	[16,17,24,25,36]
Reserve system response ability	Satisfiability: Types of emergency supplies, quantity to meet the needs of real-time capability	[5,14,15,17,26,28,36]
	Recoverability: Timely replenishment of emergency material loss ability	[5,14,15,17,26,36]
	Operability: Reserves of emergency supplies to meet the layout reasonable plan ability	[5,14,15,17,26,28,36]
	Reserve of emergency materials	[14,15,17,26,28,36]
Procurement system response ability	Availability Emergency supplies ability of providers	[16,26,28]
	Quality of goods to meet the capacity needs of emergency supplies	[16,26,28]
Emergency logistics personnel	Sufficient training for participants	[21,41]
	Experienced participants	[21,41]
	Reasonable background and specialty of participants	[22,41]

3. Methodology

Evaluating ELSR is a typical MADM problem. Thus, determining the competing criteria to be included in the structure of evaluation was the first problem to solve. The Delphi method, which considers the consensus of an expert panel, was used to form the formal decision structure; its procedure is described in Section 3.1. In Section 3.2, we introduce the D-ANP technique that was used to identify the critical factors.

3.1. Delphi Method

The Delphi technique was proposed by the RAND Corporation in the 1950s [43]. It is a forecasting and information gathering process that, instead of physically bringing people together, uses written responses from participants who remain anonymous to one another [44]. The objective of the Delphi technique is to obtain the most reliable consensus among a group of experts [45]. Researchers have primarily applied it to cases where judgmental information is indispensable, and they have typically used a series of questionnaires combined with controlled feedback [46]. Ouyang et al. [9] claimed that the Delphi method depends on the experts' experience, instincts, and values to determine outcomes. In practice, experts from different fields are usually expected to provide varying perspectives on a topic [42]. They can understand one another's perspectives in an early round of the questioning process, and they can adjust their own perspectives in the next round to attain consistency [47]. This process helps avoid direct confrontation among experts [48]. The Delphi method has been successfully used in a wide variety of situations as a tool for expert group decision making [49–52]. In this paper, the quartile deviation (*QD*), defined as one-half the interquartile range (*IQR*), which is the difference between the 25th and the 75th percentiles in a frequency distribution [44]), was applied to determine consensus.

Round One. According to the prototype decision structure based on the literature review and results of interviews, an open-ended questionnaire was distributed to each expert. The expert panel then provided opinions on whether the aspects and criteria were appropriate, as well as whether the definition of each item was clear.

Round Two. The questionnaire for this round was composed of all integrated items based on the responses returned by the panel members. They were requested to rate the necessity of items to be included in the formal decision structure. A six-point Likert-type scale [44] was used, and the relationship between rating and necessity is shown in Table 2.

Table 2. Relationship between rating and necessity.

Rating	1	2	3	4	5	6
Necessity	Strongly Unnecessary	Unnecessary	Unnecessary with reservation	Necessary with reservation	Necessary	Strongly necessary

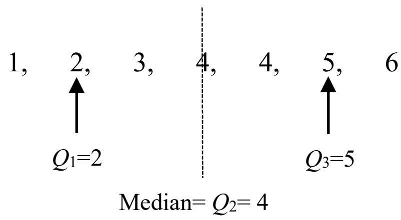
From a data analysis of the responses of round two, we obtained the median, interquartile range (*IQR*), and quartile deviation (*QD*). A numerical example is used to illustrate how to determine them.

Suppose seven experts are asked to rate the necessity of including an item in the formal decision structure, and the ratings given by them are 1, 4, 2, 5, 3, 4, and 6.

Step 1: Rank the experts' ratings from low to high:

1, 2, 3, 4, 4, 5, 6.

Step 2: Determine the median, the first quartile, and the third quartile:



Step 3: Calculate the *IQR* and *QD*. The *IQR* is defined as $IQR = Q_3 - Q_1$, and the *QD* is defined as one-half the *IQR*; thus,

$$QD = \frac{1}{2}IQR = \frac{1}{2}(Q_3 - Q_1) = \frac{1}{2}(5 - 2) = 1.5$$

Round Three. In creating the questionnaire for round three, two pieces of information for each item, the *IQR* of ratings given by the panel members, and each member's rating were used. Each panel member was requested to rate each item once again while noting the item's *IQR* in relation to the panel member's previous rating. If the new rating was beyond the *IQR*, the panel member was asked to provide a reason for deviating from a majority of the panel.

According to the measurement of consensus proposed by Faherty [53], the items that received a $QD < 0.6$ were considered to have achieved high consensus, and a moderate consensus was defined as a $QD > 0.6$ and < 1. In practice, an accepted consensus was achieved when the *QD* was no larger than one [44,53]. If consensus was not reached, we had to continue to repeat the third round of questionnaires until it was. The procedure of the Delphi technique is briefly summarized in Figure 1.

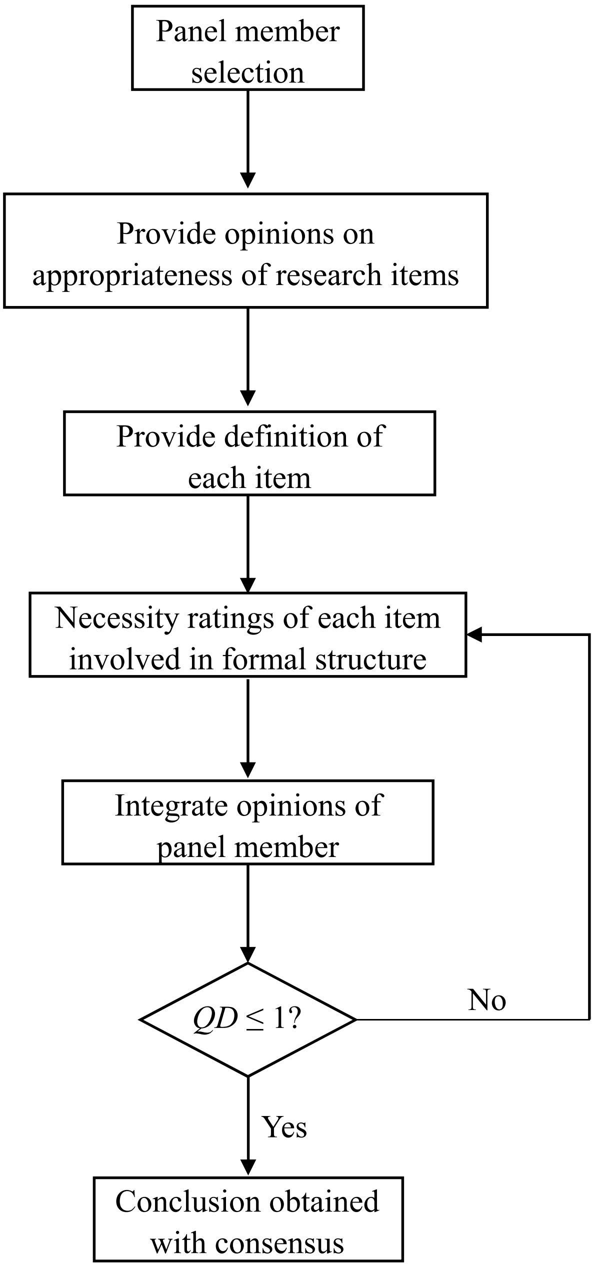


Figure 1. Procedure of the Delphi technique.

3.2. *DEMATEL-Based ANP*

Traditionally, the key factors are usually identified by calculating the relative weight of each criterion. For example, the AHP [11] and ANP [54] are classical methods to calculate weights. However, both encounter significant problems in achieving consistency in pairwise comparisons due to the limitations of human cognition [55] and shortcomings associated with the typical one-to-nine scale, especially in a high-order matrix [56]. Ouyang et al. [9] proposed the D-ANP, which consists of DEMETEL and ANP, by directly using the total influence matrix generated by DEMATEL as the unweighted supermatrix of the ANP, thus avoiding troublesome pairwise comparisons for the ANP. The procedure of the D-ANP is as follows:

Step 1: Build the direct influence matrix.

Z is first constructed using the degree of effect between each pair of elements taken from respondent questionnaires:

$$\mathbf{Z} = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{21} & \cdots & z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ z_{n1} & z_{n2} & \cdots & z_{nn} \end{bmatrix}, \quad (1)$$

where n is the number of factors and z_{ij} represents the extent to which factor i affects factor j, specified as a numerical scale. In this paper, 0 = no influence, 1 = moderate influence, and 2 = high influence [51]. All diagonal elements are zero.

Step 2: Generate the normalized direct influence matrix.

Z is then normalized to generate the normalized direct influence matrix:

$$\mathrm{X} = \lambda \cdot \mathbf{Z} = \begin{bmatrix} \lambda z_{11} & \lambda z_{12} & \cdots & \lambda z_{1n} \\ \lambda z_{21} & \lambda z_{21} & \cdots & \lambda z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \lambda z_{n1} & \lambda z_{n2} & \cdots & \lambda z_{nn} \end{bmatrix} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{21} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nn} \end{bmatrix} \quad (2)$$

where

$$\lambda = \min_{i,j} \left\{ \frac{1}{\max \sum_{i=1}^{n} z_{ij}}, \frac{1}{\max \sum_{j=1}^{n} z_{ij}} \right\} \quad (3)$$

Step 3: Generate the total influence matrix.

The total influence matrix is generated by

$$\mathbf{T} = \mathrm{X}(I - \mathrm{X})^{-1} = \begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1n} \\ t_{21} & t_{22} & \cdots & t_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ t_{n1} & t_{n2} & \cdots & t_{nn} \end{bmatrix}, \quad (4)$$

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

Causes and effects can be derived from **T** [57]. Each row was summed to obtain the value denoted by d, and each column of the total influence matrix was summed to obtain the value denoted by r. $d + r$ represents the prominence, which shows the relative importance of the corresponding factor, where a larger prominence implies greater importance; $d - r$ is the relation, where a positive relation means that the corresponding factor tends to affect other elements, referred to as a cause, and a negative relation means that the corresponding factor tends to be affected by other elements, referred to as an effect.

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

According to a previous study [10], the total influence matrix of DEMATEL can be treated as an unweighted supermatrix for the ANP. Therefore, a weighted matrix, **W**, can be obtained by normalizing **T**, and the global weight of each factor can be obtained by multiplying **W** by itself several times until a limiting supermatrix, $\mathbf{W}^*$, is derived.

Step 6: Identify the critical factors.

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

4. Empirical Study

4.1. Determining the Formal Decision Structure

Epidemic prevention and control is a huge and systematic work involving many responsible units and personnel. In order to fully understand the actual needs of epidemic prevention for emergency logistics, we made the following considerations when selecting experts. First, saving the life of diagnosed patients was the first priority. While treating patients, medical staff are at risk of infection. Therefore, medical staff will apply for necessary medical and protective materials to the logistics department of their hospital according to the actual situation. Indeed, we have to understand what doctors need. Second, there are many departments in each hospital, and the material requirements of each department must be summarized to the logistics department, so we need to know what difficulties the logistics department has in the supply of epidemic prevention. Additionally, the medical community has called logistics difficulties an important problem to solve in order to prevent the spread of an epidemic. The primary-level workers of government should not only control the large flow of personnel but also guarantee the daily life materials for the residents in the closed-off area. Residents' demand for emergency logistics is different from that of hospitals. Next, the department in charge of commerce in government is responsible for the material allocation and procurement of the whole city, so the directors of the local bureau of commerce were decided to be regarded as experts. As an emergency logistics service provider, the service ability of logistics enterprises has an important impact on ELSR, so their opinions were also considered. Finally, a logistics professor was invited to give some academic opinions. Based on the above analysis, this study used an expert panel consisting of six experts—government officials, thoracic surgeons, logistics professors, and senior managers of logistics service providers. Their backgrounds are shown in Table 3. The panel was invited to rate the necessity of including criteria for the prototype, shown in Table 1, in the formal research structure.

In the first round of the Delphi survey, the panel members suggested that aspects should be amalgamated. Since production system response ability, reserve system response ability, and procurement system response ability in Table 1 were referred to material supply capacity, they were integrated into the new aspect named the emergency material supply system in Table 4. Additionally, emergency logistics personnel often need the centralized deployment of the government, so this aspect was incorporated into the emergency logistics command and coordination system in Table 4. Additionally, the panel members suggested that criteria with similar definitions should be consolidated. For example, in the emergency logistics information system, the information release and information sharing degree have overlap to a certain extent, so they were merged into one criterion called the real time release of information in Table 4. Therefore, all such indicators were integrated according to similarities.

After the first round of the Delphi questionnaire, the prototype decision structure shown in Table 1 was integrated into four aspects and 27 criteria. The integrated decision structure is shown in Table 4.

The second-round questionnaire was composed of all integrated items shown in Table 4. Panel members were asked to rate the need to include items in the formal decision structure. We computed the mean and *QD* of the panelists' responses, and the results are shown in Table 5.

In the third round, the questionnaire included the *IQR* of ratings of the group and each panel member. The panel members were asked to assign new ratings to the no-consensus items. If a new rating was outside the *IQR*, the relevant panel member was asked to provide a reason for deviating from a majority of the panel. Table 6 shows the results of the third-round Delphi survey.

According to Table 6, after the third round of the Delphi questionnaire, a consensus of opinion was achieved on the no-consensus items. Furthermore, based on the results of the second- and third-round Delphi questionnaires, criteria with an average value of lower than four were removed from the decision structure because they were deemed unnecessary. The formal decision structure is shown in Table 7.

Table 3. Professional backgrounds of the selected six experts for the Delphi survey.

Expert	Organization	Position	Duties	Seniority (yr)
A	Municipal Bureau of Commerce	Deputy director	Purchasing and allocation of epidemic prevention materials	12
B	Subdistrict office	Secretary	Grassroots epidemic prevention in community	18
C	Thoracic surgery of a central hospital	Physician in charge	Treatment of patients	32
D	Business School of a university	Professor	Engaged in the research of emergency supply chain	23
E	A Logistics Distribution Co., Ltd.	Senior managers	Vehicle scheduling and route planning	15
F	Logistics department of a central hospital	Section chief	Purchasing and distribution of medical materials in hospital	8

Table 4. The integrated decision structure.

Aspect	Criteria
Emergency logistics information system	Accuracy of information sources Accuracy of information transmission Real time release of information Disaster monitoring and early warning Timely feedback of emergency information
Emergency logistics transportation and distribution system	Reasonable transportation and distribution route planning Timeliness of transportation and distribution of emergency materials Safety of transportation and distribution of emergency materials Reasonable choice of transportation and distribution tools
Emergency logistics command and coordination system	Quick response ability Coordination control capability Process standardization Support for advanced technologies Emergency plan Expert consultant National mobilization capacity Reasonable organizational structure Sufficient human resources Legal protection
Emergency material supply system	Emergency supply of raw materials Ability to quickly produce emergency supplies Ability to quickly finished packing Flexibility of production system Production system maintenance and operation ability Types of emergency supplies, quantity to meet the needs of real-time capability Timely replenishment of emergency material loss ability Reasonable setting of a storage and distribution center

Table 5. The results of the second round of Delphi survey.

Criteria	Ascending Order						Mean	*QD*	Classification
Accuracy of information sources	4	4	4	4	5	6	4.50	0.50	High Consensus
Accuracy of information transmission	3	3	4	5	5	6	4.33	1.00	Moderate Consensus
Real time release of information	3	3	4	4	4	6	4.00	0.50	High Consensus
Disaster monitoring and early warning	1	2	4	5	6	6	4.00	2.00	No Consensus
Timely feedback of emergency information	4	4	4	4	5	5	4.33	0.50	High Consensus
Reasonable transportation and distribution route planning	5	5	5	5	6	6	5.33	0.50	High Consensus
Timeliness of transportation and distribution of emergency materials	4	5	5	5	5	6	5.00	0.00	High Consensus
Safety of transportation and distribution of emergency materials	4	4	5	5	6	6	5.00	1.00	Moderate Consensus
Reasonable choice of transportation and distribution tools	5	5	5	5	5	6	5.17	0.00	High Consensus
Quick response ability	2	2	3	4	6	6	3.83	2.00	No Consensus
Coordination control capability	5	5	5	5	5	5	5.00	0.00	High Consensus
Process standardization	1	1	2	3	6	6	3.17	2.50	No Consensus
Support for advanced technologies	1	2	4	5	5	6	3.83	1.50	No Consensus
Emergency plan	2	2	2	3	3	3	2.50	0.50	High Consensus
Expert consultant	3	4	4	5	5	6	4.50	0.50	High Consensus
National mobilization capacity	2	2	3	3	5	5	3.33	1.50	No Consensus
Reasonable organizational structure	5	5	5	5	5	6	5.17	0.00	High Consensus
Sufficient human resources	1	3	4	4	5	6	3.83	1.00	Moderate Consensus
Legal protection	6	6	6	6	6	6	6.00	0.00	High Consensus
Emergency supply of raw materials	5	5	5	5	6	6	5.33	0.50	High Consensus
Ability to quickly produce emergency supplies	5	5	6	6	6	6	5.67	0.50	High Consensus
Ability to quickly finished packing	1	1	2	3	3	4	2.33	1.00	Moderate Consensus
Flexibility of production system	2	3	5	5	6	6	4.50	1.50	No Consensus
Production system maintenance and operation ability	2	2	3	4	5	6	3.67	1.50	No Consensus
Types of emergency supplies, quantity to meet the needs of real-time capability	3	3	3	3	4	4	3.33	0.50	High Consensus
Timely replenishment of emergency material loss ability	2	3	3	4	4	5	3.50	0.50	High Consensus
Reasonable setting of a storage and distribution center	4	4	4	4	5	6	4.50	0.50	High Consensus

Table 6. The results of the third round of Delphi survey.

Criteria	Ascending Order						Mean	QD	Classification
Disaster monitoring and early warning	2	2	3	3	3	4	2.83	0.50	High Consensus
Quick response ability	3	4	4	4	5	6	4.33	0.50	High Consensus
Process standardization	2	3	4	4	5	6	4.00	1.00	Moderate Consensus
Support of advanced technology	3	4	4	4	5	5	4.17	0.50	High Consensus
National mobilization capacity	2	2	3	3	3	4	2.83	0.50	High Consensus
Flexibility of production system	4	4	5	5	5	6	4.83	0.50	High Consensus
Production system maintenance and operation ability	2	3	3	3	4	4	3.17	0.50	High Consensus

Table 7. The formal decision structure.

Aspect	Criteria
Emergency logistics command and coordination system (A)	Quick response ability (A_1) Reasonable organizational structure (A_2) Coordination control capability (A_3) Legal protection (A_4) Process standardization (A_5) Expert consultant (A_6) Support for advanced technologies (A_7)
Emergency material supply system (B)	Emergency supply of raw materials (B_1) Ability to quickly produce emergency supplies (B_2) Flexibility of production system (B_3) Reasonable setting of a storage and distribution center (B_4)
Emergency logistics information system (C)	Accuracy of information sources (C_1) Accuracy of information transmission (C_2) Real time release of information (C_3) Timely feedback of emergency information (C_4)
Emergency logistics transportation and distribution system (D)	Reasonable transportation and distribution route planning (D_1) Timeliness of transportation and distribution of emergency materials (D_2) Safety of transportation and distribution of emergency materials (D_3) Reasonable choice of transportation and distribution tools (D_4)

4.2. Identifying Critical Factors Influencing ELSR

In this sub-section, the D-ANP method was employed to identify critical factors influencing ELSR (the results of each step are shown in the Appendix A). Specifically, the initial direct influence matrix for all criteria was calculated using Equation (1), with the results shown in Table A1. The normalized direct influence matrix was obtained using Equation (2), with the results shown in Table A2. The total influence matrix was calculated using Equation (3), with the results shown in Table A3. The prominence and relation of each criterion are shown in Table A4. According to Table A4, because the relation (i.e., $d - r$) was greater than 0, quick response ability (A_1), reasonable organizational structure (A_2), coordination control capability (A_3), legal protection (A_4), expert consultant (A_6), support for advanced technologies (A_7), emergency supply of raw materials (B_1), ability to quickly produce emergency supplies (B_2), and reasonable setting of a storage and distribution center (B_4) were classified as causes; the remaining ten criteria were classified as effects.

As shown in Table A5, a weighted supermatrix was obtained by normalizing the total influence matrix. The limiting supermatrix derived by the weighted supermatrix is shown in Table A6. The limiting supermatrix was a convergence matrix, that is the number of each row was the same and did not change. The numbers in Table A6 represent the relative weight of the criteria in the evaluation index of ERSL. For example, 0.0674 represents the weight of A_1. By ranking the weights in descending order, we were able to get the importance order of the criteria. According to the rankings' list, the panel members suggested that the criteria for the first nine items be identified as critical factors. These were quick response ability (A_1), reasonable organizational structure (A_2), coordination control capability (A_3), legal protection (A_4), expert consultant (A_6), support for advanced technologies (A_7), emergency supply of raw materials (B_1), ability to quickly produce emergency supplies (B_2), and reasonable setting of a storage and distribution center (B_4).

A causal diagram of the critical factors based on the total influence matrix is shown in Figure 2. According to Table A4, A_2 was suitable as the source because of its maximum relation. The improvement in the performance of a "reasonable organizational structure (A_2)" could help improve other criteria. A reasonable organizational structure means that it has authoritative leaders and perfect organizational functions. It can formulate some emergency laws and regulations through its authority to ensure the smooth implementation of emergency logistics activities in the condition of epidemic prevention. At the same time, it can also give the emergency logistics system a quick response ability, the ability to produce emergency suppliers, and the reasonable setting of a logistics distribution center. What is more, an improvement in A_2 can promote an improvement in A_3, while an improvement in A_3 can further help improve A_6, A_7, and B_1. A strong coordination control capability can guarantee ELSR with all kinds of professional resources and advanced technologies. Furthermore, it can optimize the allocation of raw materials used in the production of emergency materials.

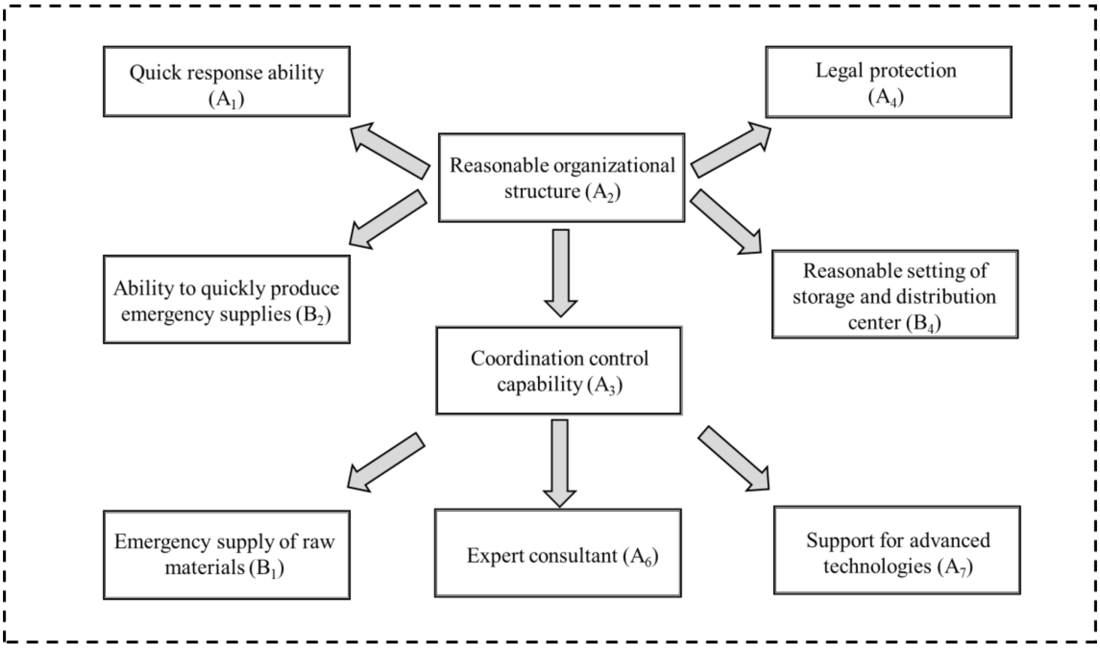


Figure 2. Causal diagram between critical factors.

4.3. Illustrative Example

As the country that had the first outbreak of COVID-19, China has made significant efforts to prevent its spread to good effect. For a country with a population of 1.4 billion, the availability of medical and other necessary materials is crucial. It is thus clear that in case of an emergency, an adequate supply of such materials is vital for maintaining social stability.

In January 2020, when the epidemic broke out in Wuhan, the central government of China immediately launched the joint defense and control mechanism, and a reasonable organizational structure was established [58]. This organizational structure played an important role in the effective prevention and control of the epidemic. After the epidemic outbreak, the first priority was to block the source of infection, so a large number of hospitals were needed to isolate the diagnosed patients. However, at that time, due to the saturation of the existing medical resources in Wuhan, a large number of symptomatic patients could not be diagnosed, and these patients who were not isolated had the risk of infecting others. This organizational structure showed an excellent responsiveness and coordination. First, a series of laws and regulations were issued to ensure that emergency materials could arrive in Wuhan smoothly from all over the country even abroad. Then, the command and coordination system organized enterprises to immediately resume the production of emergency materials to meet the material needs of medical treatment and peoples' lives. A lot of enterprises made unremitting efforts to fight the epidemic. In order to support the construction of Wuhan Lei Shen Shan Hospital, Armstrong Land Materials Company only took one day to transport 7000 square meters of building materials to the project site [59]. Poly Group delivered 36 million yuan of supplies to Wuhan Cabin Hospital within 48 hours [60]. The rapid completion of Huoshenshan hospital and Leishenshan hospital benefited from the integration of the excellent experts and the most advanced technologies and other resources by the command and coordination system. It is not difficult to see that the critical factors identified in this paper are in line with the actual situation in practice. In other words, these critical factors played important role in assessing the ELSR for epidemic prevention and control.

5. Managerial Implications

COVID-19 has put the world's governments to a severe test, especially populous countries like China. Therefore, it is important to decide how to make the best use of limited resources for epidemic prevention. ELSR plays an important role. Jiang and Yuan [61] identified the key characteristics of large-scale disasters, assessed the challenges they posed to emergency logistics, and provided a systematic literature review of emergency logistics in the context of large-scale disasters. However, there are some obvious differences between emergency logistics under epidemic prevention and control and general emergency logistics after disasters. Table 8 shows some differences between two types of emergency logistics.

According to Table 8, there are obvious differences between the two types of emergency logistics. The experience of general emergency logistics proposed by previous scholars [24,32,41] may not be applicable to the epidemic prevention and control emergency logistics. In view of how to ensure ELSR under epidemic prevention, we put forward the following suggestions:

First, the critical factors chosen here show that the command and coordination system played an important role in maintaining ELSR. According to Figure 2, because an improvement in organizational structure can drive improvements in other critical factors, it is important to ensure that the structure of the command and coordination system is reasonable. Therefore, China should consider problems in the operation of its emergency logistics system in light of the valuable practical experience accumulated in fighting COVID-19. In terms of organization and command, the joint prevention and control mechanism of the State Council has made great contributions to the epidemic prevention work. Therefore, the government should establish a long-term emergency logistics coordination mechanism, clarify responsibilities, and coordinate and organize the resources of all departments and channels, such as expert consultants and advanced technologies, to act quickly and in a timely manner in the event of epidemic outbreak. Additionally, a high-level official should be appointed as the leader of this long-term mechanism so that it can have sufficient authority to control the whole emergency logistics system. Additionally, the government should promulgate some laws and regulations to ensure ELSR in time in order to ensure the uninterrupted supply of emergency materials and the smooth flow of materials during an epidemic.

Second, both general disaster emergency logistics and pandemic emergency logistics should deliver the necessary materials for life treatment to the destination as soon as possible, because in any case, life treatment is the first priority. Additionally, the emergency logistics under the epidemic situation should also transport a large number of protective materials for the use of the common people in order to isolate the source of infection in time. As shown in Table 8, under the epidemic situation, emergency supplies are characterized by a wide range of types, a large number of people affected, and a large continuous demand, so they pose a huge challenge to the supply system of emergency materials. The stability of emergency supplies is the basis for the efficient operation of emergency logistics systems; thus, the management of suppliers is important. First, we need to establish a supplier information management system that contains all information on the emergency suppliers, such as supply type, supply capacity, and historical supply data to evaluate each supplier, better understand their capabilities, and determine the main emergency suppliers. Because the duration of the epidemic is uncertain, we should prepare for the long-term mass production of emergency materials. Raw material suppliers should quickly produce emergency materials and integrate other supply chains to expand production capacity and scale if necessary. In addition, suppliers should expand the international and domestic purchasing channels for the production of raw materials for protective articles, and they should make strategic reserves. At the same time, the government should provide financial support for the emergency materials manufacturers. For the emergency materials with excess capacity, all of them should be purchased by the government and included in the government's strategic reserves to solve the worries of the emergency materials suppliers.

Table 8. The comparison between pandemic emergency logistics and control and general emergency logistics.

	General Emergency Logistics	Pandemic Emergency Logistics
Top priority	Saving lives.	Saving lives and blocking-up the source of infection.
Types of materials	Large rescue equipment (such as excavators), professional rescue materials (such as life detector) and living materials (such as drinking water, etc.).	Medical supplies (such as life-support machines, ECMO cardiopulmonary bypass machines) and protective materials (such as masks, disinfectant, and isolation gowns); for some closed communities, living materials are also in great demand.
Service object	Victims.	All people in and near the epidemic area.
Delivery method	General distribution without special restrictions.	Contactless distribution.
Restricted traffic	Some roads may be damaged, and means of conveyance are severely restricted.	All kinds of transportation are unobstructed.
Scope of demand area	Scope of demand area.	National and global.
Duration	The duration is short, even a few days.	Uncertainty; so far, it has been going on for months.

In terms of emergency logistics transportation and distribution, compared with the disaster emergency logistics, there are no traffic restrictions for pandemic emergency logistics. Thus, as long as the emergency materials are sufficient, it is not difficult to deliver them to the destination as soon as possible. However, due to the epidemic situation, there is a great demand for epidemic prevention materials in the whole country, not only a small area, so it is necessary to establish a reasonable distribution center to meet the epidemic prevention needs of all regions. By setting up multiple logistics nodes, the network can be decentralized. A variety of distribution modes should be constructed to strengthen the capability of logistics providers to respond to emergency logistics needs. In additional, in order to minimize cross infection between people, contactless distribution is highly recommended. At present, contactless distribution is in its infancy, and there are still some problems to be solved, e.g., credit problems arising from inspection free delivery. Therefore, logistics enterprises and researchers can improve the service level of contactless distribution from the perspective of process optimization, technological innovation, equipment upgrading, etc.

6. Conclusions

This paper established a comprehensive and systematic evaluating index of ELSR for epidemic prevention, and it identified the critical factors influencing ELSR under epidemic prevention. Specifically, the classic Delphi method was employed to determine the formal decision structure through consensus among a panel of experts. A hybrid model combining the DEMATEL and ANP methods was used to solve this typical MADM problem. The results showed that the command and coordination system for emergency logistics and the emergency material supply system played an important role in ensuring ELSR. Quick response ability, reasonable organizational structure, coordination control capability, legal protection, expert consultants, support for advanced technologies, capacity to supply raw materials needed in emergencies, ability to quickly produce emergency supplies, and reasonable setting of a storage and distribution center were identified as critical factors influencing ELSR. There are significant differences between the critical factors of pandemic emergency logistics identified in this paper and general disaster emergency logistics. Traditionally, general disaster emergency logistics have focused on the capability of coordination [22,41], information systems [23,24], and the optimization of transportation routes [17,19,21,25]. Therefore, the government and all related parties should, using these identified critical factors, strive to improve ELSR and prepare for epidemic prevention.

The D-ANP method was defined as an additive model that assumed that the sum of weights of each attribute was one. Nevertheless, an assumption of additivity may not be realistic in many applications [62] because the variables are not always independent of one another. Therefore, it would be interesting and useful to replace the additive D-ANP with a non-additive one in future work. Second, in different works in the literature [42,63], the number of experts involved in Delphi method have had different ranges, so there is no consensus in academia on how many experts should be invited to participate in the Delphi method, which is worth further study. Moreover, all questionnaires used in this study were administered at the end of February and the beginning of March, which was the most difficult time in China's response to COVID-19. Therefore, we wonder whether the critical factors will change if the questionnaire is reissued after the outbreak, and we will attend to this consideration.

Finally, we would like to express our deep condolences to families and friends of the people who have died of the epidemic and to thank the medical staff for its courageous effort.

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

Appendix A

Table A1. The initial direct influence matrix.

	A_1	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**	**A_7**	**B_1**	**B_2**	**B_3**	**B_4**	**C_1**	**C_2**	**C_3**	**C_4**	**D_1**	**D_2**	**D_3**	**D_4**
A_1	0.0000	1.0000	0.5000	1.1667	1.6667	1.3333	1.3333	1.3333	1.5000	2.0000	1.5000	1.6667	1.5000	0.6667	0.6667	1.6667	1.6667	1.0000	1.0000
A_2	1.1667	0.0000	1.1667	1.1667	1.8333	1.0000	1.1667	1.3333	1.6667	1.6667	1.5000	1.6667	1.5000	1.1667	1.1667	1.5000	1.5000	1.5000	1.3333
A_3	0.8333	0.8333	0.0000	1.0000	1.6667	1.5000	1.8333	1.5000	1.6667	1.8333	1.3333	1.6667	1.6667	1.1667	1.3333	1.3333	1.5000	1.3333	1.1667
A_4	1.0000	0.8333	1.0000	0.0000	1.8333	1.1667	1.3333	0.8333	1.5000	2.0000	0.8333	1.3333	1.5000	1.1667	1.0000	1.6667	1.5000	1.1667	1.1667
A_5	0.3333	0.5000	0.5000	0.5000	0.0000	0.1667	0.3333	0.5000	0.5000	1.1667	0.5000	1.0000	0.8333	0.3333	0.5000	1.0000	0.6667	1.1667	0.8333
A_6	1.0000	0.8333	0.8333	1.1667	1.6667	0.0000	1.1667	1.0000	1.1667	2.0000	1.1667	1.5000	1.5000	1.5000	1.1667	1.5000	1.5000	1.3333	1.0000
A_7	0.6667	0.5000	0.6667	0.8333	1.3333	0.8333	0.0000	0.8333	0.6667	2.0000	0.6667	1.3333	1.1667	1.1667	1.3333	1.3333	1.5000	1.1667	1.5000
B_1	1.1667	0.6667	0.8333	0.8333	1.5000	0.6667	0.8333	0.0000	1.1667	2.0000	1.0000	1.5000	1.3333	1.1667	1.1667	1.3333	1.5000	1.3333	0.8333
B_2	0.8333	1.0000	0.6667	1.0000	1.6667	0.8333	1.3333	1.3333	0.0000	2.0000	1.0000	1.5000	1.1667	1.0000	1.0000	1.5000	1.0000	1.3333	1.3333
B_3	1.0000	0.6667	0.6667	0.6667	1.0000	0.3333	0.6667	0.6667	0.3333	0.0000	0.0000	0.3333	0.3333	0.3333	0.3333	0.5000	0.5000	0.5000	0.3333
B_4	0.8333	0.8333	0.6667	0.6667	1.1667	1.0000	0.8333	0.8333	1.0000	1.5000	0.0000	1.5000	1.3333	1.1667	1.3333	1.3333	1.3333	1.1667	1.1667
C_1	0.5000	0.3333	0.6667	0.6667	0.8333	0.5000	0.8333	0.5000	0.3333	1.5000	0.8333	0.0000	1.0000	0.6667	0.5000	0.8333	0.8333	0.6667	0.6667
C_2	0.6667	0.8333	0.6667	0.5000	1.1667	0.6667	1.0000	0.6667	0.8333	1.6667	1.0000	1.3333	0.0000	0.8333	0.8333	0.8333	1.3333	0.8333	1.0000
C_3	0.6667	0.3333	0.8333	0.6667	1.1667	0.6667	0.6667	0.8333	0.3333	1.6667	0.8333	1.3333	1.0000	0.0000	1.0000	1.5000	1.3333	1.0000	0.6667
C_4	1.0000	0.8333	0.8333	0.3333	1.0000	0.6667	0.5000	0.6667	0.5000	1.6667	0.6667	1.0000	0.8333	1.1667	0.0000	1.6667	1.5000	0.8333	1.0000
D_1	0.1667	0.3333	0.5000	0.3333	1.0000	0.3333	1.0000	0.3333	0.6667	1.3333	0.3333	0.6667	0.5000	1.0000	0.8333	0.0000	0.8333	0.6667	0.8333
D_2	1.0000	0.8333	0.5000	0.3333	0.8333	0.5000	1.3333	0.6667	0.6667	1.6667	0.6667	1.1667	1.5000	1.3333	1.3333	1.5000	0.0000	1.1667	0.8333
D_3	0.6667	0.5000	0.8333	0.3333	0.6667	0.5000	1.0000	0.5000	0.6667	1.3333	0.5000	0.8333	0.8333	1.0000	1.1667	1.3333	1.0000	0.0000	1.0000
D_4	1.1667	1.0000	1.5000	1.0000	0.8333	1.0000	0.5000	0.6667	0.8333	1.0000	0.8333	0.6667	0.6667	1.3333	0.3333	0.8333	1.0000	0.6667	0.0000

Table A2. The normalized direct influence matrix.

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	B_1	B_2	B_3	B_4	C_1	C_2	C_3	C_4	D_1	D_2	D_3	D_4
A_1	0.0000	0.0333	0.0167	0.0389	0.0556	0.0444	0.0444	0.0444	0.0500	0.0667	0.0500	0.0556	0.0500	0.0222	0.0222	0.0556	0.0556	0.0333	0.0333
A_2	0.0389	0.0000	0.0389	0.0389	0.0611	0.0333	0.0389	0.0444	0.0556	0.0556	0.0500	0.0556	0.0500	0.0389	0.0389	0.0500	0.0500	0.0500	0.0444
A_3	0.0278	0.0278	0.0000	0.0333	0.0556	0.0500	0.0611	0.0500	0.0556	0.0611	0.0444	0.0556	0.0556	0.0389	0.0444	0.0444	0.0500	0.0444	0.0389
A_4	0.0333	0.0278	0.0333	0.0000	0.0611	0.0389	0.0444	0.0278	0.0500	0.0667	0.0278	0.0444	0.0500	0.0389	0.0333	0.0556	0.0500	0.0389	0.0389
A_5	0.0111	0.0167	0.0167	0.0167	0.0000	0.0056	0.0111	0.0167	0.0167	0.0389	0.0167	0.0333	0.0278	0.0111	0.0167	0.0333	0.0222	0.0389	0.0278
A_6	0.0333	0.0278	0.0278	0.0389	0.0556	0.0000	0.0389	0.0333	0.0389	0.0667	0.0389	0.0500	0.0500	0.0500	0.0389	0.0500	0.0500	0.0444	0.0333
A_7	0.0222	0.0167	0.0222	0.0278	0.0444	0.0278	0.0000	0.0278	0.0222	0.0667	0.0222	0.0444	0.0389	0.0389	0.0444	0.0444	0.0500	0.0389	0.0500
B_1	0.0389	0.0222	0.0278	0.0278	0.0500	0.0222	0.0278	0.0000	0.0389	0.0667	0.0333	0.0500	0.0444	0.0389	0.0389	0.0444	0.0500	0.0444	0.0278
B_2	0.0278	0.0333	0.0222	0.0333	0.0556	0.0278	0.0444	0.0444	0.0000	0.0667	0.0333	0.0500	0.0389	0.0333	0.0333	0.0500	0.0333	0.0444	0.0444
B_3	0.0333	0.0222	0.0222	0.0222	0.0333	0.0111	0.0222	0.0222	0.0111	0.0000	0.0000	0.0111	0.0111	0.0111	0.0111	0.0167	0.0167	0.0167	0.0111
B_4	0.0278	0.0278	0.0222	0.0222	0.0389	0.0333	0.0278	0.0278	0.0333	0.0500	0.0000	0.0500	0.0444	0.0389	0.0444	0.0444	0.0444	0.0389	0.0389
C_1	0.0167	0.0111	0.0222	0.0222	0.0278	0.0167	0.0278	0.0167	0.0111	0.0500	0.0278	0.0000	0.0333	0.0222	0.0167	0.0278	0.0278	0.0222	0.0222
C_2	0.0222	0.0278	0.0222	0.0167	0.0389	0.0222	0.0333	0.0222	0.0278	0.0556	0.0333	0.0444	0.0000	0.0278	0.0278	0.0278	0.0444	0.0278	0.0333
C_3	0.0222	0.0111	0.0278	0.0222	0.0389	0.0222	0.0222	0.0278	0.0111	0.0556	0.0278	0.0444	0.0333	0.0000	0.0333	0.0500	0.0444	0.0333	0.0222
C_4	0.0333	0.0278	0.0278	0.0111	0.0333	0.0222	0.0167	0.0222	0.0167	0.0556	0.0222	0.0333	0.0278	0.0389	0.0000	0.0556	0.0500	0.0278	0.0333
D_1	0.0056	0.0111	0.0167	0.0111	0.0333	0.0111	0.0333	0.0111	0.0222	0.0444	0.0111	0.0222	0.0167	0.0333	0.0278	0.0000	0.0278	0.0222	0.0278
D_2	0.0333	0.0278	0.0167	0.0111	0.0278	0.0167	0.0444	0.0222	0.0222	0.0556	0.0222	0.0389	0.0500	0.0444	0.0444	0.0500	0.0000	0.0389	0.0278
D_3	0.0222	0.0167	0.0278	0.0111	0.0222	0.0167	0.0333	0.0167	0.0222	0.0444	0.0167	0.0278	0.0278	0.0333	0.0389	0.0444	0.0333	0.0000	0.0333
D_4	0.0389	0.0333	0.0500	0.0333	0.0278	0.0333	0.0167	0.0222	0.0278	0.0333	0.0278	0.0222	0.0222	0.0444	0.0111	0.0278	0.0333	0.0222	0.0000

Table A3. The total influence matrix.

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	B_1	B_2	B_3	B_4	C_1	C_2	C_3	C_4	D_1	D_2	D_3	D_4	d
A_1	1.378	2.168	1.791	2.348	3.692	2.500	2.928	2.652	2.867	4.677	2.791	3.592	3.274	2.328	2.228	3.706	3.583	2.715	2.605	53.83
A_2	2.619	1.304	2.542	2.450	4.020	2.310	2.912	2.780	3.152	4.596	2.923	3.770	3.433	2.943	2.835	3.745	3.608	3.335	3.063	58.34
A_3	2.319	2.118	1.423	2.302	3.879	2.779	3.541	2.942	3.143	4.784	2.766	3.783	3.600	2.964	3.012	3.600	3.629	3.192	2.920	58.70
A_4	2.312	1.985	2.243	1.196	3.801	2.323	2.897	2.160	2.828	4.617	2.134	3.231	3.225	2.760	2.503	3.669	3.387	2.831	2.728	52.83
A_5	1.000	1.069	1.134	1.071	0.992	0.762	1.131	1.144	1.175	2.448	1.135	1.909	1.676	1.141	1.244	1.978	1.604	1.953	1.594	26.16
A_6	2.322	1.985	2.094	2.317	3.648	1.203	2.739	2.316	2.515	4.631	2.452	3.399	3.236	3.081	2.673	3.530	3.405	2.993	2.572	53.11
A_7	1.799	1.482	1.742	1.801	2.978	1.809	1.336	1.923	1.799	4.171	1.747	2.893	2.609	2.508	2.561	3.020	3.074	2.539	2.767	44.56
B_1	2.349	1.718	1.963	1.883	3.287	1.737	2.274	1.220	2.378	4.366	2.166	3.205	2.903	2.599	2.517	3.169	3.208	2.822	2.254	48.02
B_2	2.080	2.061	1.864	2.089	3.510	1.931	2.773	2.535	1.303	4.438	2.202	3.255	2.791	2.500	2.401	3.375	2.799	2.876	2.780	49.56
B_3	1.550	1.157	1.198	1.179	1.873	0.866	1.357	1.248	0.967	1.180	0.606	1.193	1.125	1.030	0.995	1.402	1.350	1.241	1.030	22.55
B_4	1.981	1.825	1.765	1.678	2.882	2.003	2.195	1.968	2.161	3.779	1.151	3.122	2.825	2.550	2.610	3.081	2.977	2.591	2.504	45.65
C_1	1.251	0.990	1.367	1.315	1.952	1.167	1.711	1.242	1.112	2.952	1.540	1.084	1.965	1.565	1.355	1.961	1.904	1.598	1.542	29.57
C_2	1.654	1.674	1.596	1.374	2.620	1.534	2.145	1.643	1.825	3.580	1.940	2.712	1.318	2.014	1.940	2.333	2.714	2.062	2.141	38.82
C_3	1.609	1.163	1.714	1.482	2.565	1.495	1.801	1.751	1.314	3.523	1.736	2.656	2.236	1.166	2.065	2.914	2.670	2.170	1.777	37.81
C_4	1.953	1.662	1.742	1.201	2.449	1.524	1.675	1.632	1.507	3.560	1.617	2.379	2.109	2.322	1.117	3.109	2.860	2.043	2.117	38.58
D_1	0.862	0.922	1.149	0.932	1.991	0.931	1.767	1.010	1.326	2.650	0.984	1.623	1.383	1.798	1.586	1.051	1.792	1.510	1.618	26.88
D_2	2.009	1.710	1.488	1.252	2.386	1.421	2.518	1.689	1.710	3.699	1.676	2.630	2.805	2.550	2.474	3.049	1.530	2.429	2.051	41.08
D_3	1.526	1.250	1.643	1.101	1.966	1.274	2.008	1.364	1.540	3.034	1.345	2.061	1.955	2.038	2.122	2.629	2.239	1.089	2.001	34.19
D_4	2.135	1.845	2.394	1.882	2.365	1.904	1.725	1.691	1.898	2.990	1.838	2.139	2.023	2.508	1.494	2.373	2.444	1.937	1.190	38.77
r	34.709	30.088	32.851	30.852	52.858	31.473	41.434	34.908	36.521	69.676	34.749	50.635	46.492	42.364	39.732	53.694	50.779	43.925	41.253	

Table A4. The prominence and relation of each criterion.

	D	**R**	**D + R**	**D − R**
A_1	53.8250	34.7089	88.5339	19.1161
A_2	58.3398	30.0884	88.4282	28.2514
A_3	58.6966	32.8509	91.5475	25.8457
A_4	52.8285	30.8520	83.6805	21.9765
A_5	26.1592	52.8578	79.0171	−26.6986
A_6	53.1122	31.4734	84.5856	21.6388
A_7	44.5568	41.4341	85.9909	3.1227
B_1	48.0186	34.9078	82.9265	13.1108
B_2	49.5635	36.5210	86.0845	13.0425
B_3	22.5476	69.6756	92.2232	−47.1281
B_4	45.6461	34.7492	80.3953	10.8969
C_1	29.5725	50.6347	80.2071	−21.0622
C_2	38.8197	46.4921	85.3118	−7.6724
C_3	37.8070	42.3642	80.1712	−4.5573
C_4	38.5777	39.7322	78.3099	−1.1545
D_1	26.8845	53.6943	80.5788	−26.8097
D_2	41.0776	50.7793	91.8569	−9.7017
D_3	34.1858	43.9247	78.1104	−9.7389
D_4	38.7745	41.2527	80.0272	−2.4781

Table A5. The weighted supermatrix obtained by normalizing the total influence matrix.

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	B_1	B_2	B_3	B_4	C_1	C_2	C_3	C_4	D_1	D_2	D_3	D_4
A_1	0.0397	0.0721	0.0545	0.0761	0.0698	0.0794	0.0707	0.0760	0.0785	0.0671	0.0803	0.0709	0.0704	0.0550	0.0561	0.0690	0.0706	0.0618	0.0632
A_2	0.0755	0.0433	0.0774	0.0794	0.0760	0.0734	0.0703	0.0797	0.0863	0.0660	0.0841	0.0744	0.0739	0.0695	0.0714	0.0697	0.0711	0.0759	0.0742
A_3	0.0668	0.0704	0.0433	0.0746	0.0734	0.0883	0.0855	0.0843	0.0861	0.0687	0.0796	0.0747	0.0774	0.0700	0.0758	0.0671	0.0715	0.0727	0.0708
A_4	0.0666	0.0660	0.0683	0.0388	0.0719	0.0738	0.0699	0.0619	0.0774	0.0663	0.0614	0.0638	0.0694	0.0651	0.0630	0.0683	0.0667	0.0645	0.0661
A_5	0.0288	0.0355	0.0345	0.0347	0.0188	0.0242	0.0273	0.0328	0.0322	0.0351	0.0327	0.0377	0.0361	0.0269	0.0313	0.0368	0.0316	0.0445	0.0387
A_6	0.0669	0.0660	0.0637	0.0751	0.0690	0.0382	0.0661	0.0663	0.0689	0.0665	0.0706	0.0671	0.0696	0.0727	0.0673	0.0657	0.0671	0.0681	0.0623
A_7	0.0518	0.0492	0.0530	0.0584	0.0563	0.0575	0.0322	0.0551	0.0492	0.0599	0.0503	0.0571	0.0561	0.0592	0.0645	0.0563	0.0605	0.0578	0.0671
B_1	0.0677	0.0571	0.0597	0.0610	0.0622	0.0552	0.0549	0.0349	0.0651	0.0627	0.0623	0.0633	0.0624	0.0613	0.0633	0.0590	0.0632	0.0642	0.0546
B_2	0.0599	0.0685	0.0567	0.0677	0.0664	0.0613	0.0669	0.0726	0.0357	0.0637	0.0634	0.0643	0.0600	0.0590	0.0604	0.0629	0.0551	0.0655	0.0674
B_3	0.0447	0.0385	0.0365	0.0382	0.0354	0.0275	0.0327	0.0358	0.0265	0.0169	0.0175	0.0236	0.0242	0.0243	0.0251	0.0261	0.0266	0.0282	0.0250
B_4	0.0571	0.0606	0.0537	0.0544	0.0545	0.0637	0.0530	0.0564	0.0592	0.0542	0.0331	0.0616	0.0608	0.0602	0.0657	0.0574	0.0586	0.0590	0.0607
C_1	0.0360	0.0329	0.0416	0.0426	0.0369	0.0371	0.0413	0.0356	0.0304	0.0424	0.0443	0.0214	0.0423	0.0369	0.0341	0.0365	0.0375	0.0364	0.0374
C_2	0.0477	0.0556	0.0486	0.0445	0.0496	0.0487	0.0518	0.0471	0.0500	0.0514	0.0558	0.0536	0.0283	0.0476	0.0488	0.0434	0.0534	0.0469	0.0519
C_3	0.0463	0.0387	0.0522	0.0480	0.0485	0.0475	0.0435	0.0501	0.0360	0.0506	0.0500	0.0525	0.0481	0.0275	0.0520	0.0543	0.0526	0.0494	0.0431
C_4	0.0563	0.0552	0.0530	0.0389	0.0463	0.0484	0.0404	0.0468	0.0413	0.0511	0.0465	0.0470	0.0454	0.0548	0.0281	0.0579	0.0563	0.0465	0.0513
D_1	0.0248	0.0307	0.0350	0.0302	0.0377	0.0296	0.0426	0.0289	0.0363	0.0380	0.0283	0.0321	0.0297	0.0424	0.0399	0.0196	0.0353	0.0344	0.0392
D_2	0.0579	0.0568	0.0453	0.0406	0.0451	0.0451	0.0608	0.0484	0.0468	0.0531	0.0482	0.0519	0.0603	0.0602	0.0623	0.0568	0.0301	0.0553	0.0497
D_3	0.0440	0.0416	0.0500	0.0357	0.0372	0.0405	0.0485	0.0391	0.0422	0.0435	0.0387	0.0407	0.0420	0.0481	0.0534	0.0490	0.0441	0.0248	0.0485
D_4	0.0615	0.0613	0.0729	0.0610	0.0447	0.0605	0.0416	0.0484	0.0520	0.0429	0.0529	0.0422	0.0435	0.0592	0.0376	0.0442	0.0481	0.0441	0.0288

Table A6. The limiting supermatrix derived by the weighted supermatrix.

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	B_1	B_2	B_3	B_4	C_1	C_2	C_3	C_4	D_1	D_2	D_3	D_4	*Rank*
A_1	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	0.0674	3
A_2	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	2
A_3	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	0.0736	1
A_4	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	0.0655	5
A_5	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	0.0325	18
A_6	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	0.0658	4
A_7	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	9
B_1	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	0.0594	7
B_2	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	0.0617	6
B_3	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	0.0301	19
B_4	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	0.0569	8
C_1	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	0.0372	16
C_2	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	0.0488	12
C_3	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	0.0465	14
C_4	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	0.0480	13
D_1	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	0.0332	17
D_2	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	11
D_3	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	0.0428	15
D_4	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	0.0516	10

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