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RESEARCH ARTICLE

Development of a Hoisting Safety Risk Framework Based on the STAMP Theory and PLS-SEM Method

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ABSTRACT Hoisting is essential for large-scale construction projects, including urban viaducts, high-rise buildings, and undersea tunnels. However, this critical process is subject to frequent safety accidents in China, which result in many casualties and asset losses. The lack of a practical risk framework has contributed to poor safety management in this field. Most of the limited risk frameworks in this field focus only on the direct causes leading to accidents, ignoring the systematic and complex nature of lifting risks. In this study, a new risk framework for lifting is constructed by combining the STAMP (Systems-Theoretic Accident Model and Processes) theory and the quantitative analysis capability of the PLS-SEM (Partial Least Squares Structural Equation Modeling) to effectively identify, assess, and manage various potential risks in the lifting construction process. The factors were then analyzed for importance through the independence weight coefficient method. The study found that "Failure to conduct pre-operational inspections of lifting equipment and rigging components," "Physical or mental impairment of operators, such as intoxication or distraction," and "The hoisting program was not prepared under the actual working conditions at the project site and did not adequately plan for emergencies," were the factors with the top 3 highest weight. Ultimately, the framework is validated by 200 real cases from 2019 to 2024 in China. This proposed STAMP-HC framework can accurately identify the risk transfer paths in accidents, and the results of risk factor weighting can also provide a reference for risk management, with the potential to be extended to other countries.

INDEX TERMS Hoisting, partial least squares structural equation modeling (PLS-SEM), risk framework, safety management, systems-theoretic accident model and processes (STAMP), independence weight coefficient method (IWCM).

I. INTRODUCTION

Construction safety has always plagued China's construction industry with various types of accidents, commonly including but not limited to falls from height, object strikes, mechanical accidents, electrocution, structural collapses, hazardous chemical leaks, fires and explosions, heat stress, and heat stroke [1]. Construction-related deaths in the United States of America (USA) increased by 11% between 2021 and 2022, with about 1% of construction workers experiencing fatal injuries each year, the highest rate of any industry [2]. As depicted in **Fig. 1**, according to incomplete official statistics, 4,797 accidents occurred in China between 2017 and 2023, resulting in 5,461 deaths [3]. Among them, the number of larger and above accidents was 128, resulting in 527 deaths. Laeger and above accidents are those that cause more than 3 deaths, more than 10 serious injuries, or more than 10 million yuan of direct economic loss. Some studies have shown that more than 50% of accidents are related to hoisting [4]. Hoisting construction is an indispensable part of construction projects involving many materials, equipment,

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and personnel. Many significant precast elements, such as box foundations and reinforced concrete columns, weigh more than 10 tons [5]. Taking the hoisting of columns as an example, the current hoisting methods mainly include the single-engine rotation method, single-engine gliding method, and double-engine lifting method [6]. (1) Single-engine rotating method: Single-engine rotating method for lifting columns, that is, the crane lifting point is set above the center of gravity of the column, the root of the column is on the ground (to protect the foot of the column, the ground can be set up on the road wood and other cushions), the crane hooks up (sometimes it is also necessary to rotate the crane arm while hooking up), and the columns will be lifted. The whole process is the column around the root point of rotation, the rotation method. (2) Single machine sliding method: The difference with the rotating method is that a slideway is set up at the bottom of the column to reduce the sliding resistance, such as rail rows, and when the crane lifts the hook, the foot of the column slides along the slideway until the column is back to straightness, which is suitable for heavier columns. (3) Double lifting method: It uses two cranes to lift the steel column so that the bottom of the column is suspended. Then the leading crane hook, vice machine with, so the steel column in the air goes straight. The general steel column is heavier or with a larger pick wing; use this method. One study found that the average impact of a hoisting accident was approximately CNY 2.43 million in direct economic losses, 1,543 fatalities, and 0.829 injuries [7]. According to China's "Safety Management Measures for Dangerous Sub-Parts of Projects," a single lifting weight of 100kN and above using non-conventional lifting equipment and methods; lifting equipment installation projects with a lifting weight of 300kN and above; lifting equipment installation and dismantling projects with complex installation and dismantling environments that do not conform with equipment instruction manuals have all been included in the list [8]. Therefore, it is crucial to effectively manage risks in hoisting construction.

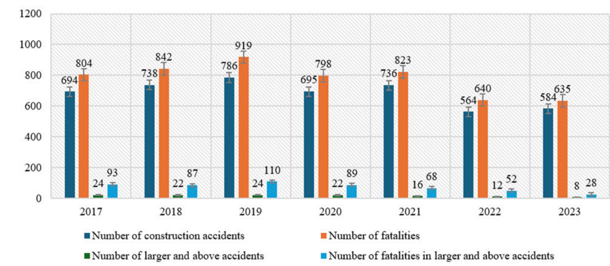

FIGURE 1. **The number of construction accidents and fatalities in China from 2017 to 2023 (Source: National Construction Quality and Safety Supervision Information Platform Public Service Portal, China).**

Although there have been some studies on risk management of lifting construction, there are some shortcomings in the previous studies. Firstly, many risk frameworks are constructed with an over-reliance on expert judgment, lack sufficient case validation, and are not widely used. For example, Wang et al. constructed a lifting construction risk framework based on Human Factors Analysis and Classification System Model (IHFACS), Improved Similarity Aggregation Method (ISAM), and Bayesian Network (BN) but validated it based on a small high-rise building only [9]. The study by Wan et al. is based on the Decision Making Experimentation and Evaluation Laboratory (DEMATEL). Nevertheless, when quantifying multiple correlation representations, they obtain initial correlation information through collective bargaining at expert meetings. Such a qualitative approach is somewhat subjective while maximizing the advantages of the experts' experience [10]. Second, some of the studies lack systematicity and comprehensiveness and fail to comprehensively consider various potential risk factors in lifting construction, resulting in the risk assessment results' lack of accuracy and reliability. For instance, Yingbo et al.'s study in 2019 only considered 14 risk factors [11]. Although many studies have shown that human factors cause more than 90% of engineering accidents, it is unreasonable for many frameworks to consider only human factors. Finally, some studies failed to fully evaluate the actual situation and characteristics of construction sites, resulting in poor operability and practicality of the research results. This is mainly because the current risk framework does not establish linkages that fully reflect the entire process of an accident. For example, Pan et al. 2021 performed lifting risk modeling based on the Systems-Theoretic Accident Modeling and Processes (STAMP) method and BN without considering risk outcomes [12]. The safety framework established by Fang et al. in 2022, based on cloud modeling and entropy weighting method-based assembly building lifting construction, on the other hand, does not consider the interactions between the dimensions [13]. How the human factor transmits risk to the operating environment and then influences the construction machinery, ultimately leading to an injury event, has not been thoroughly discussed, leading to a lack of interpretability in previous models. The study aims to develop an integrated lifting construction risk management framework based on the Stamp theory and the Partial Least Squares Structural Equation Modeling (PLS-SEM) model to fill the above research gaps. Therefore, the objectives of this study are as follows:

(1). To systematically identify potential risk factors in hoisting construction.

(2). To develop a risk management framework based on systems thinking for hoisting construction.

(3). To propose strategies to promote safety management practices in lifting construction.

The rest of this study is organized as follows: Section II reviewed the previous literature; Section III mainly details the principles and procedures of the PLS-SEM and independence weighting method (IWM). Section IV demonstrates the model results and discusses the weights ranking of risk factors. Section V discusses the response four strategies.

TABLE 1. Standard methods of accident analysis.

Method	Main Characteristics	Advantages	Disadvantages	Reference
RCA	Deep investigation of root causes.	Simplify operation and efficient identification of critical accident causes.	Neglect of complex systemic factors, difficulty in capturing interactions between factors.	[61]
FTA	Top-down analysis using fault tree structure.	Provide a visual representation of complex system failures logically and hierarchically.	Difficulty capturing dynamic aspects of the challenge, the need for accurate failure probability data, and the susceptibility to subjective error in gate construction.	[62]
ETA	Bottom-up analysis using event tree structure.	Identify and assess the sequence of events following the initial event in a potential accident scenario.	The complexity of event sequencing, the subjectivity of probability estimates, and the limited scope of analysis.	[63]
HAZOP	Team discussions using guide words to explore deviations.	Reducing engineering design flaws, improving safety and reliability, and quantifying safety analyses.	Inability to identify root causes of biases; focus on individual components, making it challenging to capture interactions present in complex systems; reliance on expert knowledge and experience.	[64]
AcciMap	Multi-layered analysis considering various levels of influence (government, company, operator, etc.).	Highly flexible taxonomy that does not require pre-defined error or failure modes; graphical representation of causal factors in complex socio-technical systems.	Emphasis on hierarchical decision-making can ignore the complexity inherent in constantly adapting and evolving systems.	[65]
HFACS	Focuses on human factors, adapted from aviation's HFACS model for industrial use,	Emphasizes human and organizational factors and provides a detailed taxonomy of human errors.	Treating events as linear sequences oversimplifies accident causation.	[66]
FRAM	Qualitative risk assessment expressed through network analysis.	Emphasis on interconnectivity within systems; modeling of complex systems.	Possibility of false resonances, difficulty quantifying emergent behavior, discrepancies between imagined and actual work, and complexity of functional identification in large systems.	[76]
STAMP	The system-theoretic model focuses on control structures and processes.	System interaction and control structure perspectives provide structured analysis frameworks, emphasize hierarchical levels of control, and promote proactive accident prevention.	Potential complexity, steep learning curve. It requires significant expertise and resources to implement effectively.	[67]

Source: Author's work.

Section VI summarizes the findings and presents the outlook for further research.

II. LITERATURE REVIEW

Accident analysis methods play a crucial role in safety management, and different methods have different focuses and application scenarios. **Table 1** summarizes the standard accident analysis methods currently used. Root Cause Analysis (RCA) prevents the recurrence of similar accidents by digging deep into the root cause of the accident. Post-event event investigations aim to identify the underlying and active factors that led to the occurrence of a particular adverse event. Still, the result is often a straightforward linear narrative that replaces more complex and productive explanations of the multiple interactions that unfolded during the event [14]. Fault Tree Analysis (FTA) uses a tree diagram structure to systematically analyze the conditions and events that lead to an accident from top to bottom. Traditional static incident trees show the hierarchy of incidents but not the architectural hierarchy of incident system components, making it challenging to map incident tree elements to specific system components [15]. In other words, this approach makes capturing risks with dynamic characteristics challenging. The lifting construction process, on the other hand, happens to be constantly changing and is not limited to people, machinery, and the environment. Event Tree Analysis (ETA) starts with the initial event and expands from the bottom up to explore all possible outcomes. This probability-based estimation method is complicated and costly to obtain an accurate estimate since, in most cases, experts have limited knowledge, incomplete information, and poor data quality, making it difficult to explain the fault entirely [16]. Hazard and Operability Study (HAZOP) systematically examines the potential dangers of work system components and operational procedures through team discussions and using guidewords. Its standard structure tends to lead the researcher into the trap of mechanically generating process bias, thereby diminishing the creativity and imagination important in hazard analysis [17]. AcciMap analysis methodology considers influences at all levels, including government, company, and operator. Due to data limitations and the presence of relatively few contributing factors at higher system levels (e.g., government and regulatory agencies), most of the contributing factors identified in the AcciMap analyses were related to sophisticated human operators and their environments, resulting in accident results that can be easily misinterpreted and used to place blame on "sophisticated" operators [18]. Human Factors Analysis and Classification System (HFACS) emphasizes human and organizational factors and provides detailed human factors error classification. Considering only human

TABLE 2. Hoisting construction risk factor system.

Categorization	ID	Risk Factor	Reference
Human control	H1	Inadequate supervision and subcontracting to unqualified companies.	[23, 24]
	H2	Lack of awareness or disregard for safety regulations and protocols.	
	H3	Failure to establish a hidden danger investigation, management, and monitoring responsibility system.	
	H4	Physical or mental impairment of operators, such as intoxication or distraction.	
	H5	Failure of operators to pass the safety education and licensing tests.	
Lifting process	L1	Inadequate lashing of heavy loads and improper selection of lifting centers.	[25, 26]
	L2	Failure to conduct pre-operational inspections of lifting equipment and rigging components.	
	L3	The hoisting program was not prepared under the actual working conditions at the project site and did not adequately plan for emergencies.	
	L4	Failure to rigorously educate operators on safety following construction programs and operating procedures.	
	L5	Failure to arrange specialized safety management personnel as required.	
Machinery failure	M1	Hooks show fatigue cracks, openings, dangerous section wear, and plastic deformation.	[27, 28]
	M2	Steel Wire Rope is twisted and fatigued, with broken wires, broken strands, corrosion, deformation, wear, and other abnormalities on the surface.	
	M3	The controller appears to have oxidized, uneven contact surfaces, and loose or worn mechanisms.	
	M4	Brake braking failures include hinge point jamming, hydraulic solenoid valve failure, brake pad dirt, etc.	
	M5	The gearbox leaks oil, and the gears are broken, worn, and eroded.	
	M6	The crane structure is aged and mechanically inadequate.	
Operating environment	O1	Limited visibility due to poor lighting conditions or obstructions.	[29, 30]
	O2	Substantial natural disasters, such as lightning, gusts of wind, earthquakes, etc., occur at the construction site.	
	O3	The construction site is crowded and cluttered, and safety warning signs are not reasonably placed.	
	O4	Chronic excessive noise and vibration on site.	
	O5	Uneven foundation bearing capacity, presence of hollow sites such as backfill, gravel land, mud land, etc.	
Injury events	I1	Fall from a height.	[31, 32]
	I2	Object strikes.	
	I3	Mechanical damage.	
	I4	Electrocution.	
	I5	Structural collapse.	
	I6	Other accidents.	

Source: Author's work.

and organizational factors is a pain point for this framework. For example, factors identified in international standards and national regulatory frameworks contributed to accidents in the oil and gas industry. Still, these identified themes were absent in the original HFACS [19]. The Functional Resonance Analysis Method (FRAM) explores how functional variability within complex socio-technical systems can lead to unexpected and often undesired events [77]. It focuses on understanding how processes typically work correctly on the front line and how this relates to predefined procedures. However, it can be subject to false resonances and uncertainty in the error lines associated with each resonance [78]. Secondly, FRAM may face challenges in analyzing emergent behaviors in complex systems as it does not always provide a quantitative assessment of these behaviors [79]. Additionally, this discrepancy between ideal workflows and actual implementations can affect the effectiveness of using FRAM to improve operational processes [80].

Many studies consider the Systems Theory Accident Modelling and Process (STAMP) as the most prominent accident analysis model available [68], [69]. Unlike traditional causal models, it proposes an extended model emphasizing system and control structures, allowing for a more thorough understanding of accidents [70]. Secondly, STAMP provides a structured framework for accident analysis that focuses on the relationships and constraints within the system that influence safety outcomes [71]. Focusing on hierarchical levels of control and systemic causes can help to explore in detail how control decisions propagate through the system, thereby helping to identify vulnerabilities and points of failure [72]. This structured approach enhances the depth of analysis and provides insights into the causes of accidents beyond traditional approaches. Third, STAMP's proactive approach to accident prevention is a significant advantage as it emphasizes system design and control enhancements for increased safety. Organizations can implement targeted interventions to correct systemic weaknesses and improve safety performance by analyzing control structures and feedback mechanisms [20]. Finally, the approach relies on three main steps: security constraints, a hierarchical security control framework, and process modeling, and the system is treated as dynamic in the approach [21]. This is a new perspective of thinking compared to the traditional approach, i.e., safety management is not defined as preventing component failure events but as a continuous control task. This control task is the imposition of the necessary constraints to limit system behavior to a safe range of variation and adaptation [22]. The basic logic of the STAMP-HC framework proposed in this study is shown in **Fig. 2**. Human factors, as the uppermost dimension, dominate the entire lifting construction risk control system. It guides the lifting process, monitors the mechanical equipment, and manages the operating environment; the lifting process controls the operating environment, and the operating environment interferes with the mechanical operation. These four dimensions ultimately lead to injuries, either directly or indirectly.

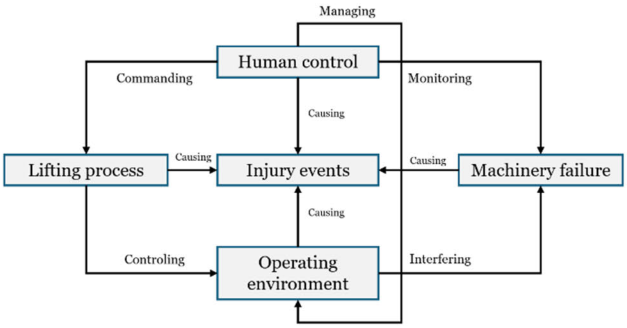

FIGURE 2. The basic logic of the STAMP-HC framework (Source: Author's work).

As displayed in **Table 2**, the summary of risk factors for hoisting safety is derived from the STAMP framework and literature review (accident cases and articles). Under Human Control (H), risks include inadequate supervision and subcontracting to unqualified companies (H1), lack of awareness or disregard for safety regulations (H2), failure to establish a hidden danger investigation system (H3), Operator impairments (H4) and inadequate safety education (H5) are significant factors. The Lifting Process (L) category addresses risks such as improper lashing of heavy loads (L1), failure to inspect lifting equipment (L2), inadequate hoisting program preparation (L3), insufficient operator safety education (L4), and lack of specialized safety management personnel (L5). Machinery Failure (M) risks include fatigue cracks and wear in hooks (M1), twisted and fatigued steel wire ropes (M2), oxidized controllers (M3), brake failures (M4), oil leaks in gearboxes (M5), and aged crane structures (M6). Operating Environment (O) risks involve poor visibility (O1), natural disasters (O2), cluttered construction sites (O3), excessive noise and vibration (O4), and uneven foundation bearing capacity (O5). Lastly, Injury Events (I) include falls from height (I1), object strikes (I2), mechanical damage (I3), electrocution (I4), structural collapse (I5), and other accidents (I6). This comprehensive categorization highlights the multifaceted nature of hoisting safety risks.

III. METHODOLOGY

Following the research objectives in the introduction section, the methodology of this study aims to address the following questions:

(1) What risk factors significantly impact the safety of lifting construction?
(2) What are the relationships between the various dimensions of risk?
(3) How are the relative weights of the risk factors distributed?
(4) How can lifting construction risk management practices be improved?

This study consists of four steps (see **Fig. 3**): (1) collecting data, (2) establishing a framework, (3) ranking the importance of factors, and (4) proposing improvement strategies.

A. DATA COLLECTION

1) ACCIDENT REPORT COLLECTION

From the Chinese government's official website (https://www.gov.cn/), 200 hoisting accident reports were collected for accident impact and validation of the feasibility of the proposed lifting risk framework. These documents are distributed on the official website of each municipal government, district government, or county government. Therefore, using a Google searcher, we used a snowballing approach to retrieve reports in China. Inclusion criteria for accident cases include (1) Accidents reported from 2019 to 2024. (2) The report details the accident's time and location, the project's name, and each participating unit. (3) The report has details of the accident, the number of casualties (including the number of people unaccounted for), and the preliminary estimated or determined direct economic losses. (4) The report has the confirmed cause and nature of the accident. (5) Measures taken after the accident and control of the accident. (6) Accident reporting unit, contact person, and contact information. (7) Other situations that should be reported according to the regulations of each province.

Fig. 4 illustrates the data distribution and spatial relationship of the impact of accident cases. Normally, the number of fatalities caused by lifting accidents is less than four, the number of injuries caused is less than five, and the direct economic loss caused is less than 10 million CNY. The number of deaths and injuries is directly proportional to the direct economic losses. **Table 3** provides a detailed summary of accident data across three categories: death, injury, and direct financial loss in CNY millions.

TABLE 3. Descriptive statistics of accident data.

Items	N	Minimum	Maximum	Mean	Standard deviation	Median
Death	200	0.000	18.000	1.295	1.483	1.000
Injured	200	0.000	33.000	0.430	2.403	0.000
Direct economic loss (CNY 10,000)	200	0.000	2100.000	176.636	235.973	130.000

Source: Author's work.

The dataset consists of 200 observations for the death category, with the number of deaths per accident ranging from 0 to 18. The mean number of fatalities is 1.295, with a standard deviation of 1.483, indicating moderate variability around the mean, and the median is 1, suggesting that half of the accidents result in one or fewer deaths. For the 'Injured' category, there are also 200 observations, ranging from 0 to 33 injuries per accident. The mean number of injuries is relatively low at 0.430. Still, the standard deviation is 2.403, showing a higher variability, and the median is 0, indicating that no injuries occur in more than half of the accidents. Lastly, the data again includes 200 observations for direct economic loss, with losses ranging from 0 to CNY 21,000,000. The mean economic loss is CNY 1,766,360, with a substantial standard deviation of CNY 235,973, highlighting significant variability, and the median loss is CNY

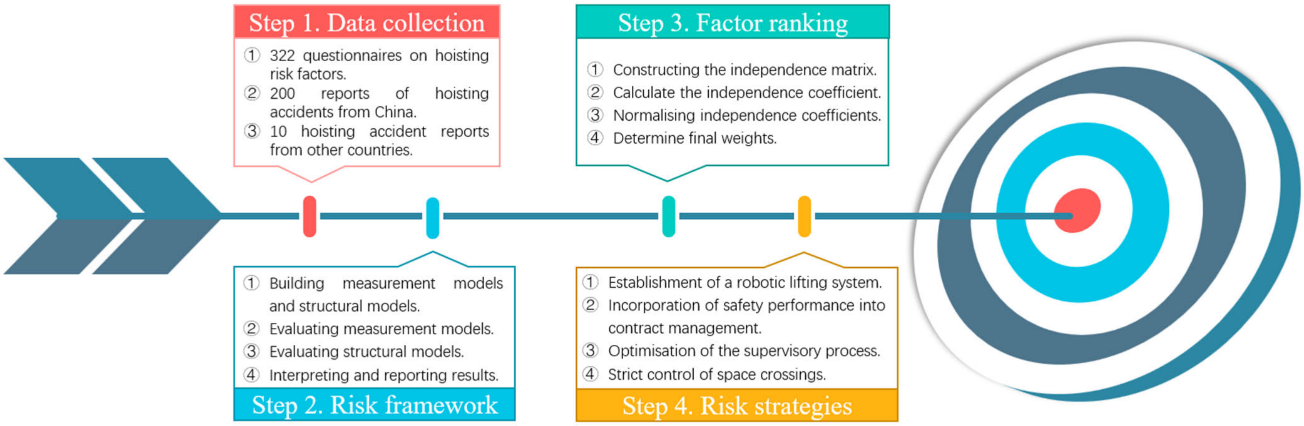

FIGURE 3. Research process (Source: Author's work).

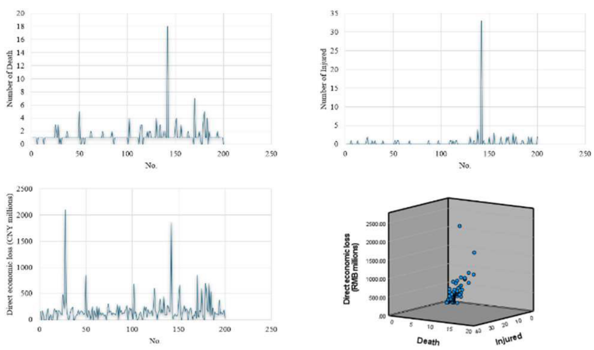

FIGURE 4. Fatalities, injuries, and direct economic losses by accident (Source: Author's work).

1,300,000, indicating that half of the accidents incur a loss of CNY 1,300,000) or less. For specific data, see **Supplementary File 1**.

2) QUESTIONNAIRE DATA COLLECTION

Guangdong is one of China's most economically developed provinces, with many infrastructure and high-rise building projects. Lifting construction is prevalent in these projects, and the need for risk management is urgent. Therefore, it was chosen as the questionnaire area for this study. In addition, Guangdong Province has a large and representative number of construction workers. A sample of the questionnaire can be found in **Supplementary File 2**. It is worth noting that this study did not involve any commercial confidentiality, medical treatment, or invasive life science experiments, and as all respondents were adults and filled in voluntarily, they had the right to withdraw from this survey at any time. Thus, the ethical review committee granted this questionnaire an ethical review exemption of the author's affiliation (see **Supplementary File 3**). Raosoft® software was used to calculate the sample size. The margin of error was set at 5%, the confidence interval was set at 95%, the population size was set at 20,000, and the response was assigned at 50%, which is publicized as follows:

$$x = Z(c/100)^2 r\,(100 - r) \tag{1}$$

$$n = Nx/((N-1)E^2 + x) \tag{2}$$

$$E = \mathrm{Sqrt}[(N-n)x/n(N-1)] \tag{3}$$

where N is the population size, r is the fraction of responses you are interested in, and $Z(c/100)$ is the critical value for the confidence level c.

It is worth noting that, according to the software prompt, the population size is more significant than 20,000, and the calculation is based on 20,000. In 2023, the number of construction industry enterprise units in Guangdong province was 11,192, and the number of employees was 3,769,600 [33]. The result shows that at least 267 samples are needed for this study.

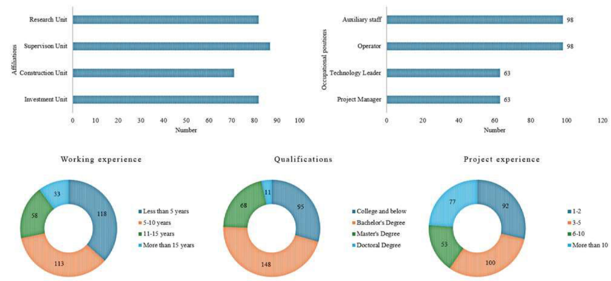

FIGURE 5. Statistics on basic information of respondents (Source: Author's work).

As illustrated in **Fig. 5**, 400 questionnaires were distributed, and 322 were returned, with a response rate of 80.5%. The questionnaire was distributed using digital and physical methods to ensure broad coverage and a higher response rate. The questionnaire was distributed primarily through an online survey platform (Questionnaire Star®), which allowed for easy access and completion by participants. The platform was chosen because of its user-friendly interface, ease of distribution, and ability to collect and analyze responses efficiently. It also allowed for real-time monitoring of reactions and automatic data compilation, which simplified the data collection process. In addition, printed copies of the questionnaire were distributed during site visits and industry conferences for on-site construction workers and professionals with limited access to digital tools. Notably, participants were selected for this study based on the following criteria to ensure diversity and knowledge of respondents: (1) Professional experience: Participants were required to have at least 1 year of work experience in the construction industry, with direct experience in lifting operations and safety management preferred. (2) Job roles: The questionnaire addressed a variety of roles within the construction industry, including auxiliary staff, managers, operators, and technical leads. This ensured a comprehensive understanding of risk from multiple perspectives. (3) Industry sectors: The respondents were drawn from various sectors of the construction industry, such as research organizations, construction companies, supervisory firms, and investment units, to consider the perspectives of each sector. (4) Educational background: In selecting participants, academically qualified professionals (e.g., engineers with relevant degrees) and senior tradespeople without formal qualifications but with extensive practical knowledge were considered.

Regarding departmental representation., the proportion of supervisory units is the highest at 27.02%, followed by research units, with a proportion of 25.47%, and the proportion of construction units is the lowest at 22.05%. Overall, the distribution of the types of units participating in the survey is relatively balanced, with a relatively large number of supervisory units. Regarding rank, the proportion of operators and support staff is the same, at 30.43%, while the proportion of project leaders and technical leaders is also the same, at 19.57%. This shows that the percentage of operators and auxiliary staff is higher and occupies a more significant percentage in this survey. In terms of work experience, the years of work experience of those who participated in the survey were mainly concentrated in the stages of less than 5 years and 5-10 years, which accounted for 36.65% and 35.09%, respectively. The proportion of personnel with more than 11 years of working experience is lower, only 28.26Overall, most of the participants in the survey have less than 10 years of working experience. In terms of education, the number of people with a bachelor's degree is the largest, accounting for 45.96%, followed by the number of people with a college degree or below, accounting for 29.5%, the number of people with a master's degree accounting for 21.12%, and the number of people with a doctoral degree accounting for 3.42%. People with bachelor's degrees have the highest percentage in this survey. Regarding project experience, the most significant number of people, 31.06%, were involved in 3-5 sizeable structural lifting operation projects. This is followed by the number of people involved in 1-2 projects with 28.57%. The number of people involved in more than 10 projects accounted for 23.91%, and those involved in 5-10 projects accounted for 16.46%. The number of people involved in more than 3 projects is relatively high.

The reliability of the questionnaire data (**see Supplementary File 4**) was analyzed by SPSS27® software, with a total of 27 items and a Cronbach. α coefficient of 0.925. The Cronbach. α coefficient is a commonly used method for assessing the reliability of questionnaires. Its value usually ranges between 0 and 1, with a higher value representing the questionnaire's internal consistency [34]. The higher the value, the greater the internal consistency of the questionnaire, which can be effectively used to measure and analyze the relevant variables in the study. Factor analysis was also carried out to assess the validity of the questionnaire. The Kaiser-Meyer- Olkin (KMO) value was used to determine the suitability of factor analysis, with a value of 0.5 or above indicating that it is suitable for factor analysis. As reflected in **Table 4**, this questionnaire's KMO value is 0.928, much higher than 0.5, indicating that the sample is appropriate for factor analysis and has high validity [35]. In addition, the p-value (0.000) of the Bartlett Sphericity Check is used to test the correlation between the variables. The closer its value is to 0, the better the correlation between the variables will be.

TABLE 4. KMO and bartlett's test.

KMO value		0.928
Bartlett Sphericity Check	Approximate chi-square	3946.852
	df	351
	p-value	0.000

Source: Author's own work.

B. PLS-SEM MODEL

PLS-SEM is a statistical technique to analyze complex relationships among variables. It combines factor analysis and regression analysis elements, and it is beneficial for exploring and modeling the relationships between observed and latent variables [36]. PLS-SEM is often chosen when the goal is prediction and theory development rather than theory testing, which makes it different from traditional Covariance Base Structural Equation Modeling (CB-SEM). There are vital aspects of PLS-SEM [37]: (1) Latent Variables: These are variables that are not directly observed but are inferred from other variables, called indicators or manifest variables. (2) Structural Model: This part of the model represents the relationships between latent variables. It is often depicted as a path diagram. (3) Measurement Model: This part of the model specifies the relationships between latent variables and their indicators. (4) Algorithm: PLS-SEM uses an iterative algorithm to estimate the path coefficients and the loadings of the indicators on their respective latent variables. (5) Non-parametric: Unlike CB-SEM, PLS-SEM does not assume a normal data distribution, making it more flexible in handling small sample sizes and non-normal data. (6) Predictive Orientation: PLS-SEM focuses on maximizing the explained variance of the dependent variables. It is often used in exploratory research to predict key target constructs.

Below are the core steps and equations used in the PLS-SEM algorithm [38]:

1) OUTER MODEL (MEASUREMENT MODEL)

The outer model describes the relationships between the latent variables (LVs) and their corresponding manifest variables (MVs).

Reflective Measurement Model:

$$X_j = \lambda_j \xi_j + \varepsilon_j \tag{4}$$

where, X_j: Indicator j; λ_j: Loading of indicator j on the latent variable ξ_j; ξ_j: Latent variable; ε_j: Measurement error.

2) INNER MODEL (STRUCTURAL MODEL)

The inner model specifies the relationships between the latent variables.

$$\xi_i = \sum_j \gamma_{ij} \xi_j + \zeta_i \tag{5}$$

where, ξ_i: Endogenous latent variable i; γ_{ij}: Path coefficient between latent variable j and latent variable i; ξ_j: Exogenous latent variable j; ζ_i: Structural error term.

As depicted in **Fig. 6**, based on the Stamp theoretical model, this study exploratively proposes the following risk framework, including ten hypotheses: (1) H1: Human control significantly affects the lifting process. (2) H2: Human control significantly affects the operating environment. (3) H3: Human control significantly affects machinery failure. (4) H4: Human control significantly affects injury events. (5) H5: The lifting process significantly affects the operating environment. (6) H6: The lifting process significantly affects the machinery failure. (7) H7: The lifting process significantly affects the injury events. (8) H8: Operating environment significantly affects machinery failure. (9) H9: Operating environment significantly affects injury events. (10) H10: Machinery failure significantly affects injury events. It is worth noting that the present risk framework focuses on establishing a human-led risk system.

C. INDEPENDENCE WEIGHT COEFFICIENT METHOD

The independence weight coefficient method (IWCM) is an objective weighting method [88]. This weighting analysis was achieved in this study through SPSSAU® software. Its idea lies in determining the weights of indicators based on the strength of the covariance between each indicator and other indicators; if the covariance between indicators is stronger, the easier it is to be represented by linear combinations of other indicators, the more repetitive the information is. Therefore, the smaller the indicator weights should be [39]. With indicator items $x = \{x_1, x_2, \ldots, x_m\}$, if the coefficient of complex correlation between indicator X_k and other indicators are more significant, so the covariance with other indicators is stronger and easier to be represented by linear combinations of different indicators, and the more repetitive the information is, the indicator's weight should be smaller [40]. That is, if the coefficient of complex correlation

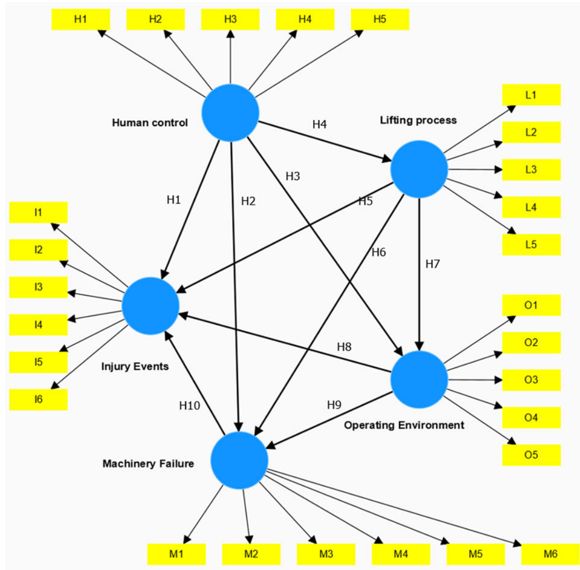

FIGURE 6. Initial STAMP-HC model (Source: Author's work).

R between the indicator and other indicators is larger, the indicator's weight is smaller.

$$R_j = \frac{\sum_{j=1}^{m} \left(x_j - \bar{x}\right)\left(\tilde{x} - \bar{x}\right)}{\sqrt{\sum_{j=1}^{m} \left(x_j - \bar{x}\right)^2 \left(\tilde{x} - \bar{x}\right)^2}} (j = 1, 2, 3, \ldots, m) \tag{6}$$

Then, the inverse of the negative correlation coefficient was selected and normalized to calculate the final weight values W_j:

$$R = \left[\frac{1}{R_1}, \frac{1}{R_2}, \frac{1}{R_3}, \cdots \frac{1}{R_m}\right] \tag{7}$$

$$W_j = \frac{\frac{1}{R_j}}{\sum_{j=1}^{m} \frac{1}{R_j}} \tag{8}$$

The IWCM calculates the weights through quantitative methods, which can reduce the bias caused by human subjective judgment and improve the objectivity and fairness of the results. The technique can better deal with the mutual independence of multiple risk factors and avoid the problem of inaccurate weight allocation due to the correlation between factors. By constructing the independence matrix and calculating the independence coefficients, the weights of the indicators can be obtained quickly, which is suitable for the rapid assessment needs in practical applications [86]. Secondly, it clarifies the basis for weight allocation, making the results easy to interpret and understand. It has been used in many fields, such as modeling the quality suitability of herbal volatile oils [87].

IV. RESULTS

A. RESULTS OF DESCRIPTIVE ANALYSIS

Table 5 provides statistical summaries for 27 survey items labeled from H1 to I6 based on responses from 322 participants. Each item was rated on a scale from 1 to 5. All items'

TABLE 5. Results of descriptive analysis (N = 322; CI = 95%).

Items	N	Minimum	Maximum	Mean	Standard deviation
H1	322	1.000	5.000	3.593	1.121
H2	322	1.000	5.000	3.665	1.070
H3	322	1.000	5.000	3.519	1.128
H4	322	1.000	5.000	3.571	1.103
H5	322	1.000	5.000	3.615	1.105
L1	322	1.000	5.000	3.646	1.102
L2	322	1.000	5.000	3.646	1.135
L3	322	1.000	5.000	3.630	1.009
L4	322	1.000	5.000	3.562	1.070
L5	322	1.000	5.000	3.693	1.060
M1	322	1.000	5.000	3.562	1.110
M2	322	1.000	5.000	3.618	1.141
M3	322	1.000	5.000	3.559	1.201
M4	322	1.000	5.000	3.671	1.115
M5	322	1.000	5.000	3.590	1.111
M6	322	1.000	5.000	3.596	1.058
O1	322	1.000	5.000	3.606	1.131
O2	322	1.000	5.000	3.668	1.073
O3	322	1.000	5.000	3.488	1.153
O4	322	1.000	5.000	3.661	1.071
O5	322	1.000	5.000	3.655	1.109
I1	322	1.000	5.000	3.602	1.134
I2	322	1.000	5.000	3.686	1.073
I3	322	1.000	5.000	3.668	1.140
I4	322	1.000	5.000	3.634	1.106
I5	322	1.000	5.000	3.609	1.148
I6	322	1.000	5.000	3.640	1.085

Source: Author's work.

minimum and maximum values are consistently 1 and 5, respectively. The mean scores for the items range from 3.488 to 3.693, indicating a generally positive inclination towards the mid-to-upper range of the scale. Standard deviations vary between 1.009 and 1.201, suggesting moderate response variability. Specifically, the items with the lowest and highest means are O3 (mean = 3.488) and L5 (mean = 3.693), respectively. Standard deviation values suggest that responses were relatively consistent, with item L3 exhibiting the lowest variability (standard deviation = 1.009) and item M3 the highest (standard deviation = 1.201).

B. RESULTS OF PLS-SEM

Due to the small sample size (N = 322), we chose PLS-SEM to analyze the data by SmartPLS® 4.0. It has gained popularity in management in recent years and is the most appropriate method for testing causality in the presence of constructs. It is the most appropriate method for testing causality in the presence of constructs. This is due to its ability to model potential constructs under non-normal conditions.

1) MEASUREMENT MODEL

A two-step procedure was used in this study to assess the measurement model and the structural model. The following quality criteria were used to evaluate the measurement model

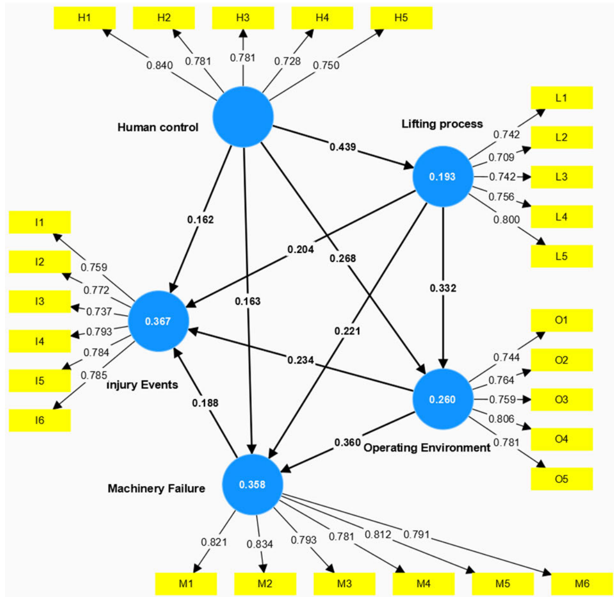

FIGURE 7. Final STAMP-HC model (Source: Author's work).

in **Fig. 7** [41], [42]: (1) Internal consistency reliability (ICR): As displayed in **Table 6**, Cronbach's alpha (α) values for all dimensions are more significant than 0.60 and are reliable. (2) Composite reliability (CR): Rho_A and Rho_C values greater than 0.70 are acceptable in exploratory studies. (2) Indicator Reliability (IR): All variables had external loading scores greater than 0.5 and were considered acceptable. (4) Convergent validity: The measurement model is internally consistent and convergent, with estimates of average variance extraction (AVE) values exceeding 0.5 for each component. (5) Discriminant validity: The heterotrait-monotrait ratio (HTMT) value for similar constructs should be less than 0.90, and for different constructs should be less than 0.85. The HTMT values for the constructs of this study are listed in **Table 7**, indicating satisfactory discriminant validity. In addition, **Table 8** shows the components achieve satisfactory discriminant validity because the square root of AVE (along the diagonal) is larger than the correlation (off-diagonal) for all the elements.

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum_{i=1}^{K} S_i^2}{S_t^2}\right) \tag{9}$$

$$CR = \frac{\left(\sum_{i=1}^{K} \lambda_i\right)^2}{\left(\sum_{i=1}^{K} \lambda_i\right)^2 + \text{var}\left(e_i\right)} \tag{10}$$

$$AVE = \frac{\sum_{i=1}^{K} \lambda_i^2}{\sum_{i=1}^{K} \lambda_i^2 + \text{var}\left(e_i\right)} \tag{11}$$

where K is the number of the factors, S_i^2 is the variance of the ith factor, S_t^2 is the total variance, λ_i is the standardized loading value of the ith factor, and var (e_i) is the error variance of the ith factor.

TABLE 6. Results of measurements model–convergent validity (N = 322; CI = 95%).

Constructs Dimensions	Items	Loading	Cronbach's alpha	Composite Reliability, Rho_A	Composite Reliability, Rho_C	Average Variance Extracted. (AVE)
Human control	H1	0.840	0.835	0.842	0.884	0.604
	H2	0.781				
	H3	0.781				
	H4	0.728				
	H5	0.750				
Injury Events	I1	0.759	0.864	0.868	0.898	0.596
	I2	0.772				
	I3	0.737				
	I4	0.793				
	I5	0.784				
	I6	0.785				
Lifting process	L1	0.742	0.806	0.807	0.866	0.563
	L2	0.709				
	L3	0.742				
	L4	0.756				
	L5	0.800				
Machinery Failure	M1	0.821	0.892	0.893	0.917	0.649
	M2	0.834				
	M3	0.793				
	M4	0.781				
	M5	0.812				
Operating Environment	O1	0.744	0.830	0.831	0.880	0.595
	O2	0.764				
	O3	0.759				
	O4	0.806				
	O5	0.781				

Source: Author's work.

TABLE 7. Discriminant validity for components using HTMT ratio of correlation (N = 322; CI = 95%).

Constructs Dimensions	Human control	Injury Events	Lifting process	Machinery Failure	Operating Environment
Human control					
Injury Events	0.494				
Lifting process	0.531	0.555			
Machinery Failure	0.471	0.531	0.537		
Operating Environment	0.493	0.579	0.547	0.611	

Source: Author's work.

TABLE 8. Discriminant validity for components using the Fornell and Larcker criterion (N = 322; CI = 95%).

Constructs Dimensions	Human control	Injury Events	Lifting process	Machinery Failure	Operating Environment
Human control	0.777				
Injury Events	0.425	0.772			
Lifting process	0.439	0.466	0.750		
Machinery Failure	0.410	0.471	0.455	0.805	
Operating Environment	0.414	0.492	0.450	0.528	0.771

Source: Author's work.

The measurement model obtains good results and can reflect the state of the underlying variables. This provides a basis for explaining how the model works.

2) STRUCTURE MODEL

Estimates of the relationships between model structures are called path coefficients. The coefficients range from +1 to −1, where +1 indicates a strong positive correlation, 0 indicates a weak or non-existent correlation, and −1 indicates a robust negative correlation [43]. PLS bootstrapping is a statistical method for obtaining many simulated samples from a single dataset for testing hypotheses. The procedure calculates standard errors and provides confidence intervals for various sample statistics when testing hypotheses. **Table 9** shows the estimated model and the estimated path coefficients and p-values for the main hypotheses. The Variance Inflation Factor (VIF) values for all paths are less than 3.5, indicating that each construct contributes to the goal separately [44].

Table 10 illustrates the indirect effect paths. According to the mediation analysis, only machinery failure lightly mediated the relationship between human control and injury events

TABLE 9. Hypothesis testing (N = 322; CI = 95%).

Hypothesis	Path coefficients	VIF	T-values	P-values
Human control -> Injury Events	0.162	1.378	2.665	0.008
Human control -> Lifting process	0.439	1.000	6.788	0.000
Human control -> Machinery Failure	0.163	1.336	2.573	0.010
Human control -> Operating Environment	0.268	1.239	3.766	0.000
Lifting process -> Injury Events	0.204	1.465	3.743	0.000
Lifting process -> Machinery Failure	0.221	1.388	3.090	0.002
Lifting process -> Operating Environment	0.332	1.239	4.898	0.000
Machinery Failure -> Injury Events	0.188	1.558	3.099	0.002
Operating Environment -> Injury Events	0.234	1.554	3.397	0.001
Operating Environment -> Machinery Failure	0.360	1.352	5.128	0.000

Source: Author's work.

TABLE 10. Indirect Effects (N = 322; CI = 95%).

Relationship	Indirect effects (β)	T-values	P-values
Human control -> Lifting process -> Machinery Failure	0.097	2.738	0.006
Lifting process -> Operating Environment -> Machinery Failure	0.120	3.332	0.001
Human control -> Lifting process -> Operating Environment	0.146	3.906	0.000
Operating Environment -> Machinery Failure -> Injury Events	0.068	2.628	0.009
Human control -> Lifting process -> Operating Environment -> Machinery Failure -> Injury Events	0.010	2.150	0.032
Human control -> Lifting process -> Operating Environment -> Machinery Failure	0.053	3.060	0.002
Human control -> Operating Environment -> Machinery Failure -> Injury Events	0.018	2.139	0.032
Human control -> Lifting process -> Operating Environment -> Injury Events	0.034	2.486	0.013
Lifting process -> Operating Environment -> Machinery Failure -> Injury Events	0.023	2.228	0.026
Human control -> Lifting process -> Machinery Failure -> Injury Events	0.018	2.143	0.032
Human control -> Operating Environment -> Injury Events	0.063	2.489	0.013
Human control -> Machinery Failure -> Injury Events	0.031	1.772	0.077
Human control -> Lifting process -> Injury Events	0.090	2.938	0.003
Human control -> Operating Environment -> Machinery Failure	0.096	3.077	0.002
Lifting process -> Operating Environment -> Injury Events	0.078	2.628	0.009
Lifting process -> Machinery Failure -> Injury Events	0.042	2.302	0.021

Source: Author's work.

TABLE 11. Assessment results of structural model (N = 322; CI = 95%).

Items	Criteria	Saturated model	Estimated model
SRMR	<0.08, Acceptable	0.051	0.051
d_ULS	>0.90, Good fit	0.995	0.995
d_G	GoF less than 0.1, No fit; GoF between 0.1 and 0.25, Small; GoF between 0.25 and 0.36, Acceptable; GoF greater than 0.36 Large.	0.294	0.294
Chi-square	-	554.048	554.048
NFI	>0.8, Acceptable	0.864	0.864

Source: Author's work.

($\beta = 0.031$, $t = 1.772$, $p = 0.077 > 0.05$). The remaining mediating pathways were all strongly linked.

The following criteria are adopted to assess the structural model shown in **Fig. 6** [45]: (1) Standardized root mean square residual (SRMR): A value less than 0.10 is considered a good fit. (2) Normed fit index (NFI): A value above 0.8 usually represents an acceptable fit. The assessment results for the model fit are summarized in **Table 11**, showing that the model is a good fit with SRMR = 0.051 and the NFI value > 0.80, and the GoF (Good of Fit) result for our model is 0.638, which is greater than 0.36 and is considered acceptable [46].

C. RESULTS OF THE INDEPENDENCE WEIGHTING ANALYSIS

The independence weighting method utilizes multiple regression methods and is weighted by calculating the coefficient of relevance R. The larger the coefficient of relevance R is, the more repetitive the information is, and the smaller the weight is; the larger the value of the coefficient of relevance *1/R* is, the larger the weight should be; and the final weight is obtained by normalizing the value of the coefficient of relevance *1/R*. The results of the weighting calculations are shown in **Table 12**. **Fig. 8** illustrates the results of the weighted ordering of the factors.

1) HUMAN CONTROL

Human control factors are critical to maintaining safety standards and ensuring competent operations. Physical or mental impairment of operators, such as intoxication or distraction, is the most vital factor (H4, 5.30%). This is because construction site work in China is usually accompanied by high pressure and intense labor, and it is common for workers to use alcohol to relax and relieve stress. The culture of alcohol is also a shared social habit in the Chinese construction industry. Prolonged uprooting makes them more likely to face

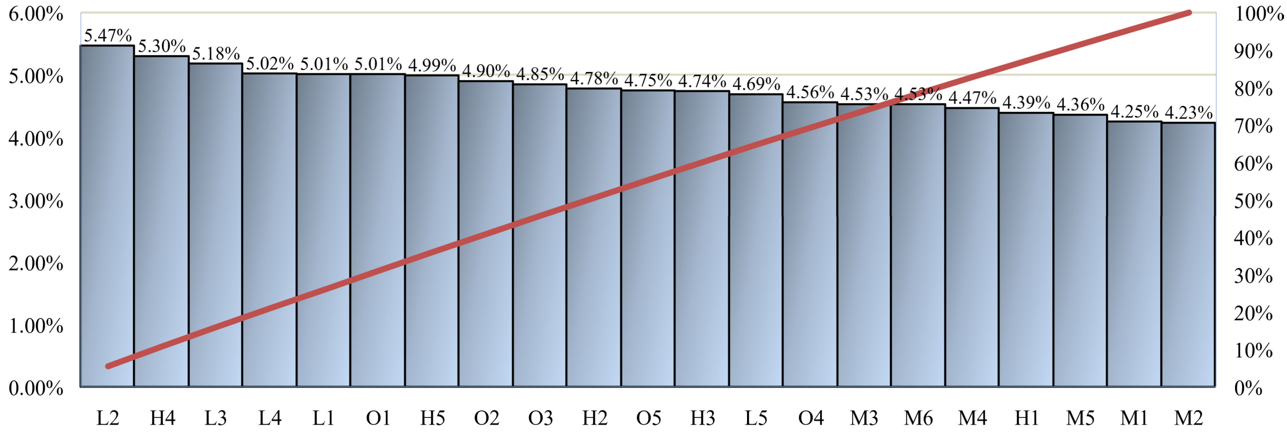

FIGURE 8. Importance ranking of hoisting risk factors (Source: Author's work).

TABLE 12. Independence weighting method calculations (N = 322; CI = 95%).

Items	Complex correlation coefficient R	The inverse of the complex correlation coefficient 1/R	Weights
H1	0.736	1.359	4.39%
H2	0.676	1.480	4.78%
H3	0.682	1.466	4.74%
H4	0.610	1.640	5.30%
H5	0.647	1.545	4.99%
L1	0.645	1.549	5.01%
L2	0.591	1.691	5.47%
L3	0.624	1.601	5.18%
L4	0.644	1.553	5.02%
L5	0.689	1.451	4.69%
M1	0.760	1.316	4.25%
M2	0.764	1.309	4.23%
M3	0.714	1.401	4.53%
M4	0.723	1.383	4.47%
M5	0.741	1.349	4.36%
M6	0.713	1.402	4.53%
O1	0.645	1.550	5.01%
O2	0.660	1.516	4.90%
O3	0.666	1.501	4.85%
O4	0.708	1.412	4.56%
O5	0.681	1.469	4.75%

Source: Author's work.

difficulties such as marital alienation and family separation. Namian et al. also highlight the impact of excessive personal superstitions inhibiting safety performance [81]. Secondly, ensuring operators pass safety education and license exams (H5, 4.99%) is the second key to maintaining high safety standards. Workers on construction sites are highly mobile, and the schedule targets are tight. As a result, many managers do not follow strict rules and regulations for worker selection. The third is the lack of awareness of compliance with safety regulations and protocols (H2, 4.78%). It is due to the low literacy level of some workers who have difficulty understanding the safety training content and are overly optimistic, which is supported by a study by Yao et al. [82]. The fourth is the lack of a system for identifying, managing, and monitoring potential hazards (H3, 4.74%). The initial cost of a risk monitoring system is high and requires significant capital investment, including purchasing equipment, software, and hiring professionals. In addition, ongoing system maintenance and data management can add significantly to operating costs, making them unaffordable for small and medium-sized companies. Lastly, subcontracting to unqualified companies (H1, 4.39%). This is due to the short-sighted behavior of some project managers, who are obsessed with short-term gains and low costs and ignore safety qualifications.

2) LIFTING PROCESS

Regarding the lifting process, the most significant factor was the lack of proper pre-operational inspection of lifting equipment and rigging components (L2, 5.47%). This included failure to carry out test lifts or carefully check the quality of the lashing materials before formal lifting. Similar situations used to occur in the past in India [83]. Secondly, there was a failure to prepare lifting programs and contingency plans based on actual site conditions (L3, 5.18%). Due to the irrational arrangement and division of labor, there were often ''many jobs in one'' on-site, which made it impossible to concentrate on their work. The third one is Failure to rigorously educate operators on safety following construction programs and operating procedures (L4, 5.02%). Poor lashing of heavy loads and improper selection of lifting centers (L1, 5.01%) ranked fourth. In many cases, the failure to select appropriate lashing points and to ensure uniform force on the lashings according to the shape and weight distribution of the members led to accidents. Finally, specialized safety managers were lacking (L5, 4.69%). Specialized safety management personnel are lacking in some remote or economically backward areas. The high mobility of the construction industry makes it difficult to retain such talents for a long time. This aligns with Ghasemi et al., who emphasized using safety incentives to retain professional safety managers [84].

3) MACHINERY FAILURE

Mechanical failures include critical issues related to lifting equipment's structural and functional integrity. The first-ranked factors are problems with the controller, such as oxidation and loosening of the mechanism (M3, 4.53%). Lifting equipment is often operated outdoors, where high humidity or rain penetration can lead to short circuits or corrosion within the controller. This is followed by the crane structure's aging or inadequate mechanical performance (M6, 4.53%). During long-term use, the external frame structure is constantly subjected to cyclic stresses (repeated tension and compression), leading to gradual fatigue loss of metal materials and micro-cracks. This stress is mainly concentrated in welds, holes, and corners. The third is brake failure (M4, 4.47%). Galvanic corrosion may exist between metal components, such as brake pads and brake bands. Excessive spacing of brakes can also affect braking effectiveness. The fourth is Gearbox problems, such as oil leakage and damaged gears (M5, 4.36%). Many sites use low-quality or expired lubricants to save costs, leading to increased friction in gears and bearings. Dust and metal shavings also contribute to the deterioration of lubrication performance. Deterioration of seals leads to lubricant leakage, further exacerbating gearbox damage. The fifth factor is that hooks show fatigue cracks, openings, dangerous section wear, and plastic deformation (M1, 4.25%). For example, hooks subjected to overloads or shock loads can cause deformation of the lugs or other parts of the hook. Finally, the Steel Wire Rope is twisted and fatigued, with broken wires, broken strands, corrosion, deformation, wear, and other abnormalities on the surface (M2, 4.23%). It has been subjected to prolonged use and frequent lifting operations, resulting in wear and fatigue. In some cases, instead of replacing the deteriorated wire ropes in time, the operators used sisal ropes as a substitute.

4) OPERATING ENVIRONMENT

The operating environment has a significant impact on the safety of lifting operations. The first factor is inadequate lighting or obstacles (O1, 5.01%t). This is because many construction operations are carried out at night. Without adequate lighting equipment or improper placement, there are likely to be visual dead spots or parts of the area that are too dark with fiber optics. The second is the severe and uncontrollable risk of natural disasters such as lightning, high winds, and earthquakes (O2, 4.90%). Lifting equipment usually includes metal materials such as hooks with cranes. Lightning may cause control systems and sensors to fail. High winds increase the swing of lifted objects in the air, incredibly lightweight and bulky components (lightweight diaphragm walls). The construction industry in Malaysia also faces a similar situation of poor safety culture [85]. Thirdly, construction sites are crowded and cluttered with inadequate safety signs (O3, 4.85%). Cluttered sites make the walking paths of workers unclear. In case of emergency, it is difficult for first aid equipment and supplies to be transported to the correct location in the first place. The fourth is unstable foundations (O5, 4.75%). Crane loads are transferred to the foundation through outriggers or tracks, and the foundation needs to distribute these loads evenly. If the foundation does not have sufficient bearing capacity, the crane's outriggers may sink, resulting in tipping or overturning. Last is the impact of site vibration and noise (O4, 4.56%). Verbal communication between workers becomes difficult in high-noise environments, leading to misunderstandings or untimely information transfer. Some warning signals, such as sirens and alarms, are easily drowned out in a high-noise environment. Notably, long-term injuries can easily be overlooked. For example, continuous noise and vibration can increase workers' psychological stress and affect emotional stability, leading to anxiety and irritability. Prolonged exposure to such environments can cause fatigue and damage workers' hearing, reducing reaction time and concentration.

D. CASES VALIDATION

To ensure the validity of the developed framework, this study validates the developed STAMP-HC risk framework with examples based on 200 cases previously collected on the official website of the Chinese government. The steps of case validation are (1) identification of risk factors through the summary of causation in the accident report and (2) identification of risk transmission pathways through the detailed case description. It is found that the risk framework has strong compatibility and applicability and can accurately reflect the risk transfer process in lifting accidents. Five cases were randomly selected for detailed presentation in **Table 13**. In the first case, a collapse of the tower crane's upper structure led to a severe imbalance and eventual toppling, illustrating the pathway from inadequate supervision (H1) and insufficient safety education (H5) through uninspected lifting equipment (L2) and aged crane structure (M6) to structural collapse (I5). The second case involved an operator falling and being injured by a tipping steel beam, tracing a path from disregard for safety protocols (H2) through lack of operator safety education (L4, L5) and a cluttered site (O3) to the object strike (I2). In the third case, the failure of the balancing arm during lifting resulted in a fatal fall, connecting the inability to establish a danger investigation system (H3) and inadequate safety education (L4, L5) through an aged crane structure (M6) to the fall from height (I1). The fourth case highlighted the improper installation of a gantry crane leading to a catastrophic fall, following the path from disregard for protocols (H2) and insufficient operator licensing (H5) through an inadequate lifting plan (L3) and fatigued wire rope (M2) to the fall (I1). In the fifth case, the toppling of a crane due to improperly fixed concrete blocks was traced from disregard for protocols (H2) and operator impairment (H4) through improper lashing (L1, L5) and aged crane structure (M6) under adverse site conditions (O3, O5) to structural collapse (I5). The sixth case involved a sling breaking during pump installation under adverse weather, mapping from disregard for protocols (H2) through an inadequate lifting plan (L3), fatigued sling (M2), and adverse weather (O2) to the injury from object strike (I2). Lastly, the seventh case detailed the mechanical failure of a crane jib leading to a fatal fall, starting from the failure to establish a danger investigation system (H3) through uninspected lifting equipment (L2) and fatigued wire rope (M2) to mechanical damage (I3). These cases collectively validate the risk model by illustrating the interconnected pathways of human control, lifting process, machinery failure, operating environment, and injury events contributing to hoisting incidents. It is worth noting that the additional sixth and seventh cases are from Norway and Singapore, respectively, again demonstrating good practicality and effectiveness. There is, therefore, reason to believe that the framework could be extended to more regions.

V. DISCUSSION

A. ESTABLISHMENT OF A ROBOT-LED LIFTING CONSTRUCTION SYSTEM

Many of the cases in this study have shown that in lifting operations, operators and other site staff are exposed to personal safety risks, such as falls from height and strikes from objects, mainly because human operators are susceptible to fatigue, distraction, or operator error during lifting. However, robots can work continuously without these factors, freeing humans from these high-risk environments and reducing operational errors.

In March 2024, the introduction of NVIDIA corporation's Blackwell meant a thousand-fold increase in AI arithmetic over the last eight years [47]. Since then, the cost and energy consumption of building and running real-time generative AI large-scale language models on trillions of parameters has been reduced by nearly 96%. Against this backdrop, intelligence is also becoming an irreversible trend in the construction industry. As depicted in **Fig. 9**, this study proposes developing a robot-based lifting system. Common types of robots include mobile robots, arm robots, or combined systems. There are multiple reasons for creating a robot-driven lifting construction system, involving several factors such as safety, efficiency, accuracy, cost, and labor. Firstly, robots can work in hazardous environments overhead, underground, and in inclement weather, reducing worker exposure to high-risk sites. Navid et al. 2020 proposed an automated lifting path planning method for heavy crawler cranes, assuming continuous translational (i.e., X and Y directions) and discrete rotational motions of the object as it passes through obstacles in the workspace, which can find the shortest path for the planar motion of the lifted object in a congested modular construction project [48]. Second, robots can work long hours without interruption and are not limited by fatigue or rest time, significantly improving construction efficiency and project progress. They perform tasks following predetermined procedures and standards, reducing the variation of human operation during construction and improving the consistency and quality of construction. Taniguchi et al. 2024 developed a lifting collaborative robot by deriving the velocity displacement of a lifting maneuver performed by a human and reflecting it in the robot [49]. Third, robots can perform precision measurements and operations to ensure high-precision execution of lifting tasks, particularly important for complex and demanding construction tasks. Liu et al., in 2024, proposed a robot-assisted mounting system that uses multiple robots to control the component's attitude precisely. First, the target mounting pose of the element is extracted from a building information model, and then an optical marker-based approach is used to locate the robots and the pre-drilled holes. The robots will move according to the planned path and drive the component to the target installation position. The average positional deviation of the end-effector penetrating the pre-drilled hole is <1.2 mm and the average angular deviation is $<1^\circ$ [50]. Fourth, the construction industry faces labor shortages in many countries and regions. Robots can partially or wholly replace human labor, and advanced robotics can attract more young and skilled people to the construction industry. Jiang et al. 2024 proposed a transfer learning-based recognition framework to identify unsafe lifting behaviors of tower cranes, precisely tilting lifting, sudden braking, and sudden unloading, with an accuracy of 76.74% [51]. Based on visual recognition, the truss construction robot performs well in the gripping and lifting positioning process of composite concrete floor slabs. Facing the cross operation, the robot can change the gripping path independently to prevent collision with the offset inclined web reinforcement [52].

B. RECOMMENDATION FOR INCLUSION OF SAFETY MANAGEMENT OBJECTIVES IN CONTRACTS

During case validation, the authors' team found that general contractors were hiring small and micro-construction firms in many projects without incorporating safety plans into their contract selection criteria or the necessary budgets for safety plans and equipment allocations. This also resulted in contractor contractors not providing adequate safety resources. Therefore, by incorporating safety objectives into contract management, stakeholders are compelled to provide resources and support to maintain a commitment to

TABLE 13. Case description and validation.

No.	Brief description	Path validation	Accident photos
1	The tower crane's inner set frame and above the structure from the upper part of the tower suddenly fell to the tower, crushing the upper part of the first section of the tower, resulting in a vast tower shaking, pulling off the tower crane attached to the wall tie rod, the tower crane lost balance, from the foundation section of the tower above, the lifting arm, the balancing arm all toppled.	H1, H5 -> L2 ->M6 ->I5	
2	Operators in the rear of the carriage to complete a steel beam tied hooks began to lift, the process of lifting the steel beam touched the outside of the tightly together with another steel beam and made it tipped over in the rear of the carriage of the operators see the situation with their hands to support the steel beam, unsteady feet from the carriage fell to the ground. It was tipped over to the steel beam pressed to the waist and legs.	H2 -> L4, L5 -> O3 -> I2	
3	In the process of lifting and dismantling the last balancing block, the lower chord of the front and rear sections of the balancing arm disconnected, and the rear section of the balancing arm fell and overturned, changing from a horizontal state to an approximate vertical state, suspended in the air by the balancing arm tie rods. The three operators on the rear section of the balancing arm fell.	H3 -> L4, L5 -> M6 -> I1	
4	The operator did not follow the protocol for installing the gantry crane and directed another operator to stand on the gantry crane main girder on the right side of the designated position to hold it in preparation for the welding operation. When the lifting operation lifted the main girder to a height of about 8 meters from the ground, suddenly, four slings broke successively, causing the main girder and the operator to fall together.	H2, H5 -> L3 -> M2 -> I1	
5	Reinforced concrete blocks that were cut before the operator had been fixed with a wire rope on the hook of the car crane; the moment of cutting reinforced concrete blocks disconnected, the car crane overturned, resulting in reinforced concrete blocks and the crane arm toppling over.	H2, H4 -> L1, L5 -> M6 -> O3, O5 -> I5	
6	The installation of the raw water pumps encountered several interruptions due to weather and technical and operational factors. While members of the work team were lifting the pump off the deck, the sling broke, injuring two people standing nearby. The cable connected to the pump fell into the sea and struck two men, one of whom fell into the sea and the other lying head down on the deck.	H2 -> L3-> M2 -> O2 -> I2	
7	After the load has been picked up, the crane jib is lowered to reach the intended unloading position. The entanglement of the right cable results in a mechanical limitation of the luffing function of the crane arm. With the slack in the luffing wire rope, the entangled right cable begins to bear the weight of the lifting arm and the suspended load. Under continued stress, the right cable eventually breaks at the point of wrapping, and the swingarm falls downward in free fall. The hook block and load also fell to the ground, striking the deceased and another laborer who was working nearby.	H3 -> L2-> M2 -> I3	

Source: Case reports (1-5) and images from an open-source file on the Chinese government website. Case reports (6) from https://www.havtil.no/contentassets/370f70c8df9547c696172cf82d0bf712/2017_1321_eng-granskingsrapport-tambar-personskade-dodsulykke-maersk-interceptor.pdf. Case reports (7) from https://www.mom.gov.sg/-/media/mom/documents/safety-health/learning-reports/learning-report-tower-crane-failure.pdf

a safe working environment. A study in 2020 [53] highlighted the importance of allocating security risk in contracts, which can minimize third-party negligence claims under tort.

Firstly, the safety objectives of the construction enterprise should be listed in the contract management, including production safety accident control index, safe production, and civilized accident management objectives. Secondly, the construction enterprise training content should include: (1) the newly promulgated laws and regulations on production safety, safety technology standards, and normative documents. (2) Advanced production safety technology and management experience. (3) Typical accident case analyses. We also recommended that a particular office for the supervision of production safety expenses be set up to ensure that the relevant costs are applied to the fees required for safety technology measures, safety education and training, labor protection, emergency preparedness, and necessary safety evaluation, monitoring, testing, and demonstration. In addition, construction companies can make special announcements/discussions in advance during safety protocol meetings or safety awareness programs to ensure that all employees are aware of the efforts of senior management and site supervisors to improve safety [54].

C. OPTIMIZING THE FORMAT OF SAFETY INSPECTIONS

As the weighting results show, the essence of risk factors (L1 and L2) is the failure of security inspections. Safety personnel must handle many meetings, documents, statements, commitments, programs, notices, and other information. This is because building construction safety inspections include daily inspections, regular safety inspections, recurrent safety inspections, seasonal safety inspections, holiday safety inspections, start-up and resumption safety inspections, professional safety inspections, and equipment and facility safety acceptance inspections. Although such a system covers a wide range of areas, there are many

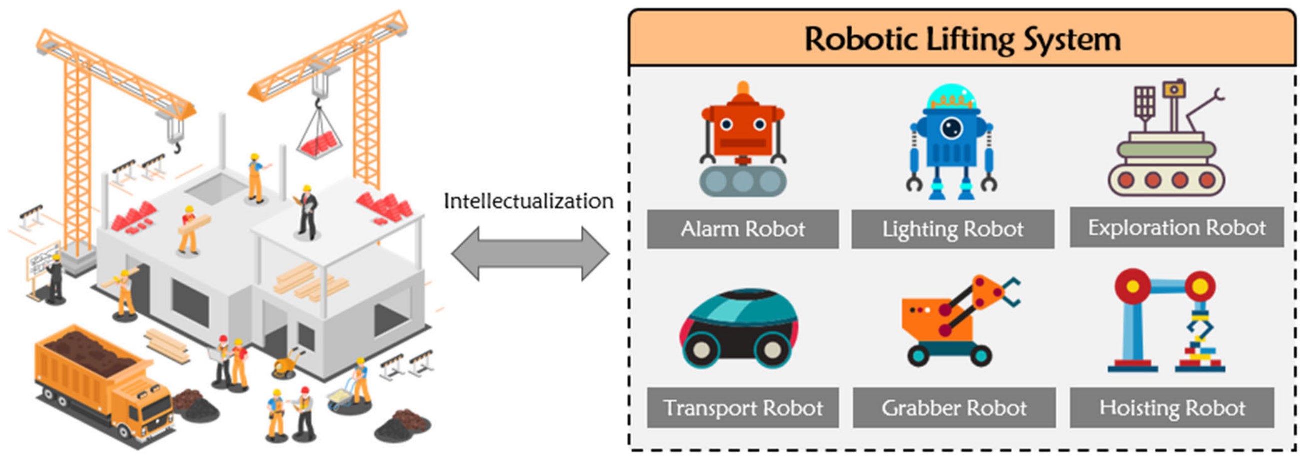

FIGURE 9. Robot-based lifting system (Source: Author's work).

problems in its actual implementation. Firstly, multi-level and multi-frequency inspections will soon lead to duplication of work and waste of resources. Frequent inspections also increase the burden on construction units, making it difficult for them to focus on actual safety management and problem-solving. Secondly, the effectiveness of safety inspections often depends on the professionalism and responsibility of the inspectors. However, in practice, the level of inspectors varies, and sometimes there is even formalism or going through the motions. Contractors are driven by profit and often play between accident risk and financial gain [55]. Many contractors who win tenders at low prices make more profits by compressing the cost of safety measures.

Therefore, this study suggests that when the subjective willingness of construction contractors to neglect safety management becomes stronger, government regulators can substantially increase penalties as a warning to others [56]. Secondly, an innovative safety inspection system based on a mobile phone application should be developed to streamline the inspection process and to integrate safety inspections across multiple projects at the company level. We also recommend developing protocols for the safe preparation and flight of drones in the construction industry to ensure their safe and effective use for safety inspections [57].

D. STRICT CONTROL OF CROSS-CUTTING OPERATIONS

Crossing operations are part of the risk factor (L3), which refers to crossing different types of work and operations simultaneously and in place. Most of the current site layout planning methods are from two-dimensional planar space, ignoring three-dimensional spatial factors; therefore, we propose to use unmanned Aerial Vehicle (UAV) based three-dimensional (3D) reconstruction for lifting site mapping and layout planning methods in the future [58]. Secondly, safety barriers such as safety shelters or safety nets should be installed within the fall radius of the crossover operation. When safety isolation measures have not yet been installed, a cordoned-off isolation zone should be set up, and personnel should be studied to enter the isolation zone. Third, the lifting strategy adapted to local conditions is also crucial. Some scholars have proposed the diagonal traction lifting construction scheme without bracing for the cable truss structure, i.e., to complete the assembly of upper and lower radial cables, ring cables, slings, and compression rods at low altitude without stress, to lift the cable rod system to high altitude by diagonal traction of upper radial cables through the jacks fixed in the upper radial anchor nodes, and then to actively tension the lower radial wires at the end, to make the whole structure reach the designed shape and pre-stressing level [59]. Finally, safety nets should be set up for cross-operation, erect scaffolds, and safety protection sheds. When construction is carried out on the facades of multi-story and high-rise buildings, a fixed safety protection net should be set up on the first floor and every four floors, and at the same time, a safety protection net should be set up that is raised with the height of the construction. Some alternatives to cranes could also be adopted. A new inclined construction hoist has been proposed for the efficient transport of resources in the construction of irregularly shaped high-rise buildings, which significantly reduces the total operating cost by 26.0%, the total resource transport time by 28.8%, and the direct transport time to the highest floor by 11.0% [60].

E. SIGNIFICANCE OF THE STUDY

Previous research [73] relied on a small amount of accident data and case studies, resulting in an insufficiently comprehensive indicator system and, thus, insufficient representativeness and reliability of the analyzed results. The framework developed in this study is based on the results of 200 accident reports and 322 questionnaires, which is more adequate in terms of evidence. Lifting construction risks are caused by a combination of factors. Still, previous studies [74] failed to fully consider the complex interactions between these factors when constructing the risk framework, resulting in a risk assessment model that may not fully reflect the actual situation. The framework developed in this study considers the interactions between factors of different dimensions and provides a quantitative visualization of the action pathways. Some frameworks that adopt a single methodology [75] fail to take full advantage of the strengths of multiple approaches for comprehensive analyses due to the lack of integration of various methods and techniques. The framework of the current building block provides practicality and interpretability by integrating the strengths of qualitative and quantitative methods.

Therefore, the study contributes to the body of knowledge in several ways. Firstly, it fills an essential gap in the existing literature by creating a novel and comprehensive framework for lifting safety risk assessment by integrating STAMP with PLS-SEM. This integration allows for a more systematic and thorough analysis of safety risks, going beyond the traditional approach that usually analyses individual risk factors in isolation. Second, this study empirically validates the proposed framework through actual case studies, demonstrating the applicability and robustness of the framework in real-world scenarios. This validation increases the credibility and reliability of the framework, making it a valuable tool for researchers and practitioners. Thirdly, by identifying and modeling the complex interactions between various risk factors, the study provides new insights into the underlying mechanisms and system weaknesses that lead to lifting incidents. These insights can inform the development of more effective safety management strategies and interventions. Finally, combining STAMP, PLS-SEM, and IWM methods to form a new hybrid approach also provides a methodological reference for analyzing accidents of other types or in different industries.

VI. CONCLUSION

Lifting operations are vital in building construction, but high risks accompany them. Although previous studies have explored its safety issues, the status quo of frequent accidents has never been improved. The reason for this is that many of the earlier frameworks are not practical enough, which include unvalidated indicator factors, consideration of human factors only, failure to consider the transmission relationship between the dimensions of risk, and inability to accurately respond to the chain of development of safety accidents (reflecting only the causes of accidents). This study aims to establish a lifting safety risk framework based on STAMP theory and PLS-SEM methodology to reveal the risk transfer mechanism and contribute to safety management. Firstly, the study summarizes the factors affecting lifting safety and the main types of accidents through a literature review and the STAMP theory. Then, a quantitative risk management framework was constructed using the PLS-SEM method through 322 questionnaires obtained in Guangdong Province, China. Through the independence weight coefficient method, the relevant factors were weighted and ranked to identify the highest risk factors that need to be prioritized for management. Finally, the risk framework was validated based on 200 real lifting accident cases from China and some lifting accident cases from overseas, such as Singapore and Norway. The results show that the framework effectively identifies and responds to accident causation and risk transfer in the lifting process, which helps reduce the accident rate and optimizes the safety management process. Compared with previous studies, this study is more systematic and comprehensive. In addition, the study is based on real-life cases, which makes it more credible, and the framework is not only applicable to China but also has the potential to be extended to other countries. Overall, the STAMP-HC risk framework constructed in this study can help industry practitioners and researchers understand the critical risks faced by China and other similar developing countries when lifting construction and bridge the knowledge gap regarding accidents in this niche area. Combining STAMP, PLS-SEM, and IWM methods to form a new hybrid approach also provides a methodological reference for analyzing accidents of other types or in different industries.

Although this study has achieved significant results in constructing a framework for lifting construction risk, some limitations remain. Firstly, this study may still not cover all accident cases despite the extensive case data in this study. Future studies may consider further collaborating with the government to expand the case base. Second, the questionnaire data of this study came from Guangdong Province, which reduces the generalizability of the findings. Finally, this study suggests that an automated assessment and monitoring system based on intelligent algorithms such as Transformer Architecture (TA), Particle Swarm Optimization (PSO), and Bat Algorithm (BA) could be developed in the future. Future research could also try, e.g., dynamic Bayesian network (DBN) and conduct sensitivity analyses to explore how different model specifications or assumptions affect the robustness of the findings.

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