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Research on Safety Assessment Methods for Lifting Machinery Based on Semi-Quantitative Risk Theory

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Abstract: *Based on the semi-quantitative risk theory, this paper establishes a safety evaluation system tailored to lifting machinery and develops a corresponding safety assessment software system. By comprehensively identifying hazards, defining the weights of influencing factors, and constructing a standardized algorithm model, the system enables a thorough assessment of safety risks associated with lifting machinery. This safety evaluation system and software provide a scientific basis for the safety management of lifting machinery, helping to prevent accidents, enhance the safety and operational reliability of lifting equipment, safeguard the well-being of operators, and improve the overall efficiency of equipment utilization.*

Keywords: *Semi-Quantitative Risk Theory, Lifting Machinery, Safety Evaluation*

1. Introduction

With the continuous development of China's economy, lifting machinery has become a fundamental component in industries such as nuclear power, aerospace, shipbuilding, municipal engineering, transportation, and petrochemicals. The number of lifting machines and their geographical distribution are growing rapidly. However, frequent accidents involving lifting operations have resulted in a high casualty rate, with accident rates reaching approximately 25%. Moreover, fatalities caused by lifting machinery accidents rank first among all types of mechanical accidents annually [1-2]. Therefore, strengthening the safety management of lifting machinery and preventing accidents has become an urgent priority.

Currently, the statutory periodic inspection system is widely adopted to ensure the safe operation of lifting machinery and prevent accidents. While this system provides a basic safeguard for equipment safety to some extent, it has notable limitations. Due to its fixed inspection items and intervals, the system fails to account for variations among enterprises and individual equipment. As a result, general equipment may undergo excessive inspections, while high-risk equipment might be inadequately inspected. To address these issues, this paper proposes a safety evaluation system for lifting machinery based on the semi-quantitative risk theory.

Risk assessment involves evaluating the safety or hazard level of a system based on system identification and safety analysis, following relevant standards, regulations, and safety indicators. The goal is to classify the degree of risk and propose safety measures to control system hazards, considering the current level of scientific and technological development as well as economic conditions. Current safety evaluation methods for lifting machinery are mainly categorized into three types: qualitative, quantitative, and semi-quantitative approaches, also referred to as experience-based risk assessment, probabilistic risk assessment, and relative risk assessment, respectively [3-5].

In recent years, substantial progress has been made in the field of safety evaluation for lifting machinery, indicating increased attention to safety concerns across various sectors in China. Hu Jingbo [6] provided a detailed analysis of a crane safety monitoring platform architecture based on industrial big data, addressing challenges in platform construction from multiple perspectives, such as data sources, collection technologies, preprocessing, storage, analysis, mining, platform architecture, and software implementation. Huang Jian [7] designed an IoT-based information platform for special equipment, targeting the phenomenon of high-frequency data transitions in traditional platforms. These

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developments highlight the continuous progress in the construction of digital platforms for special equipment in China.

Dow Chemical Company in the United States introduced the Dow Fire and Explosion Index, a classic quantitative tool for assessing the hazard level of chemical production systems. By evaluating fire and explosion indices, this method accurately reflects the safety status of hazardous chemical production facilities and predicts potential economic losses. In the 1990s, Fault Tree Analysis (FTA) technology underwent further advancements, including the development of dynamic fault tree analysis [8-9], the introduction of binary decision diagram (BDD) methods to improve computational efficiency for complex systems [10-11], and its application in reliability and safety analysis of software systems. These methods continue to evolve and improve.

Currently, both domestic and international scholars have conducted in-depth studies on various risk assessment methods within their respective research fields. However, most of these methods are limited to specific scenarios and environments, with reduced applicability to other contexts. In China, the safety of lifting machinery primarily relies on a "periodic maintenance and post-incident repair" model managed by maintenance units, supplemented by periodic regulatory inspections. However, for large-scale lifting machinery, there is still a lack of structural health monitoring and safety early warning technologies. Therefore, this paper focuses on developing a safety evaluation system for lifting machinery based on the semi-quantitative risk theory and designing corresponding safety assessment software.

2. Influencing Factors and Weightings

Lifting machinery encompasses a wide variety of types, with significant differences in structural designs, operating principles, stress conditions, and working environments. Therefore, to develop a safety risk evaluation model applicable to all types of lifting machinery, it is essential to begin by studying the influencing factors.

The LEC safety evaluation method is a semi-quantitative approach used to assess hazards in potentially dangerous working environments. It evaluates the risks and hazards faced by personnel operating in such environments. This method calculates a risk value, D, which is determined by the product of three risk-related factor indicators:

$$D = L \times E \times C$$

In the formula:

L — the likelihood of an accident occurring;

E — the frequency of human exposure to the hazardous environment;

C — the consequences resulting from an accident, should one occur);

D — the level of risk.

3. Research on the algorithm model of safety assessment

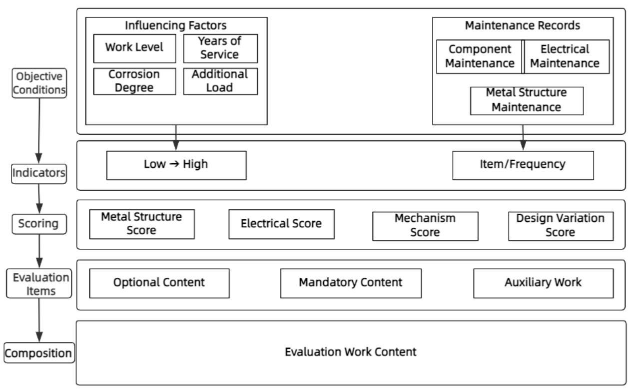

Figure 1: Diagram of the Standardized Algorithm Model for Evaluation Items

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The overall framework of the standardized algorithm model for the safety assessment of lifting machinery in this paper is shown in Figure 1. Based on the macro inspection of the factory design data, daily use and maintenance records of the user unit, on-site environment and appearance, the scoring standards for the influencing factors and their weights of lifting machinery are defined. This section mainly quantifies the influencing factors and weight distribution of each assessment unit sub-item such as metal structure, mechanism, electrical system, design difference and other modules, calculates the risk level, and then combines the algorithm model to derive the score domain of each module, which can automatically match the optional assessment content items, and establish an accurate and scientific standardized algorithm model for the safety assessment project of lifting machinery in combination with the auxiliary work of the required content and customer needs.

3.1 Metal Structure Analysis

In the scoring process for the metal structure module, four key influencing factors are primarily considered: fatigue level, service life, degree of corrosion, and wind load. The fatigue level is determined by comparing the design working grade with the actual working grade, and the corresponding score is calculated using an appropriate algorithm.

Before establishing the assessment items for a specific crane, basic information parameters such as service life and degree of corrosion can be input based on the actual condition of the assessment object. This allows for the determination of the risk levels for the influencing factors within the metal structure module. The total score for the metal structure is calculated as:

Metal Structure Score = Working Grade Risk Level + Service Life Level + Corrosion Level + Additional Load Level.

3.2 Electrical Scoring

Based on the daily maintenance and repair records of the assessed object, the electrical module is evaluated in terms of fault frequency and maintenance status. If maintenance records are missing, external inspections and tests are conducted to verify the effectiveness of components such as electrical wiring for aging, emergency stop switches, and overload protection devices. Similarly, scores are assigned according to the electrical score to determine whether further electrical testing or circuit analysis is necessary. For details, refer to Table 1.

Table 1 Electrical Scoring

Score		Service life		
		<5 years	5~10 years	>10 years
Electrical Maintenance Status	NA	Low Score	Low Score	Medium Score
	Occasional	Low Score	Medium Score	High Score
	Often	Medium Score	High Score	High Score

3.3 Mechanism Scoring

The mechanisms of lifting machinery include hoisting mechanisms, traveling mechanisms, luffing mechanisms, and slewing mechanisms, each consisting of various components and safety protection devices. Similarly, the mechanism score is determined based on the working grade and service life. If the score falls within the high-score range, vibration monitoring is required, as shown in Table 2.

Table 2 Mechanism Scoring

Score		Service Life		
		<5 years	5~10 years	>10 years
Working Grade	Light	Low Score	Low Score	Medium Score
	Medium	Low Score	Medium Score	High Score
	Heavy	Medium Score	High Score	High Score

3.4 Design Variation Scoring

In this study, the scoring of the design variation module is based on the evaluation of the repair content and frequency related to the metal structure, as shown in Table 3. In particular, if changes to structural dimensions, such as span, result in altered stress points, leading to situations like weld cracking and subsequent repair welding. It is necessary to conduct material analysis and finite element

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analysis.

Table 3 Design Variation Scoring

Score		Maintenance frequency		
		Rarely	Occasionally	Frequently
Repair Content	Bolt Loosening	Low Score	Low Score	Medium Score
	Weld Cracking	Low Score	Medium Score	High Score
	Structural Changes	Medium Score	High Score	High Score

3.5 Nondestructive Testing of Wire Ropes and Rail Measurement Evaluation

By performing a macroscopic inspection of surface defects on the wire rope (such as broken wires on the surface, birdcaging, bending, or flattening) and considering its service life, it can be determined whether nondestructive testing of the wire rope is necessary.

Similarly, through no-load operation tests, issues such as rail gnawing or abnormal noise can be identified. Additionally, by inspecting the degree of rail wear, it can be determined whether further measurements of rail parameters, such as height difference, straightness, and gauge are required for rail evaluation.

3.6 Mandatory Content and Auxiliary Tasks

The core content of the assessment work includes inspecting the surrounding environment of the evaluated object, conducting an external appearance review, and performing load capacity testing. Auxiliary tasks include surface grinding, paint touch-ups, preparation of equipment for working at height, the use of drones, and the allocation of support personnel. All of these must be discussed and confirmed in detail with the evaluation unit based on the specific requirements of the assessment.

4. Comparison and Validation of Safety Assessment Methods

In this study, a safety assessment management platform was utilized, with reference to the methods and procedures outlined in "Condition Monitoring and Safety Assessment of Gantry Cranes in Hydropower Stations" and "Safety Evaluation of Gates in Xin'anjiang Hydropower Station." The safety assessment was conducted on the old gantry crane, and the accuracy of the evaluation was verified through on-site inspections.

Using the algorithmic model developed for this project, the scores for each assessment unit were calculated and categorized, as shown in Table 4. The results suggested that the assessment should focus on thickness measurement, non-destructive testing, electrical testing, and vibration testing. The client's requested assessment scope for this project included thickness measurement, non-destructive testing, vibration testing, finite element analysis, and comprehensive electrical testing. A comparison with the actual assessment results indicates that the recommended evaluation content closely aligns with the client's requirements.

The assessment results are as follows:

The thickness of the main girder web has decreased by approximately 10% compared to its design thickness; Ultrasonic testing detected five internal micro-cracks; Stress distribution was found to be satisfactory; Electrical testing identified two contactor pull-in faults; Finite element analysis revealed no structural defects.

Table 4 Example of Comparison

Assessment Unit	Score Range	Recommended Assessment Items (Software)	Actual Assessment Items
Metal Structure	Medium	Thickness Measurement, Non-Destructive Testing	Thickness Measurement, Non-Destructive Testing
Electrical Systems	Medium	Electrical Testing	Electrical Testing
Mechanisms	High	Vibration Testing	Vibration Testing
Design Deviations	Low	-	Finite Element Analysis
Wire Rope	2 years	-	-
Rail	No Rail Wear Observed	-	-

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5. Conclusion

This study conducts an in-depth exploration of safety assessment for lifting machinery based on semi-quantitative risk theory.

(1) A comprehensive review of various hazard sources for lifting machinery was conducted, leading to the development of a multi-faceted hazard source database. This database incorporates factors such as the equipment itself, emergency incidents, operational practices of the user unit, and personnel safety measures. Detailed equipment information was collected to establish corresponding evidence for identified hazards. Additionally, a reasonable scoring model was used to quantitatively analyze influencing factors such as workload levels and service life, laying a solid foundation for assessment. Based on this groundwork, the LEC method was employed to study the weight of influencing factors. After repeated testing and adjustments, standard values were determined, improving the accuracy of the assessment algorithm model.

(2) A robust standardized algorithmic framework was developed to calculate risk levels for sub-projects under assessment units, including metal structures, electrical systems, mechanisms, and design deviations. For each sub-project, scores were quantified based on specific influencing factors and their weight distributions. For example, metal structures were assessed based on fatigue and service life, electrical systems were evaluated based on maintenance and repair conditions, mechanisms were analyzed by combining workload levels and service life, and design deviations were assessed based on repair content and frequency. Auxiliary aspects, such as wire rope testing and rail measurements, were also incorporated into the framework. This systematic model integrates essential and supplementary evaluation tasks, providing strong support for safety assessment practices.

(3) The application of this safety assessment system and software was validated through a case study of the old gantry crane at the Xin'anjiang Hydropower Plant. Compared with traditional methods and on-site inspections, the proposed method’s recommended assessment items aligned closely with actual needs. It accurately identified issues such as changes in the thickness of the main girder web, internal cracks, and electrical faults, demonstrating its effectiveness and practicality. The results confirm that this method can provide a scientific basis for the safety management of lifting machinery, aiding in accident prevention and enhancing safe operation. However, further research is needed to address aspects such as work environments and safety management practices, to continuously improve the safety assurance system for lifting machinery.

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