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Crane Safety Assessment Method Based on Entropy and Cumulative Prospect Theory

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Abstract: Assessing the safety status of cranes is an important problem. To overcome the inaccuracies and misjudgments in such assessments, this work describes a safety assessment method for cranes that combines entropy and cumulative prospect theory. Firstly, the proposed method transforms the set of evaluation indices into an evaluation vector. Secondly, a decision matrix is then constructed from the evaluation vectors and evaluation standards, and an entropy-based technique is applied to calculate the index weights. Thirdly, positive and negative prospect value matrices are established from reference points based on the positive and negative ideal solutions. Thus, this enables the crane safety grade to be determined according to the ranked comprehensive prospect values. Finally, the safety status of four general overhead traveling crane samples is evaluated to verify the rationality and feasibility of the proposed method. The results demonstrate that the method described in this paper can precisely and reasonably reflect the safety status of a crane.

Keywords: cumulative prospect theory; crane; safety evaluation; entropy

1. Introduction

Cranes, highly risky specialized pieces of equipment, are widely used in industrial and mining enterprises, real estate, ports, railway transportation, and construction [1]. Due to the risks associated with cranes, their safety problems have received widespread attention [2,3]. According to China's General Administration of Quality Supervision, Inspection and Quarantine, there were 2.1044 million registered cranes in China in 2015 [4]. Hence, problems influenced by factors such as service life, environmental impact, equipment failure, operator error, and inadequate training constitute a significant threat to human life and property. In 2015, 257 special equipment accidents were reported in China, killing 278 people and injuring 320. Crane accidents represented 30.74% of the total [4], and were responsible for 41.01% of all deaths [4], an increase of 27.42% and 16.32%, respectively, on the figures for 2014. Thus, crane safety has become the focus of occupational safety supervision in China, and crane safety assessments are emerging as an important means of preventing accidents and reducing the number of casualties.

There have been a number of studies on crane safety assessments. Xu and Jiang [5] studied a fuzzy analytic hierarchy process (FAHP) for determining the safety status of cranes, and Hu et al. [6] evaluated a safety classification for bridges and gantries based on FAHP. Zhao et al. [7] applied FAHP to evaluate the structural safety of shipbuilding cranes, while Xu and Li [8] constructed a three-scale analytic hierarchy process for assessing the hazard degree of the hoisting mechanism of a crawler crane. Chen and Zhang [9] developed a grey model for evaluating the safety of the gantry system in a portal crane. In reality, fuzzy evaluation methods are widely used because their mathematics is easy to understand and calculate. However, the maximum membership principle (MMP) of comprehensive fuzzy evaluations is not suitable for determining safety grades [10–12]. To overcome the limitations of

MMP, Yang et al. [13] used unascertained measurement theory (UMT) for crane safety assessments, but their assessment results were affected by the selection of confidence criteria. This is because higher confidence values give more conservative results. If lower confidence intervals are selected, the results may not be reliable. In addition, the above methods often use the analytic hierarchy process to calculate index weights, which cannot clearly reveal the potential information provided by each index value.

Intelligent assessment methods can avoid those shortages above. Intelligent assessment approaches based on machine learning, such as back-propagation artificial neural networks [14], fuzzy neural networks [15], and support vector machines [16], have been applied to crane safety evaluations, but these techniques depend on reliable and typical standard samples, which are often unavailable. Therefore, intelligent risk assessment approaches are rarely used in practice for crane safety assessments.

Via a study of the literature, there are three major limitations for crane safety assessment based on fuzzy evaluation approaches: (i) the existing crane safety studies are based on expected utility theory which assumes that people are completely rational. However, this theory has been queried by behavioral economists and psychologists using the Allais paradox and the Ellsberg paradox [17]. When assessing crane safety, the evaluators are not absolutely rational and the evaluation results are inevitably linked to the subjectivity of the evaluators. The risk attitude of evaluators should not be neglected; (ii) index weights are usually calculated by subjectively weighting method, which cannot sufficiently reflect the index evaluation value information itself; and (iii) crane safety grade is often determined on MMP or confidence criteria which may lead to unreasonable results.

Regarding to the aforementioned limitations, this work aims to propose a crane safety assessment model based on entropy and cumulative prospect theory. Entropy was originally introduced to information theory by Shannon [18], and has become a popular method for objective weight determination [19]. Proposed prospect theory [20] was proposed by Kahneman and Tversky. It later was developed into cumulative prospect theory (CPT) [21]. CPT states that decision-makers are not perfectly rational, but instead display a limited degree of rationality [22]. Other descriptive decision theories have been developed, such as disappointment theory [23,24], regret theory [25], and third-generation prospect theory [26]. However, CPT is regarded as one of the popular of these descriptive decision theories [27–30]. Advances by psychologists and behavioral economists mean that CPT provides a well-supported descriptive paradigm for decision-making based on bounded rationality [22]. Thus, CPT is an attractive alternative for improving the rationality of evaluation results. In this study, on one hand we are using entropy to obtain objective weights about the importance of crane risk factors, and on the other hand we are using cumulative prospect theory to determine the safety grade of the crane.

The remainder of this paper is organized as follows: In Section 2, the entropy method and CPT are briefly introduced. The proposed method for crane safety assessments, which combines the concepts of entropy and CPT, is presented in Section 3. Section 4 presents a case study in which the proposed method is used to assess the safety grade of a general overhead traveling crane. In Section 5, the results obtained from this case study are discussed and compared with those from other methods. Finally, Section 6 presents our conclusions.

2. Methodology

2.1. Entropy Method

In light of the basic principle of information theory, the degree of disorder in a system can be measured by the information entropy, which evaluates the amount of useful information in accordance with the objective data. If an attribute has higher information entropy with a lower variation in attribute value, it implies that such an attribute should be assigned a lower weight. In contrast, if an attribute possesses lower information entropy with a higher variation in attribute value, it should have a higher weight. Entropy has become an effective method for determining the objective weights [31–34]. Chen et al. [35] used entropy to calculate the objective weights in a risk index for a tower crane, and Wang et al. [36] determined the objective weights of water quality metrics in Meiliang Bay (part of Lake Taihu, China) by using an entropy-based method. Zou et al. [19] used an entropy approach to calculate weights for water quality assessment indicators, whereas Malekian and Azarnivand [37] integrated Shannon's entropy with the Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) technique to prioritize the flood risk in the Shemshak Watershed of Iran. Tian et al. [38] have used an entropy method to calculate factor weights and reduce the influence of subjective judgments on the weight coefficients.

The determination of weights based on entropy proceeds as follows:

Let $\boldsymbol{X}$ be a decision matrix with n alternatives and m attributes. $\boldsymbol{X}$ is expressed as:

$$\begin{gathered}\mathbf{X} = (x_{ij})_{n\times m} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \\ i = 1,2,\cdots,n;\ j = 1,2,\cdots,m\end{gathered} \tag{1}$$

where x_{ij} is the assessed value of the ith alternative to the jth attribute.

The normalized value r_{ij} of an attribute can be calculated by:

$$\begin{gathered}r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \\ j = 1,2,\cdots,m\end{gathered} \tag{2}$$

The entropy of the jth attribute can be expressed as:

$$\begin{gathered}H_j = -\frac{\sum_{i=1}^{n} r_{ij} \ln r_{ij}}{\ln n} \\ j = 1,2,\cdots,m\end{gathered} \tag{3}$$

The weight of the entropy of the jth attribute is calculated as:

$$w_j = \frac{1 - H_j}{m - \sum_{j=1}^{m} H_j} \tag{4}$$

where $0 \leq w_j \leq 1$ and $\sum_{j=1}^{m} w_j = 1$.

2.2. Cumulative Prospect Theory

CPT reflects the subjective attitude of the decision-maker toward risk [32]. It has been successfully applied to various decision problems that consider the decision maker's risk attitude. Cheng et al. [39] solved the problem of international entry decisions for construction firms using fuzzy preference relations and CPT, and Li et al. [40] proposed a method for trapezoidal intuitionistic fuzzy multiple attribute decision-making problems based on CPT and Dempster-Shafer theory. Lu and Jin [41] combined grey system theory and CPT for the selection of an optimal bus dispatching scheme, while Li et al. [42] determined the best alternative in an urban transit network using grey system theory and CPT.

CPT determines the utility of positive gains and negative losses with respect to a reference point. CPT assumes that people will select the alternative according to a comprehensive prospect value, which is calculated as [21,39,40]:

$$V_i = \sum_{j=1}^{m} v_{ij}{}^{+}\pi^{+}(\omega_j) + \sum_{j=1}^{m} v_{ij}{}^{-}\pi^{-}(\omega_j)\ , i = 1,\ 2,\ \ldots,\ n \tag{5}$$

where $v_{ij}{}^{+}$ and $v_{ij}{}^{-}$ represent positive and negative prospect values, respectively. $\pi^{+}(\omega_j)$ and $\pi^{-}(\omega_j)$ are the nonlinear weight functions of gains and losses. According to [21], $v_{ij}{}^{+}$ and $v_{ij}{}^{-}$ are calculated as:

$$v_{ij} = \begin{cases} v_{ij}{}^{+} = (\Delta x_i)^{\alpha}, & \Delta x \geq 0 \\ v_{ij}{}^{-} = -\theta(-\Delta x_i)^{\beta}, & \Delta x < 0 \end{cases} , i = 1,\ 2,\ \ldots,\ n \tag{6}$$

where Δx_i is the difference between x_i and the reference point x_0 [40], α and β are the exponent parameters, and θ is the loss aversion factor. We use $\alpha = \beta = 0.88$ and $\theta = 2.25$ [21]. Figure 1 shows the prospect value function with an asymmetric S-shape [20]. The value function reflects three behavioral principles which are reference dependence, loss aversion, and diminishing sensitivity.

(1) Reference dependence: The decision-maker normally perceives outcomes as gains or losses based on a reference point. Thus, the value function includes two parts: the gain domain and the loss domain.

(2) Loss aversion: In accordance with Figure 1, the value function is steeper in the loss domain than in the gain domain. This indicates that the decision maker is more sensitive to losses than to absolutely corresponding gains.

(3) Diminishing sensitivity: when faced with gains, the decision-makers exhibit risk-averse tendency. When faced with losses, they exhibit risk-seeking tendency.

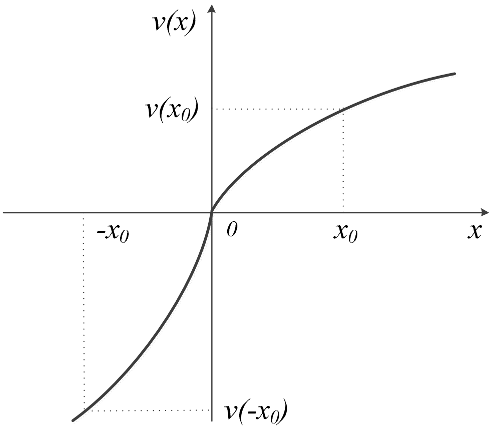

Figure 1. The shape of value function.

The prospect weight function of gains and losses can be expressed as [21]:

$$\pi(\omega_j) = \begin{cases} \pi^{+}(\omega_j) = \dfrac{\omega_j{}^{\gamma^{+}}}{\left[\omega_j{}^{\gamma^{+}} + (1-\omega_j)^{\gamma^{+}}\right]^{\frac{1}{\gamma^{+}}}} \\ \pi^{-}(\omega_j) = \dfrac{\omega_j{}^{\gamma^{-}}}{\left[\omega_j{}^{\gamma^{-}} + (1-\omega_j)^{\gamma^{-}}\right]^{\frac{1}{\gamma^{-}}}} \end{cases} , j = 1,\ 2,\ \ldots,\ m \tag{7}$$

where γ^{+} and γ^{-} are model parameters and ω_j is the weight of the index. We set $\gamma^{+} = 0.61$ and $\gamma^{-} = 0.69$ [21].

3. Method for Crane Safety Assessment

The proposed method for crane safety assessment, composed of entropy and CPT, has three stages: (1) problem description; (2) objective weights calculation with entropy; (3) determine crane safety grade with CPT. In the first stage, crane evaluation indices and standard are determined. Then experts' options for indexes are collected. Finally, the evaluation vector is established. In the second stage, indices used in crane safety assessment are assigned weights with entropy. In the third stage, overall prospect values for cranes are ranked and the safety grade can be determined by using CPT. The procedure of the proposed approach for crane safety assessment is provided in Figure 2. The proposed method for crane safety assessment is as follows.

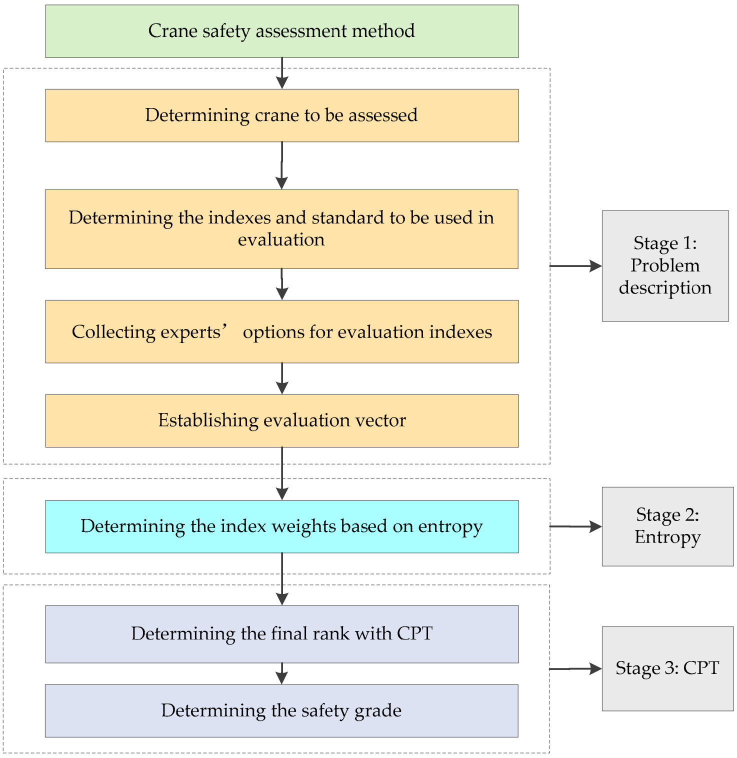

Figure 2. The flowchart of the proposed method.

3.1. Establish Evaluation Vector

This process transforms the evaluation matrix of various criteria into an evaluation vector. Let the crane safety grade variable be h ($h = 1, 2, \ldots, c$). Using expert judgments for the evaluation indices, the evaluation matrix $\mathbf{Q}$ is obtained as:

$$\mathbf{Q} = q_{(jh)} = \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1c} \\ q_{21} & q_{22} & \cdots & q_{2c} \\ \vdots & \vdots & \vdots & \vdots \\ q_{m1} & q_{m2} & \cdots & q_{mc} \end{bmatrix} \tag{8}$$

$$j = 1, 2, \cdots, m;\ h = 1, 2, \cdots, c;\ q_{ih} = \frac{n}{N}$$

where q_{jh} is the probability of index j with respect to grade h, n is the number of experts who assigned grade h to index j, and N is the number of experts.

The evaluation vector of these indexes can be described as:

$$\mathbf{U} = \mathbf{N}_{c\times 1}{}^{\mathrm{T}}\mathbf{Q}_{m\times c}{}^{\mathrm{T}} \tag{9}$$

where $\boldsymbol{N}_{c\times 1}$ consists of median values of the standard interval scores. $\boldsymbol{Q}_{m\times c}$ is the evaluation matrix formulated by the experts.

3.2. Determine the Index Weight

For comparison with assessment standards, a decision matrix $\boldsymbol{X}$ is established. The matrix $\boldsymbol{X}$ consists of the lower limits of standard index scores and the crane scores to be evaluated. The weights of the indices can then be calculated by the entropy method introduced in Section 2.1.

3.3. Determine the Positive and Negative Prospect Value Matrices

Let the normalized decision-making matrix of X be denoted as R. The positive ideal solution (PIS) can be expressed as $\boldsymbol{S}^+ = (r_1^+, r_2^+, \ldots, r_m^+)$, and the negative ideal solution (NIS) can be expressed as $\boldsymbol{S}^- = (r_1^-, r_2^-, \ldots, r_m^-)$. CPT assumes that a person's attitude toward gains and losses is different. When faced with gains, people tend to be "risk averse". However, when faced with losses, they tend to be "risk seeking". CPT is based on a reference point that determines the degree of preference for one alternative over another. The PIS and NIS can be viewed as the reference points [42–44].

According to Equation (6), the positive prospect value matrix can be expressed as:

$$\mathbf{V}^+ = ({v_{ij}}^+)_{n\times m} = \begin{bmatrix} {v_{11}}^+ & {v_{12}}^+ & \cdots & {v_{1m}}^+ \\ {v_{21}}^+ & {v_{22}}^+ & \cdots & {v_{2m}}^+ \\ \vdots & \vdots & \vdots & \vdots \\ {v_{n1}}^+ & {v_{n2}}^+ & \cdots & {v_{nm}}^+ \end{bmatrix} \tag{10}$$

where ${v_{ij}}^+ = 0.88(r_{ij} - {r_j}^-)$; $i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$.

Similarly, the negative prospect value matrix can be expressed as:

$$\mathbf{V}^- = ({v_{ij}}^-)_{n\times m} = \begin{bmatrix} {v_{11}}^- & {v_{12}}^- & \cdots & {v_{1m}}^- \\ {v_{21}}^- & {v_{22}}^- & \cdots & {v_{2m}}^- \\ \vdots & \vdots & \vdots & \vdots \\ {v_{n1}}^- & {v_{n2}}^- & \cdots & {v_{nm}}^- \end{bmatrix} \tag{11}$$

where ${v_{ij}}^- = -2.25({r_j}^+ - r_{ij})^{0.88}$; $i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$.

3.4. Determine the Safety Grade

The overall prospect value V_i for each alternative is calculated by Equation (5). The safety grade of the crane can then be determined by ranking V_i for each alternative S_i.

4. Case Study

Cranes are widely used in industrial production processes. Crane safety problems are, therefore, a significant concern for numerous enterprises, as well as the Special Equipment Inspection Institute. Of the different types of cranes, general overhead cranes are commonly used and have a high accident rate [45,46]. Thus, to illustrate the proposed method, we determined the safety grade of a general overhead traveling crane. For comparison with the proposed model, sample data from four general overhead traveling cranes [5,13] are also examined. The index system includes four subsystems: portal frame (B1), hoisting mechanism (B2), operation mechanism (B3), and staff and management factors (B4). A total of 16 key criteria across these four subsystems [5,13] are used in the safety assessment of general overhead traveling cranes. These criteria are listed in Table 1. According to previous studies, the safety grades for general overhead traveling cranes were divided into four categories [5,6,13], i.e., very low, low, medium, and high risk, denoted as I, II, III, and IV, respectively. The grade standard is given in Table 2.

Table 1. Evaluation index system for a general overhead traveling crane.

Subsystem	Evaluation Indexes
Portal frame B1	Structure link C1 Cracks and distortion C2
Hoisting mechanism B2	Hoisting ropes C3 Pulley block C4 Hook C5 Brake C6 Hoisting drum C7 Safety device C8 Electrical equipment C9
Operation mechanism B3	Orbit C10 Wheel C11 Safety device C12 Electrical equipment C13
Stuff and management B4	Safety management C14 Personnel quality C15 Security assurance C16

Table 2. Safety grades for general overhead traveling crane.

Safety Grade	Score of Evaluation Indexes	Description of Safety State
I	$3.5 \leq u < 4$	Very low risk (In safety state)
II	$2.5 \leq u < 3.5$	Low risk (Most indexes are certified)
III	$1.5 \leq u < 2.5$	Medium risk (Most indexes are unqualified)
IV	$1 \leq u < 1.5$	High risk (Must stop using)

4.1. Establishing the Evaluation Vector

Ten experts were invited to judge the crane safety status according to Tables 1 and 2. The probability of every index with respect to grade h (h = I, II, III, IV) is presented in Table 3 [5,13]. For example, C1 of sample 1 was judged as belonging to grade I by two experts, to grade II by five experts, and to grade III by three experts. None of the experts judged this index as belonging to grade IV. Thus, the evaluation vector for this index can be written as (0.2, 0.5, 0.3, 0) [5]. The remaining indices were judged in a similar manner.

Table 3. Judgments given by experts.

Index	Sample 1				Sample 2				Sample 3				Sample 4			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
C1	0.2	0.5	0.3	0	0.1	0.2	0.4	0.3	0.2	0.3	0.3	0.2	0.2	0.3	0.3	0.2
C2	0.5	0.3	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.2	0.3	0.2	0.5	0.2	0.3	0
C3	0	0.2	0.4	0.4	0	0.2	0.3	0.5	0.1	0.2	0.3	0.4	0.2	0.3	0.2	0.3
C4	0.3	0.4	0.3	0	0.1	0.3	0.3	0.3	0.2	0.3	0.3	0.2	0.3	0.4	0.2	0.1
C5	0.1	0.5	0.4	0	0	0.3	0.4	0.3	0.2	0.3	0.2	0.3	0.2	0.4	0.3	0.1
C6	0.4	0.5	0.1	0	0.2	0.3	0.2	0.3	0.1	0.4	0.3	0.2	0.4	0.3	0.2	0.1
C7	0.6	0.2	0.1	0.1	0.2	0.2	0.1	0.5	0.3	0.2	0.3	0.2	0.3	0.3	0.2	0.2
C8	0.2	0.4	0.4	0	0.2	0.3	0.3	0.2	0.2	0.3	0.3	0.2	0.3	0.2	0.4	0.1
C9	0	0.2	0.5	0.3	0	0.2	0.4	0.4	0	0.4	0.2	0.4	0.4	0.2	0.3	0.1
C10	0.2	0.4	0.2	0.2	0.1	0.4	0.2	0.3	0.2	0.3	0.3	0.2	0.3	0.5	0.2	0
C11	0	0.2	0.7	0.1	0	0.2	0.4	0.4	0	0.3	0.3	0.4	0.3	0.3	0.2	0.2
C12	0.1	0.1	0.8	0	0.1	0.2	0.4	0.3	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.2
C13	0.3	0.5	0.2	0	0.2	0.4	0.2	0.2	0.2	0.3	0.3	0.2	0.4	0.3	0.2	0.1
C14	0.3	0.4	0.2	0.1	0.2	0.3	0.2	0.3	0.2	0.2	0.4	0.2	0.4	0.3	0.2	0.1
C15	0	0.1	0.6	0.3	0	0.1	0.4	0.5	0.2	0.2	0.4	0.2	0.3	0.3	0.2	0.2
C16	0.2	0.3	0.5	0	0.1	0.3	0.2	0.4	0.1	0.4	0.2	0.3	0.5	0	0.3	0.2

The judgments given by the experts for four general overhead traveling crane samples were defuzzified according to Equation (9) and Table 3. For example, the fuzzy assessment results for C1 of sample 1 were defuzzified as follows:

$$u_{c1} = 0.2 \times \frac{4+3.5}{2} + 0.5 \times \frac{3.5+2.5}{2} + 0.3 \times \frac{2.5+1.5}{2} + 0 \times \frac{1.5+1}{2} = 2.85$$

The other fuzzy assessment results were handled similarly. The defuzzified results for the four samples are presented in Table 4.

Table 4. Defuzzification for fuzzy assessment results of four samples.

Sample	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
1	2.85	3.10	1.90	2.93	2.68	3.20	3.18	2.75	1.98	2.60	2.13	2.28	3.03	2.85	1.88	2.65
2	2.15	2.33	1.83	2.25	2.08	2.43	2.18	2.50	1.90	2.35	1.90	2.15	2.60	2.43	1.73	2.18
3	2.50	2.58	2.08	2.50	2.43	2.43	2.58	2.50	2.10	2.50	2.00	2.33	2.50	2.40	2.40	2.35
4	2.50	3.08	2.43	2.85	2.68	2.93	2.68	2.65	2.83	3.03	2.68	2.68	2.93	2.93	2.68	2.73

4.2. Calculating the Weights of Evaluation Indexes

To reduce the effect of subjective judgments, the proposed model uses an entropy method to calculate the weights of indexes. According to Table 2, four typical crane samples were established based on the lower limits value of the standard evaluation index score interval. These are denoted by I#, II#, III#, and IV#. The decision matrix based on the evaluation standard and defuzzification values of the four crane samples were then obtained as:

$$\mathbf{X} = \begin{array}{cc} \begin{array}{cccccccccccccccc} \mathrm{C1} & \mathrm{C2} & \mathrm{C3} & \mathrm{C4} & \mathrm{C5} & \mathrm{C6} & \mathrm{C7} & \mathrm{C8} & \mathrm{C9} & \mathrm{C10} & \mathrm{C11} & \mathrm{C12} & \mathrm{C13} & \mathrm{C14} & \mathrm{C15} & \mathrm{C16} \end{array} & \\ \left[\begin{array}{cccccccccccccccc} 3.5 & 3.5 & 3.5 & 3.5 & 3.5 & 3.5 & 3.5 & 3.5 & 3.5 & 3.5 & 3.5 & 3.5 & 3.5 & 3.5 & 3.5 & 3.5 \\ 2.5 & 2.5 & 2.5 & 2.5 & 2.5 & 2.5 & 2.5 & 2.5 & 2.5 & 2.5 & 2.5 & 2.5 & 2.5 & 2.5 & 2.5 & 2.5 \\ 1.5 & 1.5 & 1.5 & 1.5 & 1.5 & 1.5 & 1.5 & 1.5 & 1.5 & 1.5 & 1.5 & 1.5 & 1.5 & 1.5 & 1.5 & 1.5 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 2.5 \\ 2.85 & 3.10 & 1.90 & 2.93 & 2.68 & 3.20 & 3.18 & 2.75 & 1.98 & 2.60 & 2.13 & 2.28 & 3.03 & 2.85 & 1.88 & 2.65 \\ 2.15 & 2.33 & 1.83 & 2.25 & 2.08 & 2.43 & 2.18 & 2.50 & 1.90 & 2.35 & 1.90 & 2.15 & 2.60 & 2.43 & 1.73 & 2.18 \\ 2.5 & 2.58 & 2.08 & 2.50 & 2.43 & 2.43 & 2.58 & 2.50 & 2.10 & 2.50 & 2.00 & 2.33 & 2.50 & 2.40 & 2.40 & 2.35 \\ 2.5 & 3.08 & 2.43 & 2.85 & 2.68 & 2.68 & 2.68 & 2.65 & 2.83 & 3.03 & 2.68 & 2.68 & 2.93 & 2.93 & 2.68 & 2.73 \end{array}\right] & \begin{array}{c} \# \\ \# \\ \# \\ \# \\ \mathrm{sample1} \\ \mathrm{sample2} \\ \mathrm{sample3} \\ \mathrm{sample4} \end{array} \end{array}$$

The normalized decision-making matrix was obtained using Equation (2) as:

$$\mathbf{R} = \begin{bmatrix} 0.5106 & 0.4811 & 0.5609 & 0.4961 & 0.5141 & 0.4836 & 0.4927 & 0.5008 & 0.5420 & 0.4977 & 0.5461 & 0.5266 & 0.4829 & 0.4944 & 0.5451 & 0.5133 \\ 0.3647 & 0.3436 & 0.4006 & 0.3544 & 0.3672 & 0.3454 & 0.3520 & 0.3577 & 0.3871 & 0.3555 & 0.3901 & 0.3761 & 0.3449 & 0.3531 & 0.3894 & 0.3666 \\ 0.2188 & 0.2062 & 0.2404 & 0.2126 & 0.2203 & 0.2072 & 0.2112 & 0.2146 & 0.2323 & 0.2133 & 0.2340 & 0.2257 & 0.2070 & 0.2119 & 0.2336 & 0.2200 \\ 0.1459 & 0.1374 & 0.1603 & 0.1417 & 0.1469 & 0.1382 & 0.1408 & 0.1431 & 0.1549 & 0.1422 & 0.1560 & 0.1504 & 0.1380 & 0.1412 & 0.1558 & 0.1466 \\ 0.4157 & 0.4261 & 0.3045 & 0.4153 & 0.3937 & 0.4421 & 0.4477 & 0.3935 & 0.3066 & 0.3697 & 0.3323 & 0.3430 & 0.4181 & 0.4026 & 0.2928 & 0.3886 \\ 0.3136 & 0.3203 & 0.2933 & 0.3189 & 0.3055 & 0.3357 & 0.3069 & 0.3577 & 0.2942 & 0.3341 & 0.2964 & 0.3235 & 0.3587 & 0.3432 & 0.2695 & 0.3197 \\ 0.3647 & 0.3546 & 0.3333 & 0.3544 & 0.3569 & 0.3357 & 0.3632 & 0.3577 & 0.3252 & 0.3555 & 0.3120 & 0.3505 & 0.3449 & 0.3390 & 0.3738 & 0.3446 \\ 0.3647 & 0.4233 & 0.3894 & 0.4040 & 0.3937 & 0.4048 & 0.3773 & 0.3792 & 0.4383 & 0.4308 & 0.4181 & 0.4032 & 0.4043 & 0.4139 & 0.4174 & 0.4003 \end{bmatrix}$$

Equations (3) and (4) were then used to calculate the entropy weight of each index. To analyze the sensitivity of the assessment results to different weights, we also considered 16 subjective weights for general overhead traveling cranes [5]. The subjective and objective weights of general overhead traveling cranes are listed separately in Table 5.

Table 5. Weights of assessment indices.

Index	Subjective Weight Vector W_1 [5]	Objective Weight Vector W_2
C1	0.1190	0.0629
C2	0.0560	0.0619
C3	0.0726	0.0624
C4	0.0384	0.0626
C5	0.0861	0.0630
C6	0.0657	0.0620
C7	0.0384	0.0620
C8	0.0481	0.0633
C9	0.0588	0.0619
C10	0.0666	0.0627
C11	0.0503	0.0623
C12	0.0666	0.0632
C13	0.0586	0.0625
C14	0.0788	0.0627
C15	0.0350	0.0615
C16	0.0613	0.0631

4.3. Establishing Positive and Negative Prospect Matrices

According to the normalized decision-making matrix $\boldsymbol{R}$, the PIS and NIS were acquired as:

$$\boldsymbol{S}^{+} = (0.5106, 0.4811, 0.5609, 0.4961, 0.5141, 0.4836, 0.4927, 0.5008, 0.5420, 0.4977, 0.5461, 0.5266, 0.4289, 0.4944, 0.5451, 0.5133),$$

$$\boldsymbol{S}^{-} = (0.1459, 0.1374, 0.1603, 0.1417, 0.1469, 0.1382, 0.1408, 0.1431, 0.1549, 0.1422, 0.1560, 0.1504, 0.1380, 0.1412, 0.1558, 0.1466).$$

According to Equations (10) and (11), the positive and negative prospect matrices were then calculated as follows:

$$\mathbf{V}^{+} = \begin{bmatrix} 0.4116 & 0.3906 & 0.4471 & 0.4013 & 0.4141 & 0.3924 & 0.3989 & 0.4047 & 0.4338 & 0.4024 & 0.4367 & 0.4229 & 0.3919 & 0.4101 & 0.4361 & 0.4135 \\ 0.2626 & 0.2492 & 0.2852 & 0.2560 & 0.2642 & 0.2503 & 0.2545 & 0.2582 & 0.2768 & 0.2567 & 0.2786 & 0.2698 & 0.2500 & 0.2552 & 0.2782 & 0.2638 \\ 0.0999 & 0.0948 & 0.1085 & 0.0974 & 0.1005 & 0.0952 & 0.0968 & 0.0982 & 0.1053 & 0.0976 & 0.1059 & 0.1026 & 0.0951 & 0.0971 & 0.1058 & 0.1003 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.3158 & 0.3351 & 0.1820 & 0.3196 & 0.2919 & 0.3507 & 0.3536 & 0.2957 & 0.1903 & 0.2717 & 0.2171 & 0.2347 & 0.3263 & 0.3070 & 0.1740 & 0.2869 \\ 0.2078 & 0.2242 & 0.1694 & 0.2181 & 0.1979 & 0.2400 & 0.2061 & 0.2582 & 0.1766 & 0.2340 & 0.1777 & 0.2136 & 0.2646 & 0.2447 & 0.1476 & 0.2136 \\ 0.2626 & 0.2608 & 0.2136 & 0.2560 & 0.2533 & 0.2400 & 0.2664 & 0.2582 & 0.2107 & 0.2567 & 0.1950 & 0.2427 & 0.2500 & 0.2402 & 0.2618 & 0.2404 \\ 0.2626 & 0.3322 & 0.2735 & 0.3079 & 0.2919 & 0.3125 & 0.2812 & 0.2808 & 0.3297 & 0.3351 & 0.3078 & 0.2981 & 0.3121 & 0.3186 & 0.3073 & 0.2991 \end{bmatrix}$$

$$\mathbf{V}^{-} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0.4315 & -0.3924 & -0.4492 & -0.4032 & -0.4160 & -0.3942 & -0.4008 & -0.4066 & -0.4358 & -0.4043 & -0.4387 & -0.4249 & -0.3937 & -0.4019 & -0.4381 & -0.4154 \\ -0.7610 & -0.7222 & -0.8266 & -0.7420 & -0.7657 & -0.7255 & -0.7376 & -0.7483 & -0.8021 & -0.7441 & -0.8074 & -0.7820 & -0.7246 & -0.7397 & -0.8062 & -0.7646 \\ -0.9261 & -0.8789 & -1.0060 & -0.9030 & -0.9318 & -0.8829 & -0.8976 & -0.9106 & -0.9761 & -0.9055 & -0.9826 & -0.9516 & -0.8819 & -0.9002 & -0.9811 & -0.9304 \\ -0.2830 & -0.1752 & -0.6793 & -0.2459 & -0.3494 & -0.1366 & -0.1470 & -0.3156 & -0.6300 & -0.3685 & -0.5788 & -0.5061 & -0.2026 & -0.2751 & -0.6697 & -0.3601 \\ -0.5385 & -0.4506 & -0.7053 & -0.4907 & -0.5664 & -0.4184 & -0.5117 & -0.4066 & -0.6591 & -0.4572 & -0.6635 & -0.5533 & -0.3589 & -0.4266 & -0.7240 & -0.5304 \\ -0.4135 & -0.3647 & -0.6115 & -0.4032 & -0.4416 & -0.4184 & -0.3724 & -0.4066 & -0.5860 & -0.4043 & -0.6268 & -0.4878 & -0.3937 & -0.4371 & -0.4764 & -0.4698 \\ -0.4135 & -0.1829 & -0.4767 & -0.2760 & -0.3494 & -0.2404 & -0.3366 & -0.3524 & -0.3064 & -0.2080 & -0.3684 & -0.3568 & -0.2401 & -0.2451 & -0.3679 & -0.3301 \end{bmatrix}$$

4.4. Determining the Safety Grade

The overall prospect values of the four crane samples were calculated using Equation (5). Finally, the safety grades were determined according to the overall prospect values V_i. The assessment results are given in Table 6.

Table 6. Safety grades of general overhead traveling cranes given by CPT.

Code	**Subjective Weight Vector W_1 [5]**			**Objective Weight Vector W_2**		
	Overall Prospect Value V_i	**Rank**	**Grade**	**Overall Prospect Value V_i**	**Rank**	**Grade**
1#	0.9596	1	I	0.9596	1	I
2#	−0.2246	4	II	–0.2271	4	II
3#	−1.3072	7	III	–1.3241	7	III
4#	−1.8742	8	IV	–1.8986	8	IV
1	−0.0927	3	II	–0.1006	3	II
2	−0.569	6	III	–0.5811	6	III
3	−0.356	5	III	–0.3589	5	III
4	0.060	2	II	0.0690	2	II

The safety grade of the crane based on the overall prospect value can be obtained from Table 6. Using the subjective weight vector $\boldsymbol{W}_1$, the overall prospect values V_i for the crane safety grades were found to be as follows:

Grade I: $V_i \geq 0.9596$.
Grade II: $-0.2271 \leq V_i < 0.9596$.
Grade III: $-1.3241 \leq V_i < -0.2271$.
Grade IV: $-1.89 \leq V_i < -1.3241$.

When we adopted the objective weight vector $\boldsymbol{W}_2$, the overall prospect values V_i for the crane safety grades were as follows:

Grade I: $V_i \geq 0.9596$.
Grade II: $-0.2246 \leq V_i < 0.9596$.
Grade III: $-1.3072 \leq V_i < -0.2246$.
Grade IV: $-1.8742 \leq V_i < -1.3072$.

The results in Table 6 indicate that, regardless of whether we use the subjective weight vector $\boldsymbol{W}_1$ or the objective weight vector $\boldsymbol{W}_2$, the safety grades and rankings are consistent. It can be concluded that the assessment results are not particularly sensitive to different weights.

5. Results and Discussion

To verify that crane safety assessment using a CPT-based method is rational for engineering applications, the results using the proposed model were compared with those given by FAHP [5], UMT [13], and the variable sets (VS) approach. The comparative results demonstrate that the CPT method is superior to FAHP and UMT. The results given by each method for the same four crane samples are presented in Table 7. The standard lower limits of each grade and the average values for the four samples are shown in Figure 3. When using objective weight vector $\boldsymbol{W}_2$, the inaccurate results are due to MMP of FAHP or the confidence criterion of UMT. The cause of error is similar with subjective weight vector $\boldsymbol{W}_1$, and the analysis and discussion are also similar. Thus, we omit a discussion of the results obtained by objective weight vector $\boldsymbol{W}_2$, and only analyze and discuss the results given by subjective weight vector $\boldsymbol{W}_1$.

Table 7. Comparisons of the evaluation results of different methods.

Sample	**Subjective Weight Vector W_1 [5]**					**Objective Weight Vector W_2**			
	***M* (FAHP, UMT, VS)**	**FAHP**	**UMT**	**VS**	**CPT**	**FAHP**	**UMT**	**VS**	**CPT**
1	(0.204, 0.347, 0.356, 0.093)	III	III	II	II	III	III	II	II
2	(0.104, 0.259, 0.301, 0.336)	IV	IV	III	III	IV	IV	III	III
3	(0.168, 0.284, 0.291, 0.258)	III	III	III	III	III	III	III	III
4	(0.322, 0.291, 0.248, 0.139)	I	III	II	II	I	III	II	II

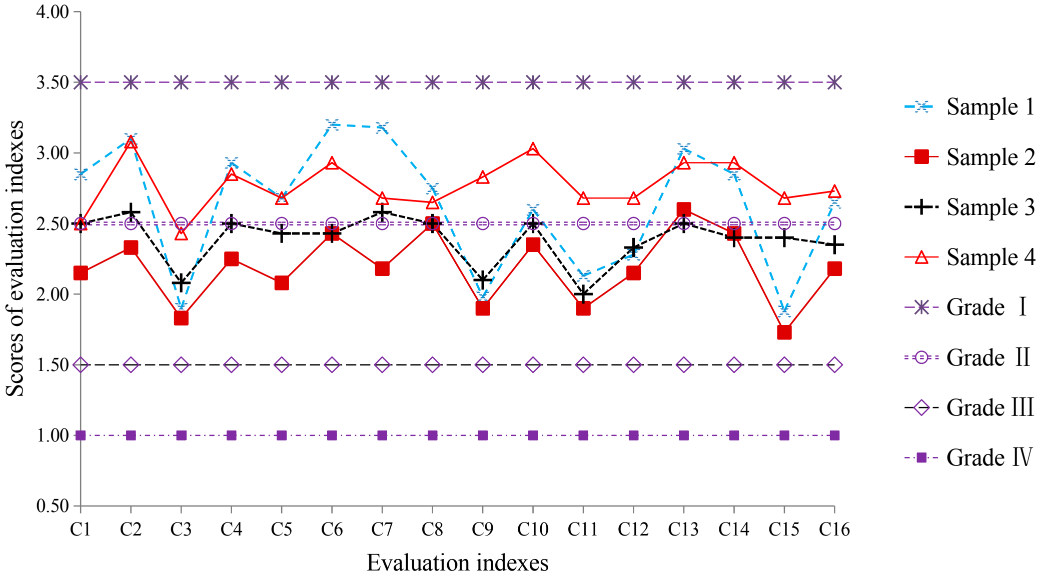

Figure 3. Average scores of sample evaluation indices.

5.1. Comparison and Analysis of the Crane Safety Grade Results Given by FAHP

Xu and Jiang [5] assessed sample 1 using the FAHP method. We calculated the other three samples using Xu's method. From Table 7, the crane safety grades given by FAHP are clearly different from those given by CPT. For example, sample 4 is assigned a safety grade of II by CPT and a grade of I by FAHP. We now analyze the reasonableness of these results.

According to Table 4, the mean value vector of the 16 indexes for sample 4 is $\boldsymbol{u}$ = (2.5, 3.08, 2.43, 2.85, 2.68, 2.93, 2.68, 2.65, 2.83, 3.03, 2.68, 2.68, 2.93, 2.93, 2.68, 2.73), whereas the standard index score range for grade 1 is $u \geq 3.5$. None of the 16 mean index values of sample 4 is greater than 3.5 (grade I), but the FAHP method determined sample 4 to be grade I. This is because FAHP determines the safety grade based on MMP. For instance, FAHP concludes that the crane safety is grade I based on the maximum relative membership degree of grade I crane safety being 0.322. It is clear from Table 7 that the fuzzy comprehensive evaluation value vector is $\boldsymbol{M}_4$ = (0.322, 0.291, 0.248, 0.139). Although the relative membership degree of crane safety is greatest for grade I, the sum of the relative membership degrees for grades II, III, and IV is larger than that of grade I. Hence, the assessment result given by FAHP is unreasonable. In fact, according to Table 4 or Figure 3, the average score of C3 for sample 4 is 2.43, which belongs to grade III, and the other 15 indexes have average sample scores in grade II. This strongly indicates that sample 4 should belong to grade II.

The method proposed in this paper determines the safety grade according to the ranking of the overall prospect values of samples and the lower limits of the evaluation standard. Regardless of whether we adopt subjective weights or objective weights, Table 6 indicates that the ranking order of the eight evaluation vectors is $V_{\mathrm{I}\#} > V_{\mathrm{sample4}} > V_{\mathrm{sample1}} > V_{\mathrm{II}\#} > V_{\mathrm{sample3}} > V_{\mathrm{sample2}} > V_{\mathrm{III}\#} > V_{\mathrm{IV}\#}$. It can be concluded that sample 4 should belong to grade II, and the result given by CPT is more reasonable than that of FAHP.

5.2. Comparison and Analysis of the Crane Safety Grade Results Given by UMT

Yang and Xu [13] assessed the same four samples using UMT and entropy weights (although the calculation of entropy weights in [13] is incorrect). We used the subjective weight vector $\boldsymbol{W}_1$ [5] to compare UMT with CPT. The crane safety grades given by UMT (Table 7) are clearly different from those calculated by CPT. For sample 2, CPT assigns a safety grade of II, whereas UMT categorizes this sample as grade IV. We now analyze the results from the UMT and CPT methods. For the same root problem as discussed at the start of this section, the cause of the errors is similar for both subjective weight vector $\boldsymbol{W}_1$ and objective weight vector $\boldsymbol{W}_2$. Thus, only sample 2 is examined in detail.

UMT uses a confidence criterion to determine safety grades. However, there is no rigorous approach for selecting the most appropriate confidence value λ. In general, the confidence range is $0.5 \leq \lambda \leq 0.7$, and λ is usually set as 0.6 or 0.7 [13,47]. We used a confidence value of $\lambda = 0.7$ [13] to determine the safety grade of sample 2. The fuzzy evaluation vector of sample 2 is $\boldsymbol{M}_2$ = (0.104, 0.259, 0.301, 0.336). Since 0.104 + 0.259 + 0.301 + 0.336 > 0.7, but 0.104 + 0.259 + 0.301 < 0.7, the crane safety grade of sample 2 is categorized as grade IV. However, according to Table 4 or Figure 3, the mean value vector of the 16 indexes of sample 2 is $\boldsymbol{u}$ = (2.15, 2.33, 1.83, 2.25, 2.08, 2.43, 2.18, 2.50, 1.90, 2.35, 1.90, 2.15, 2.60, 2.43, 1.73, 2.18), and the index standard score range of grade 4 is $1 \leq u < 1.5$. None of the 16 mean index values of sample 2 is between 1 and 1.5 (grade IV), but the UMT method determined sample 2 to be in grade IV. Clearly, this result exaggerates the risk of sample 2.

No matter whether we adopt subjective weights or objective weights, it can be concluded that sample 2 should belong to grade III. Only the mean value of index C13 in sample 2 is in grade II, with the other 15 indexes in grade III. Thus, the grade III result given by CPT is more reasonable than the UMT determination. For the same reason, the grade III result for sample 1 [5,13] given by FAHP and UMT is unreasonable. The safety grade for sample 1 should be grade II, as obtained by CPT (Table 7). The grades given by FAHP and UMT for sample 3 are correct and match the grade assigned by the CPT method, but this is purely coincidence.

In addition, the proposed assessment method can easily compare cranes that have the same grade. For instance, sample 1 and sample 4 both have safety grade II (Table 6). According to the CPT method proposed in this paper, the overall prospect value of $V_{\text{sample4}} > V_{\text{sample1}}$, which implies that the safety state of sample 4 is better than that of sample 1. Similarly, both samples 2 and 3 are in safety grade III. As $V_{\text{sample3}} > V_{\text{sample2}}$, the safety state of sample 3 is better than that of sample 2. The above analysis verifies that the safety assessment results determined by the proposed method are reasonable and accurate.

5.3. Comparison and Analysis of the Crane Safety Grade Results Given by VS

The VS assessment method avoids some of the limitations of MMP that may result in unreasonable assessments [34,48]. According to VS, the grade characteristic value H [49] of a sample can be calculated as:

$$H = (1, 2, 3, 4) \cdot \mathbf{M}' \tag{12}$$

where 1, 2, 3, 4 correspond to safety grades I, II, III, and IV. $\mathbf{M}' = (m_1\ m_2\ m_3\ m_4)'$ is the fuzzy comprehensive evaluation vector of the four safety grades.

Based on the standards of the four grades, the grade identification rule [50] is as follows:

$$\begin{cases} 1 < H(x) \leq 1.5 \\ \text{it belongs to grade } 1(\text{I}); \\ 1.5 < H(x) \leq 2.5 \\ \text{it belongs to grade } 2(\text{II}); \\ 2.5 < H(x) \leq 3.5 \\ \text{it belongs to grade } 3(\text{III}); \\ 3.5 < H(x) \leq 4 \\ \text{it belongs to grade } 4(\text{IV}). \end{cases} \tag{13}$$

Let us consider sample 1 with subjective weight vector $\boldsymbol{W}_1$. As $\boldsymbol{M}_1$ = (0.204, 0.347, 0.356, 0.093) [5,13] (see Table 7), the safety grade of sample 1 can be determined using Equation (12) as:

$$H_1 = (0.204 \times 1) + (0.347 \times 2) + (0.356 \times 3) + (0.093 \times 4) = 2.338$$

Using Equation (13), it can be concluded that sample 1 belongs to grade II. The assessment results for the other samples given by VS are listed in Table 7. From Table 7, our results suggest that samples 1 and 4 can be classified as grade II. The samples 2 and 3 can be classified as grade III. It is clear that the results obtained by CPT are completely consistent with those given by VS. It is anticipated that the proposed method will become a feasible approach for crane safety assessment.

In this paper, we focus on developing a novel crane safety assessment approach. Compared with FAHP, UMT, and VS, the advantages of the proposed method are summarized as follows:

(1) FAHP, UMT, and VS based on expected utility theory assume the evaluators are totally rational. Thus, they fail to consider the evaluators' behavior and psychological factors in crane safety assessment process. The proposed method is based on 'bounded rationality' using CPT. It fully considers the evaluators' bounded rationality and incorporates the evaluators' behavior and psychological factors into crane safety assessment.

(2) Compared with the traditional crane safety assessment method, the proposed approach obtains index weights based on entropy which fully utilizes information provided by evaluation index values. Thus, subjective errors on crane safety assessment can be avoided as far as possible.

(3) FAHP and UMT use MMP and confidence criteria to determine crane safety grade. However, both of them may cause unreasonable results. The proposed method determines crane safety grade by ranking overall prospect values. It avoids the limitations of MMP and confidence criteria. In crane safety assessment, there are a large number of fuzzy and uncertain information. In this situation, the risk attitude of evaluators should be considered. However, VS method cannot deal with this complex situation. Although this case gives the same results for these two methods, the proposed method is more reasonable and appropriate to this situation. Therefore, the results obtained in this paper are acceptable.

6. Conclusions

Crane safety assessment is a significant issue affecting people's lives and property. The safety grade of a crane should be reasonably evaluated with respect to different attributes. However, the accuracy of the evaluation results is affected by MMP (FAHP) and confidence criteria (UMT). Therefore, a more scientific and reasonable method is needed for crane safety assessments.

This work proposed a method for crane safety assessments using CPT and entropy. Entropy was used to calculate index weights, and CPT was applied to calculate the overall prospect values. The safety grade was then identified according to the ranking of the overall prospect values. A case study demonstrated that the proposed method is suitable for crane safety assessments. The assessment results can help to identify the safety state of crane equipment, allowing effective measures to be taken to improve its security and reliability. Therefore, the method proposed in this paper has real practical value.

Through a comparative study, it was found that the existing crane safety grades given by FAHP methods may be inaccurate as a result of the improper use of MMP. In addition, the UMT method may exaggerate the risk, which will affect the decision-making process. Compared with the assessment results given by FAHP and UMT, the proposed method generates precise and reasonable evaluations of the crane safety grade. In addition, the proposed method can also compare the safety state of different cranes that have the same safety grade. Thus, the proposed method is superior to both FAHP and UMT methods, and provides an alternative for evaluating crane safety. Compared with VS method, the main advantage of the proposed method is that it considers the evaluators' behavior factor.

Although the method proposed in this study was applied to a crane safety grade assessment, it could also be used in other fields, such as flood classification, slope stability evaluation, and other risk assessment problems. Since subjective and objective weighting methods have both advantages and disadvantages, an integrated weighting method may provide a more scientific means of assigning weights and highlighting the importance of each index to crane safety. In future work, if an advanced combined weighting model could be coupled with CPT, the reliability and rationality of the crane evaluation results may be further improved. Moreover, measures of crane safety criteria and the weights of the criteria may not be precisely determined by elevators. Thus, applications of fuzzy numbers for describing criteria values and weights can also be considered as part for future research prospects.

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