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Resilience assessment for the emergency supplies security system based on a matter-element extension method

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Abstracts

The emergency supplies security system (ESSS) plays a vital role in preventing major disasters and ensuring people's safety. Resilience is an important benchmark to characterize the ability of disaster resistance of the ESSS. However, the ESSS complexity and resilience dynamic evolution make ESSS resilience assessment challenging. This study develops a hierarchical ESSS resilience assessment system comprising three dimensions and twelve criteria, and proposes a dynamic resilience assessment model based on a matter-element extension method. Subsequently, a case study is conducted to demonstrate the applicability of the proposed model. The assessment results indicate that the ESSS resilience in the sample cities has improved over the past five years. However, there are still some shortcomings such as low response rates and high operating costs. This study provides a valuable criteria reference and effective model support for ESSS resilience assessment, which is beneficial for decision makers to clarify the resilience profile, identify the weakness and promote resilience improvement.

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Keywords: Emergency supplies security system (ESSS); Resilience assessment; Matter-element extension method

1. Introduction

Emergency supplies are essential for the effective implementation of rescue and relief, the protection of the affected people's lives, and the rapid restoration of social order [1]. In recent years, due to the frequent disasters, the governments around the world have paid great attention to the construction of the emergency supplies security system (ESSS) and its effectiveness in post-disaster response [2]. Resilience, as an important benchmark for characterizing disaster response capacity, has become a research hotspot in many fields, such as national resilience, urban resilience, and supply chain resilience. How to carry out ESSS resilience assessment has become an important issue to be solved

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urgently, which is beneficial to clarify the resilience profile, identify the weaknesses and promote resilience improvement. However, ESSS is a complex system involving procurement, storage, deployment, and transportation [3], while the resilience has inherent dynamic evolutionary characteristics [4], and the superposition of both increases the difficulty of ESSS resilience assessment. In existing studies from the related fields, Ben-Dor et al. argued that national resilience consists of four major components: patriotism, optimism, social integration, and trust in political and public institutions [5]. Zhang and Huang proposed a loss ratio function for national resilience assessment [6]. Huang et al. divide urban resilience into three dimensions: social, economic, and ecological [7]. Liu et al. utilized factor analysis to transform 39 indicators of urban economy, society, infrastructure, and environment into urban natural disaster resilience criteria [8]. Dixit et al. constructed supply chain networks and used structure parameters to calculate resilience scores [9]. These related studies provide criteria and method references for ESSS resilience assessment but cannot address the aforementioned difficulty. In this paper, a hierarchical resilience assessment system is constructed, and a dynamic assessment model based on the matter-element extension method is proposed and verified. The rest of this paper is organized as follows. Section 2 presents a hierarchical system and a quantitative model for ESSS resilience assessment. Section 3 demonstrates the applicability of the proposed model through a case study and the conclusions of this study are summarized in section 4.

2. Resilience assessment system and model for the ESSS

2.1. Resilience assessment dimensions and criteria

The ESSS encompasses various domains, such as procurement, storage, deployment, and transportation, and its resilience to risk requires a multidimensional characterization [3]. Based on the related studies [5–9], realistic requirement analysis [1–4] and expert judgment, this study divides the ESSS resilience assessment system into three dimensions: withstanding capability B_1, recovering capability B_2, and adaptive capability B_3. And a hierarchical ESSS resilience assessment system is presented in Table 1, which contains three dimensions and twelve criteria C_i, $i = 1, 2, ..., 12$.

Table 1. Hierarchical resilience assessment system for the ESSS.

ESSS resilience assessment dimensions	ESSS resilience assessment criteria
Withstanding capability B_1	Sufficiency of emergency supply reserve quantity C_1
	Reasonableness of the emergency supply categories configuration C_2
	Level of emergency supply warehouse infrastructure construction C_3
	Efficiency of emergency supply warehouse operation C_4
Recovering capability B_2	Timeliness of emergency response C_5
	Ability of emergency supply demand prediction C_6
	Degree of emergency supply security information sharing C_7
	Reliability of working staff C_8
Adaptive capability B_3	Ability of emergency supply stockpile cost reduction C_9
	Level of emergency supply provider risk sharing C_{10}
	Ability of risk event review C_{11}
	Level of cross-departmental collaboration C_{12}

2.2. Model design for resilience assessment

2.2.1. Rationale of model design

The matter-element extension method combines matter-element theory and extension theory to express the quantitative and qualitative changes of the objects [10]. This study proposes a dynamic resilience assessment model for the ESSS based on the matter-element extension method. The model can describe the variability of the ESSS resilience dynamically and transform the qualitative description into a quantitative one. Its correlation function does not depend on subjective judgment and can diagnose the degree of affiliation of each assessment criterion with each level. This allows the model to reveal more information on resilience levels, identify key factors affecting the ESSS resilience level, and make development suggestions.

2.2.2. Main procedures of the proposed model

The step-by-step modeling procedure is described as follows.

Step 1: Determine the resilience matter-element.

Assume that the resilience level of the ESSS at time t is $N(t)$, the criteria set is C, and the set of the criteria value is $V(t)$. And the *i*th criterion of the ESSS resilience assessment system is c_i, and its corresponding value is $v_i(t)$, $i=1,2,...,n$. The resilience matter-element of the ESSS can be described in the following form:

$$R(t)=(N(t),C,V(t))=\begin{bmatrix} n & c_1 & v_1(t) \\ & c_2 & v_2(t) \\ & \vdots & \vdots \\ & c_n & v_n(t) \end{bmatrix} \tag{1}$$

Step 2: Determine the classical domain and extensional domain.

The proposed model classifies the assessment results into m resilience levels, where the classical domain matter-element represents the interval values of the criteria for different levels. Among them, the *j*th level of the ESSS resilience assessment system is represented by $N_j\,(j=1,2,....,m)$, the *i*th criterion is $c_i\,(i=1,2,...,n)$, and the range of the criteria c_i for the *j*th measure level is (a_{ji},b_{ji}). Then, the classical domain matter-element R_j is defined as:

$$R_j=\left(N_j,C_i,V_{ji}\right)=\begin{bmatrix} n_j & c_1 & v_{j1} \\ & c_2 & v_{j2} \\ & \vdots & \vdots \\ & c_n & v_{jn} \end{bmatrix}=\begin{bmatrix} n_i & c_1 & \left(a_{j1},b_{i1}\right) \\ & c_2 & \left(a_{j2},b_{i2}\right) \\ & \vdots & \vdots \\ & c_n & \left(a_{jn},b_{jn}\right) \end{bmatrix} \tag{2}$$

The extensional domain matter-element represents the interval values of the criteria, where N_p represents the set of all ESSS resilience measure levels. The range of values for c_i in the resilience assessment system is $V_{pi}=(a_{pi},b_{pi})$. Then, the extensional domain matter-element R_p is defined as:

$$R_p=\left(N_p,C_i,V_{pi}\right)=\begin{bmatrix} N_p & c_1 & v_{p1} \\ & c_2 & v_{p2} \\ & \vdots & \vdots \\ & c_n & v_{pn} \end{bmatrix}=\begin{bmatrix} p & c_1 & \left(a_{p1},b_{p1}\right) \\ & c_2 & \left(a_{p2},b_{p2}\right) \\ & \vdots & \vdots \\ & c_n & \left(a_{pn},b_{pn}\right) \end{bmatrix} \tag{3}$$

Step 3: Determine the matter-element to be assessed.

The matter-element of the ESSS resilience levels N_x at the time point t to be assessed is defined as $R_x(t)$.

$$R_x(t)=\begin{bmatrix} N_x & c_1 & v_1(t) \\ & c_2 & v_2(t) \\ & \vdots & \vdots \\ & c_n & v_n(t) \end{bmatrix} \tag{4}$$

Step 4: Determine the correlation function.

The correlation function $K(X(t))$ is defined as:

$$K\left(X(t)\right)=\begin{cases} -\rho\left(X(t),X_o\right)/\left|X_o\right| & \left(X(t)\in X_o\right) \\ \rho\left(X(t),X_o\right)/\left(\rho\left(X(t),X_p\right)-\rho\left(X(t),X_o\right)\right) & \left(X(t)\notin X_o\right) \end{cases} \tag{5}$$

where $X(t)$, X_o, X_p denote the value of the criteria in the matter-element $R_x(t)$, the interval value of the classical domain matter-element R_j and the interval value of the extensional domain matter-element R_p, respectively. $\rho\left(X(t),X_o\right)$ represents the distance between the $X(t)$ and the finite interval $X_o=(a_o,b_o)$ of the classical domain, and $\rho\left(X(t),X_p\right)$ represents the distance between the value $X(t)$ and the finite interval $X_p=(a_p,b_p)$ of the extensional domain, $\left|X_o\right| = \left|b_o - a_o\right|$.

$$\rho\left(X(t), X_o\right) = \left|X(t) - \frac{1}{2}\left(a_o + b_o\right)\right| - \frac{1}{2}\left(b_o - a_o\right) \tag{6}$$

$$\rho\left(X(t), X_p\right) = \left|X(t) - \frac{1}{2}\left(a_p + b_p\right)\right| - \frac{1}{2}\left(b_p - a_p\right) \tag{7}$$

Step 5: Calculate the comprehensive correlation and determine the resilience level.

The comprehensive correlation degree refers to the affiliation degree of the criteria to each resilience measure level, which consists of the correlation function, the criteria, and its weights:

$$K_j(N_x(t)) = \sum_{i=1}^{n} w_i K_j(x_i(t)) \tag{8}$$

where $K_j(N_x(t))$ represents the comprehensive correlation of the matter-element $R_x(t)$ to be assessed for the jth resilience measure level, $K_j(x_i(t))$ represents the single criterion correlation of the ith criterion for the jth resilience measure level, and w_i represents the weight of each criterion and satisfies $\sum_{i=1}^{n} w_i = 1$.

The proposed model uses the principle of maximum affiliation degree. If $K_{ji}(t) = \max(K_j(x_i(t)))$, it means that the ith criterion of the ESSS resilience assessment system reaches the jth resilience level. If $K_{jx}(t) = \max(K_j(N_x(t)))$, it means that the matter-element $N_x(t)$ to be assessed reaches the jth resilience level. Finally, the scientific and reasonable assessment results of the ESSS resilience level are obtained.

3. Case study

3.1. Data collection and processing

In this case study, the ESSS resilience assessment for six sample cities in J province, China is conducted based on data from 2018 to 2022. The ESSS resilience level is divided into five levels: Level 1, Level 2, Level 3, Level 4, and Level 5. The study uses the expert scoring method, which combines the survey results of seven industry experts in J province and the statistical data, to construct the matter-elements for assessment. The criteria are based on a hundred-point system, and the division standard is consistent, as shown in Table 2.

Table 2. ESSS resilience level and scoring standard.

Resilience level	Level 5	Level 4	Level 3	Level 2	Level 1
Score	0~19	20~39	40~59	60~79	80~100

The ESSS resilience assessment system has different roles and importance for each assessment criterion, so it is essential to assign reasonable weights to each criterion and dimension to measure their contribution to the overall. This study used the Delphi method to assign weights to each assessment criterion and dimension in the system based on the knowledge, experience, and personal opinions of seven experts in J province. It also calculated the comprehensive weights of each assessment criterion as 0.2164, 0.1233, 0.0613, 0.0276, 0.2198, 0.0292, 0.0969, 0.0827, 0.0110, 0.0171, 0.0599, and 0.0548, respectively.

3.2. Resilience assessment results

The resilience assessment results of the ESSS for six sample cities in province J from 2018 to 2022 are shown in Table 3, denoted as City A, B, C, D, E, and F, respectively. Overall, the ESSS resilience in six sample cities in J province has increased significantly. Compared with 2018, the affiliation degree of the ESSS resilience to Level 1 in 2022 for the six sample cities increased by a maximum of 58.42% and a minimum of 33.69%. For instance, ESSS resilience in City D reached Level 1 in 2020 and continued to improve in the next two years, with increases of 18.56% and 23.61% in 2021 and 2022, respectively. The increased ESSS resilience in each city corresponds to the fact that the 14th Five-Year National Emergency System Plan issued by the State Council of China includes the ESSS construction in the national construction plan.

Table 4 shows the correlations of the resilience criteria in City A. The resilience of most criteria improved in 2020-2022. The diagnostic information from individual criteria shows that although City A reached Level 1 in 2022, two criteria did not reach Level 2. City A still needs to further enhance its ESSS resilience, and the ability of emergency supply demand prediction C_6 and the ability of emergency supply stockpile cost reduction C_9 are the key factors limiting the resilience enhancement in City A.

Table 3. Comprehensive correlation and the resilience assessment results.

City	Year	Level 5	Level 4	Level 3	Level 2	Level 1	Resilience
City A	2018	-0.43691	-0.36631	-0.37833	-0.49137	-0.57669	Level 4
	2019	-0.49098	-0.36471	-0.31583	-0.37597	-0.50940	Level 3
	2020	-0.63097	-0.51297	-0.42917	-0.28191	-0.42516	Level 2
	2021	-0.71667	-0.63213	-0.52500	-0.35437	-0.34143	Level 1
	2022	-0.78519	-0.72381	-0.63583	-0.50762	-0.25682	Level 1
City B	2018	-0.47249	-0.34573	-0.35833	-0.39237	-0.54309	Level 4
	2019	-0.52599	-0.41142	-0.33083	-0.34202	-0.49373	Level 3
	2020	-0.61211	-0.49792	-0.37750	-0.25293	-0.40700	Level 2
	2021	-0.66146	-0.56250	-0.44250	-0.30888	-0.37898	Level 2
	2022	-0.75648	-0.68690	-0.56167	-0.38611	-0.34912	Level 1
City C	2018	-0.56154	-0.45173	-0.35750	-0.34405	-0.46302	Level 2
	2019	-0.59343	-0.48214	-0.37417	-0.33781	-0.44993	Level 2
	2020	-0.68981	-0.60119	-0.45667	-0.32479	-0.36382	Level 2
	2021	-0.76481	-0.69762	-0.57667	-0.35278	-0.32138	Level 1
	2022	-0.82685	-0.77738	-0.68833	-0.50278	-0.25542	Level 1
City D	2018	-0.67905	-0.58512	-0.44417	-0.34365	-0.39090	Level 2
	2019	-0.72282	-0.64237	-0.51417	-0.32183	-0.37528	Level 2
	2020	-0.80926	-0.75476	-0.65667	-0.47917	-0.26125	Level 1
	2021	-0.86296	-0.82381	-0.75333	-0.60000	-0.21275	Level 1
	2022	-0.90093	-0.87262	-0.82167	-0.70278	-0.16250	Level 1
City E	2018	-0.56439	-0.43793	-0.41667	-0.35060	-0.48024	Level 2
	2019	-0.58964	-0.46569	-0.36250	-0.32154	-0.46779	Level 2
	2020	-0.64964	-0.54345	-0.45500	-0.34958	-0.41177	Level 2
	2021	-0.70071	-0.61439	-0.48750	-0.36915	-0.37499	Level 2
	2022	-0.76204	-0.69405	-0.57167	-0.39444	-0.31841	Level 1
City F	2018	-0.32304	-0.38821	-0.49167	-0.60841	-0.69677	Level 5
	2019	-0.43591	-0.36701	-0.45833	-0.54167	-0.63437	Level 4
	2020	-0.48158	-0.35285	-0.37917	-0.40514	-0.55275	Level 4
	2021	-0.53667	-0.39762	-0.32917	-0.36496	-0.47590	Level 3
	2022	-0.61132	-0.48995	-0.39250	-0.34511	-0.43929	Level 2

Table 4. Resilience criteria correlation in City A.

City A	2022						2021	2020
	Level 5	Level 4	Level 3	Level 2	Level 1	Resilience	Resilience	Resilience
C_1	-0.86667	-0.82857	-0.76000	-0.60000	-0.10000	Level 1	Level 1	Level 2
C_2	-0.81111	-0.75714	-0.66000	-0.43333	-0.35000	Level 1	Level 2	Level 2
C_3	-0.74444	-0.67143	-0.54000	-0.35000	-0.36111	Level 2	Level 2	Level 2
C_4	-0.75556	-0.68571	-0.56000	-0.40000	-0.35294	Level 1	Level 2	Level 2
C_5	-0.91111	-0.88571	-0.84000	-0.73333	-0.10000	Level 1	Level 1	Level 2
C_6	-0.50000	-0.35714	-0.25000	-0.25000	-0.43750	Level 3	Level 3	Level 4
C_7	-0.92222	-0.90000	-0.86000	-0.76667	-0.15000	Level 1	Level 1	Level 2
C_8	-0.94444	-0.92857	-0.90000	-0.83333	-0.25000	Level 1	Level 1	Level 2
C_9	-0.48889	-0.34286	-0.20000	-0.25806	-0.43902	Level 3	Level 4	Level 4
C_{10}	-0.68889	-0.60000	-0.44000	-0.10000	-0.39130	Level 2	Level 2	Level 2
C_{11}	-0.91111	-0.88571	-0.84000	-0.73333	-0.10000	Level 1	Level 1	Level 1
C_{12}	-0.87778	-0.84286	-0.78000	-0.63333	-0.05000	Level 1	Level 2	Level 2

4. Conclusions

A robust and uniform ESSS ensures the safety of people's lives and property, as well as social harmony and stability. This study developed a hierarchical resilience assessment system consisting of three dimensions (withstanding capability, recovering capability, and adaptive capability) and twelve criteria. It also proposed a dynamic resilience assessment model for the ESSS based on the matter-element extension method and applied it to six sample cities in J province. The result analysis indicated that the proposed model can effectively diagnose the resilience of each dimension and each criterion of the ESSS, and the calculation results are consistent with the reality. Although the sample cities have made great progress in the ESSS resilience, they still face some challenges. First, the city's storage infrastructure is not functional enough, and the utilization rate is not high enough to meet the needs of modern emergency supply security. Second, there is a lack of unified management and scheduling, and it is difficult to achieve information sharing. Third, there is a shortage of professional management personnel and auxiliary decision-making support functions. In the future, multiple initiatives should be taken to strengthen the ESSS and improve its ability to cope with disasters and accidents.

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