Research on Condition Evaluation Method for Concrete Box-Girder Bridges Based on Analytic Hierarchy Process

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Abstract. Concrete continuous box-girder bridges, boasting excellent mechanical performance and construction convenience, have seen prevalent applications in bridge engineering. However, during long-term operation, these bridges are susceptible to various external environmental factors, leading to issues such as prestress loss, creep and shrinkage, and cracking, which subsequently affect structural safety. In light of this, for the sake of scientific assessment of the health status of bridges, this paper proposes a condition evaluation method for concrete box-girder bridges based on health monitoring data. The method opted for four types of evaluation indicators as the first level: cumulative test results, deformation and stress verification, trend analysis of monitoring data, and periodic inspection data. By applying the Analytic Hierarchy Process (AHP) to a continuous rigid frame bridge on a certain highway to calculate the weight of each indicator, this method enables a comprehensive evaluation of the bridge's condition, providing effective decision support for bridge operation, maintenance, and reinforcement.

Keywords: concrete box-girder bridges, condition evaluation, Analytic Hierarchy Process, Health Monitoring, Structural Safety

1 Introduction

Admittedly, concrete continuous box-girder bridges embrace outstanding flexural stiffness and structural performance, leading to extensive utilization in both highway and railway applications. Yet, during prolonged operation, these bridges are prone to issues such as prestress loss, creep, shrinkage, and cracking arising from load effects, material aging, environmental corrosion, and temperature variations. In severe cases, these issues can compromise traffic safety and even result in structural damage to the bridge. Therefore, a scientific and reasonable evaluation of the bridge structure's condition is of great significance for ensuring its long-term safe operation.

Currently, bridge condition evaluation methods are primarily categorized into two types: (1) load-carrying capacity evaluation, which focuses on the bridge's load-bearing capacity and safety margin; and (2) condition evaluation, which emphasizes the health status and performance degradation of the bridge structure. Common evaluation methods include fuzzy comprehensive evaluation, neural network approaches, reliability

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analysis, and the Analytic Hierarchy Process (AHP), among others. In China, bridge evaluation methods typically involve disassembling the structure into components, linking each component to upper-level indicators through weight calculations, and employing a hierarchical-comprehensive evaluation approach to ultimately classify the bridge into one of five categories [1].

Fabianowski et al. (2021) [2] proposed a bridge condition evaluation method based on artificial neural networks, which can adaptively learn from monitoring data to improve evaluation accuracy. Rogulj et al. (2021) [3] assessed the health condition of road bridges using a fuzzy expert system, albeit with its heavy reliance on expert experience and relatively robust subjectivity. Darban et al. (2022) [4] applied the AHP method to structural health monitoring of concrete bridges in Iran, as a means to determine the weights of various evaluation indicators, enhancing the scientific rigor of the assessment. Additionally, Sun et al. (2022) [5] proposed a foundation pit health assessment model based on fuzzy AHP, a testament to the applicability of the AHP method in structural health assessment. Fu et al. (2022) [6] used a hierarchical method to analyze multi-source data for bridge safety monitoring during reconstruction and demolition, and demonstrated the effectiveness of this approach in ensuring the safety of bridges under construction.

Despite the advancements achieved, existing assessment methods still face several challenges. Some approaches depend on large-scale datasets and substantial computational resources, limiting their applicability in real-time scenarios. Others rely heavily on expert judgment, making it difficult to effectively integrate multi-source information. Many methods lack a systematic framework that combines real-time monitoring data with trend analysis, leading to potential gaps in early warning capabilities and long-term performance prediction.While AHP-based methods offer a structured evaluation approach, they often struggle to dynamically incorporate real-time monitoring data, preventing them from capturing evolving bridge conditions. Furthermore, the absence of integration with continuous monitoring systems results in static assessments that fail to promptly respond to immediate changes in bridge behavior.

To address these limitations, this study proposes a novel condition assessment method for concrete box girder bridges that integrates bridge health monitoring data. Emphasizing multi-source data fusion, the method incorporates four key assessment indicators: cumulative test results, deformation and stress validation, monitoring data trend analysis, and periodic inspection data. A hierarchical model is constructed, and the feasibility of the approach is verified through weight calculation of the indicators. This method enables a more systematic and data-driven evaluation, mitigating the fragmentation issues present in existing assessment approaches.

2 Traditional Hierarchical Model

The AHP represents a systematic approach to multi-criteria decision analysis. It ensues by breaking down the target problem into hierarchical levels, assigning weights based on the relationship between factors at each level and the overall problem, and ultimately deriving a composite score. In the context of bridge structures, AHP facilitates the division of the problem into multiple levels, harmonizes the evaluation results of various indicator types, and integrates both quantitative and qualitative aspects.

China's *Standards for Technical Condition Evaluation of Highway Bridges* (JTG/T H21-2011) [7] employs a hierarchical weighting method. Bridges are categorized into three components: superstructure, substructure, and deck system, with separate technical condition scores calculated for each. The technical condition of bridges is classified into five distinct categories. In essence, the traditional indicator system for evaluating the working condition of bridge structures, as illustrated in Figure 1, divides the bridge into three hierarchical levels: system, structure, and component.

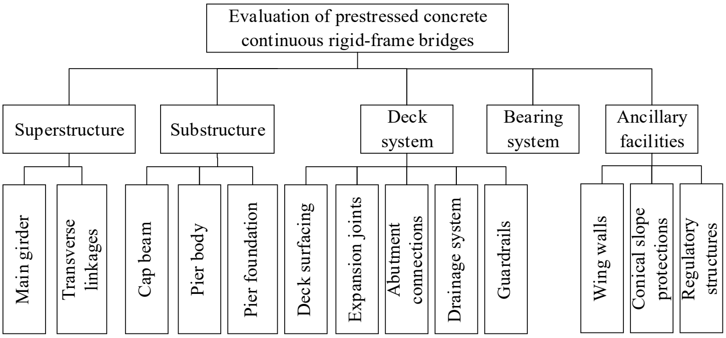

Fig. 1. Classic hierarchical model for bridges

3 Construction of the Evaluation Indicator System

This paper takes a three-span prestressed concrete continuous rigid-frame bridge as a case study (as visualized in Figure 2), with a span combination of 95 m + 180 m + 95 m. The main bridge employs a single-box, single-cell prestressed concrete continuous box girder with varying cross-sections, designed for a two-way, four-lane highway. The load rating is Class I for highways, and the safety level is Grade I.

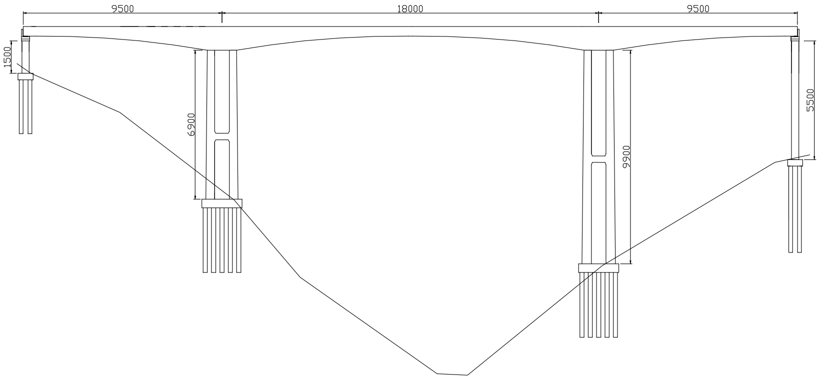

Fig. 2. Elevation view of the case study bridge

During the health monitoring of this bridge, a large amount of monitoring data was collected. By systematically analyzing the types and characteristics of the health monitoring data, this study selects four key data categories as the core data sources: cumulative test results, deformation and stress verification, trend analysis and periodic inspection data. These four data categories reflect the structural response and performance evolution of the bridge from different perspectives, comprehensively covering both short-term condition changes and long-term performance trends. The integration of multi-source data mitigates the limitations of a single data source, ensuring the comprehensiveness and reliability of the assessment results and providing a scientific and systematic data base for bridge condition assessment.

(1) Bridge classification evaluation method-I based on cumulative test data: By accumulating long-term test data, potential abnormal areas of the bridge are identified, and the bridge condition is preliminarily classified, providing a reference for further evaluation.

$$C_h + C_{gx} + kC_f = C \tag{1}$$

1) Substituting C_f into the above equation for calculation using the maximum or minimum test values yields the measured k-value (noting that different C-values should be used for bridges of different ages).

2) It then progresses to determining the category by assessing which interval the measured k-value falls into.

(2) Evaluation method-II based on deformation and stress verification: Utilizing the measured deformation and stress data of the bridge, the structural response under design loads is verified to assess its safety and load-bearing capacity, ensuring compliance with design requirements (as shown in table 1). This method is used to validate structural safety.

Based on the analysis of mid-span displacement and stress, a predicted stress value relative to displacement can be obtained for a measurement point. By comparing the measured stress, after accounting for environmental and other loads, with the predicted stress, the following coefficient k is derived.

$$k = \left|\frac{\sigma_{measured} - \sigma_{predicted}}{\sigma_{measured}}\right| \tag{2}$$

Table 1. Evaluation of technical grades for verification and analysis of deformation and stress data

Load-bearing capacity grade	Grading criteria	Condition description	Countermeasure	Comment
1	5%> k ≧0	Compliance with design specifications	It is deemed safe and needs enhanced monitoring	
2	10%≧ k ≧5%	Compliance with regulatory standards	Load limits should be adjusted	
3	k ≧10%	Adjustment for internal forces	Traffic control or bridge closure ensues	

(3) Evaluation method-III based on trend analysis of monitoring data: This method proceeds with trend analysis on long-term monitoring data to assess the variation patterns in a bridge's condition, predict its future health status, and provide early warning of potential deterioration issues. It is used for long-term health monitoring and trend prediction.

Trend analysis of monitoring data can be performed monthly, revealing year-over-year and month-over-month trends. Generally, the trends for stress and deformation show rapid changes immediately after the bridge opens to traffic, followed by a slowdown in the rate of change. After 10 years, these parameters typically stabilize, remaining unchanged for the next 10 to 20 years. From 20 to 50 years, there is a very slow decline, which accelerates from 50 to 90 years. Trend analysis can be combined with traffic information, such as maximum axle weight and the percentage of heavy vehicles.

The trends in measured strain changes have been thoroughly analyzed during data preprocessing, with analyses conducted on daily, weekly, and monthly cycles. In future research, incremental values over longer periods will be considered and compared to a baseline model. The evaluation criteria for measured trends will consider the following standards:

$$s_i = \left|\frac{\sigma_{i+1} - \sigma_i}{t_{i+1} - t_i}\right| \tag{3}$$

$$k = \left|\frac{s_i - s_{baseline\ model}}{s_{baseline\ model}}\right| \tag{4}$$

By substituting test values into the above equation for calculation, the measured k-value is obtained. The category is determined by assessing which interval the measured k-value falls into (as shown in table 2).

Table 2. Grade evaluation for trend analysis of monitoring data

Load-bearing capacity grade	Grading criteria	Condition description	Countermeasure
1	5%> k ≧0	Compliance with design specifications	It is deemed safe and needs enhanced monitoring
2	10%≧ k ≧5%	Compliance with regulatory standards	Load limits should be adjusted
3	k ≧10%	Adjustment for internal forces	Traffic control or bridge closure ensues

(4) Condition evaluation method-IV based on periodic inspection data: This method combines periodic inspection data to assess the current condition of a bridge, identify deterioration in critical structural components, and provide data support for formulating appropriate maintenance and reinforcement measures. It is used for periodic inspection and maintenance decision-making. For highway bridges, a periodic inspection is conducted every three years, based on which the classification of the bridge can be determined.

This study integrates four evaluation methods—cumulative test results, deformation and stress verification, trend analysis, and periodic inspection data—with the Analytic

Hierarchy Process (AHP) to establish a three-tier analytical model (as shown in Figure 3). In this model, the four evaluation methods serve as top-level indicators, forming a hierarchical assessment framework alongside traditional evaluation models. This approach not only retains the structural advantages of AHP but also enhances the responsiveness to real-time monitoring data through dynamic weight calculation, thereby significantly improving the timeliness and accuracy of bridge condition assessment.

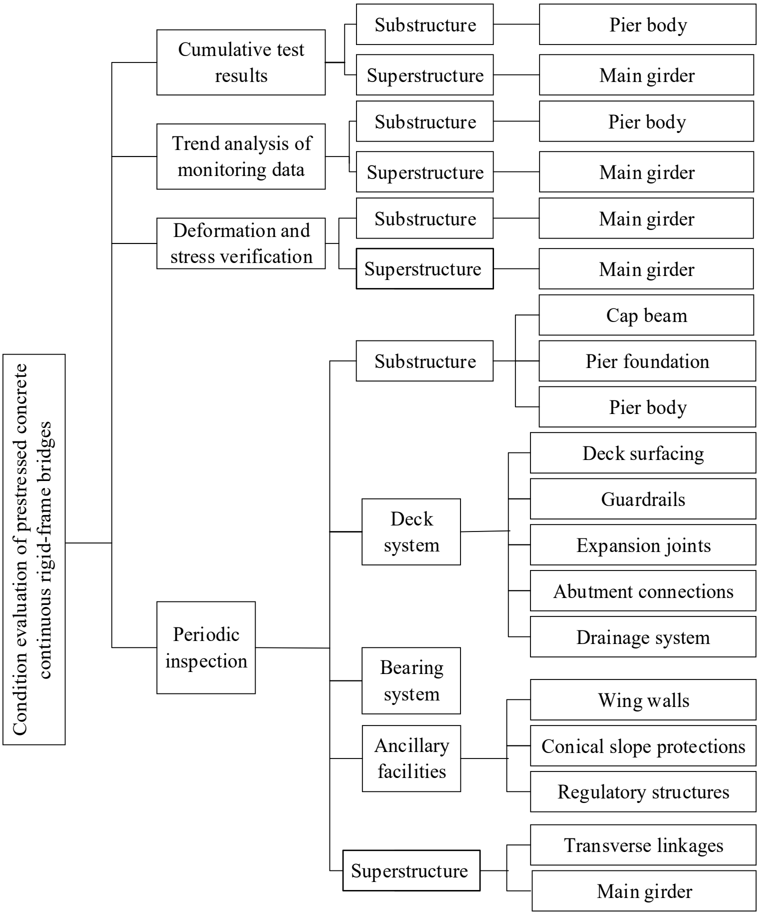

Fig. 3. AHP model based on four evaluation methods

4 Weight Calculation of Evaluation Indicators

The AHP is a method commonly used in multi-criteria decision analysis. Its basic steps are as follows:

(1) Construction of the hierarchical model: The bridge condition evaluation is divided into the objective layer, criterion layer, and indicator layer. The indicator set based on the hierarchical model is shown in Table 3. The weights for each layer need to be calculated separately. When calculating weights, the "1-9" scale method is used to compare pairs of indicators (as indicated by Table 4). Taking the first layer as an example, the top-level indicators consist of four factors, i.e., $D = \{A_1, A_2, A_3, A_4\}$. The influence of these four factors on the upper-level factor is calculated to determine their importance relative to a certain factor in the upper layer.

Table 3. Indicator set of the condition evaluation

Condition evaluation	Cumulative test results A_1	Superstructure B_1	Main girder C_1	/	/
		Substructure B_2	Pier body C_2	/	/
	Trend analysis of monitoring data A_2	Superstructure B_3	Main girder C_3	/	/
		Substructure B_4	Pier body C_4	/	/
	Deformation and stress verification A_3	Superstructure B_5	Main girder C_5	/	/
		Substructure B_6	Pier body C_6	/	/
	Ancillary facilities A_4	Superstructure B_7	Main girder C_7	Transverse linkages C_8	/
		Substructure B_8	Cap beam C_9	Pier body C_{10}	Pier foundation C_{11}
		Deck system B_9	Deck surfacing C_{12}	Guardrails C_{13}	Expansion joints C_{14}
			Abutment connections C_{15}	Drainage system C_{16}	/
		Bearing system B_{10}	/	/	/
		Ancillary facilities B_{11}	Wing walls C_{17}	Conical slope protections C_{18}	Regulatory structures C_{19}

(2) Construction of the judgment matrix: The "1-9 scale method" is used to compare the importance of each pair of indicators and construct a judgment matrix.

Table 4. Scale definitions

Scale	Definition
1	Two indicators have the same influence.
3	One indicator is slightly more important than the other.
5	One indicator is more important than the other.
7	One indicator is significantly more important than the other.
9	One indicator is more important than the other.
2, 4, 6, 8	Intermediate values exist between the odd-numbered scales.

Taking the condition assessment evaluation $\boldsymbol{D} = \{\boldsymbol{A_1}, \boldsymbol{A_2}, \boldsymbol{A_3}, \boldsymbol{A_4}\}$ as an example, a judgment matrix is established, as shown in Table 5.

Table 5. Judgment matrix of indicators

	A_1	A_2	A_3	A_4
A_1	1	a_1/a_2	a_1/a_3	a_1/a_4
A_2	a_2/a_1	1	a_2/a_3	a_2/a_4
A_3	a_3/a_1	a_3/a_2	1	a_3/a_4
A_4	a_4/a_1	a_4/a_2	a_4/a_3	1

where $a_{ij} = 1$ (when $i = j$), and $a_{ij} = 1/a_{ji}$.

(3) Calculation of weight vector: The weight of each evaluation indicator is calculated using the geometric mean method.

By inviting experts to score and judge each evaluation indicator factor, a judgment matrix between the evaluation method and the safety assessment objective is obtained.

$$D = \begin{bmatrix} 1 & 5 & 3 & 1 \\ 0.2 & 1 & 2 & 1/5 \\ 1/3 & 1/2 & 1 & 1/5 \\ 1 & 5 & 5 & 1 \end{bmatrix} \tag{5}$$

The weights are calculated using the geometric mean method, and a consistency check is performed on the judgment matrix.

$$D_i = \left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}} (i = 1,2, \dots n) \tag{6}$$

where $D = (1.96799, 0.53183, 0.427287, 2.236068)^T$.

After normalization, the weight vector is obtained.

$$DD = \frac{D}{\sum_{k=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}} (i = 1,2, \dots n) \tag{7}$$

where $DD = (0.38, 0.11, 0.09, 0.42)^T$.

(4) Consistency check: It aims to ensure the rationality of the judgment matrix.

Theoretically, once the judgment matrix is constructed, the weights of the factors can be calculated. However, due to the subjective nature of the process, even for experienced experts, a consistency check is necessary for the constructed judgment matrix to mitigate this issue.

Greatest characteristic root:

$$\lambda_{max} = \sum_{i=1}^{n} \frac{[aW_i]_j}{n(W_i)_j} = 4.1389 \tag{8}$$

Consistency indicator:

$$CI = \frac{\lambda_{max-n}}{n-1} = 0.0463 \tag{9}$$

Table 6. Random indicator (RI) values

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.14	1.45	1.49	1.51

From this, the consistency ratio (CR) of the judgment matrix M can be obtained, where the value of RI is retrieved from table 6.

$$CR = \frac{CI}{RI} = 0.051 < 0.1 \tag{10}$$

Therefore, the above matrix passes the consistency check and is usable.

(5) Comprehensive evaluation: Based on the weights of the evaluation indicators, the comprehensive score of the bridge condition is calculated. After verification, the weight results for each layer are shown in Table 7.

Table 7. Indicator weights

Top layer	Weight	Indicator layer	Weight	Bottom indicator layer	Weight	Bottom indicator layer	Weight
A_1	0.38	B_1	0.33	C_1	1	/	
		B_2	0.67	C_2	1	/	
A_2	0.11	B_3	0.33	C_3	1	/	
		B_4	0.67	C_4	1	/	
A_3	0.09	B_5	0.33	C_5	1	/	
		B_6	0.67	C_6	1	/	
A_4	0.42	B_7	0.31	C_7	0.58	C_8	0.42
		B_8	0.40	C_9	0.30	C_{10}	0.25
				C_{11}	0.45	/	/
		B_9	0.15	C_{12}	0.20	C_{13}	0.20
				C_{14}	0.20	C_{15}	0.20
				C_{16}	0.20		
		B_{10}	0.05	/			
		B_{11}	0.09	C_{17}	0.33	C_{18}	0.33
				C_{19}	0.34		

The specific implementation approach is designed based on two points:

(1) The real-time bridge evaluation results are calculated through weighted computation using the aforementioned four evaluation conclusions, with the following weights: I-38%, II-11%, III-9%, and IV-42%.

(2) After scoring using the above method, based on the theory of interval arithmetic, the score interval for the overall condition of the bridge is obtained through hierarchical weighting. Then, the grade membership function is used to determine the bridge's grade status.

The four evaluation methods are all classified into qualitative indicators such as "Class 1," "Class 2," "Class 3," "Class 4," and "Class 5." The advantage of this classification is that it eliminates the need for dimensionless processing of different underlying indicators. However, the disadvantage is that the underlying indicators are all qualitative, requiring conversion into a scoring system and summation of hierarchical weights. The final score is used to judge the category of the bridge's technical condition. The typical function form proposed by Professor Wang Guangyuan [8] is adopted to establish the membership of the bridge's service performance grade (as shown in figure 4).

Fig. 4. Grade membership function

Based on the aforementioned grade membership function, the score obtained is an interval, which requires interval arithmetic. Then, using the weight values calculated in the previous section, a weighted calculation is performed to obtain the comprehensive evaluation grade of the bridge. Only positive interval arithmetic is used here, so only addition and subtraction operations within positive intervals are considered. For two interval numbers, they are defined as M and N, respectively, where $M = [m^+, m^-]$, and $N = [n^+, n^-]$ $(m, n \geq 0)$. Thus,

$$M + N = [m^+ + n^+, m^- + n^-] \tag{11}$$

$$M - N = [m^+ - n^+, m^- - n^-] \tag{12}$$

5 Conclusion

Based on the results of this study, the following conclusions can be drawn:

(1) To achieve a comprehensive and systematic assessment of bridge condition, a method has been proposed that integrates cumulative test results, deformation and stress validation, monitoring data trend analysis and periodic inspection data. Using the Analytic Hierarchy Process (AHP), this approach overcomes the limitations of individual assessment methods and provides a hierarchical assessment framework.

(2) Based on the hierarchical framework, the weights at each level were calculated and validated through consistency checks, confirming the feasibility of this integrated multi-source data fusion analytical hierarchy method and increasing the scientific rigour and reliability of bridge condition assessment.

(3) Integrating real-time monitoring data with a hierarchical evaluation approach improves the accuracy and stability of bridge maintenance decisions. However, the applicability of this method is limited for bridges without long-term health monitoring

systems. Future research can focus on optimizing the evaluation index system and integrating machine learning techniques to further improve prediction accuracy, intelligent assessment and proactive infrastructure management, ultimately contributing to the long-term safety, durability and sustainability of bridge structures.

Acknowledgments

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References

1. Guo T, Li A, Li Z, and Han X (2004) Research progress on structural condition assessment methods for long-span bridges. J. Southeast Univ. (Nat. Sci. Ed.), 34(5).
2. Fabianowski D, Jakiel P, and Stemplewski S (2021) Development of artificial neural network for condition assessment of bridges based on hybrid decision-making method – feasibility study. Expert Syst. Appl.
3. Rogulj K, Kilić Pamuković J, and Jajac N (2021) Knowledge-based fuzzy expert system for the condition assessment of historic road bridges. Appl. Sci.
4. Darban S, Ghasemzadeh Tehrani H, Karballaeezadeh N, and Mosavi A (2021) Application of analytical hierarchy process for structural health monitoring and prioritizing of concrete bridges in Iran.
5. Sun J, Sun K, Gong L, Gu S, and Hao H (2022) Health assessment of foundation pit based on the fuzzy analytical hierarchy process. Adv. Civ. Eng.
6. Fu M, Liang Y, Feng Q, Wu B, and Tang G (2022) Research on the application of multi-source data analysis for bridge safety monitoring in the reconstruction and demolition process. Buildings.
7. Ministry of Transport of the People's Republic of China (2011) Technical condition evaluation standard for highway bridges: JTG/T H21-2011.
8. Wang G, and Tan D (1990) Stochastic fuzzy optimization design method for structures. In: Chinese Association of Systems Engineering (Ed.). Proceedings of the Fifth Annual Conference of the Fuzzy Mathematics and Fuzzy Systems Committee of the Chinese Association of Systems Engineering. Chinese Association of Systems Engineering, p. 3.