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Research Article

System Hazard Analysis of Tower Crane in Different Phases on Construction Site

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Tower crane accidents frequently occur in the construction industry, often resulting in casualties. The utilization of tower cranes involves multiple phases including installation, usage, climbing, and dismantling. Moreover, the hazards associated with the use of tower cranes can change and be propagated during phase alternation. However, past studies have paid less attention to the differences and hazard propagations between phases. In this research, these hazards are investigated during different construction phases. The propagation of hazards between phases is analyzed to develop appropriate safety management protocols according to each specific phase. Finally, measures are suggested to avoid an adverse impact between the phases. A combined method is also proposed to identify hazard propagation, which serves as a reference and contributes to safety management and accident prevention during different tower crane phases in the construction process.

1. Introduction

In construction sites, tower cranes are used for the vertical and horizontal transportation of materials [1]. It is essential equipment for most construction projects, especially for high-rise buildings [2]. Typically, they need to be reinstalled on the construction site once the components of the tower crane leave the factory. As the height of a construction project increases, tower cranes are necessary, and they eventually must be climbed. Furthermore, maintenance and dismantlement must be performed. Thus, a tower crane is not only a piece of auxiliary equipment in construction but also a construction object with complicated processes [3]. This negatively impacts on-site construction safety. In this investigation, 149 accident analysis reports on a tower crane in construction sites in China were collected for the period from 2015 to 2019. The accidents resulted in a total of 216 deaths and 89 injuries and led to adverse social impacts. Therefore, it is essential to analyze the hazards associated with the deployment of tower cranes on construction sites to prevent such accidents.

Tower cranes on construction sites consist of the following phases: installation, usage, climbing, and dismantling. According to the investigated accidents, the processes and constructors are not the same for the different construction phases. This results in the occurrence of different types of accidents during different phases. Moreover, hazards propagate between each phase and the propagation also affects the safety of the tower crane. Therefore, it is necessary to analyze the hazards associated with each construction phase and to explore the differences and interrelations between them.

To investigate the characteristics and propagation of hazards during the different construction phases of a tower crane, a combination of the IDEF0 (ICAM Definition method) along with the STAMP (Systems-Theoretic Accident Model and Processes) and its analysis technology STPA (System Theoretic Process Analysis) is adopted. This approach was undertaken to develop a safety system model for tower cranes on-site and to further identify the corresponding hazards that are present during the different phases. The combinatorial methods are found effective in exploring the hazards propagation in the workflow. The results of this study show the differences in the hazards in different tower crane phases, which can provide a specific target for accident prevention. The research also explains the hazard propagation between the different phases in an attempt to avoid the accidents caused by the hazards of previous phases.

The research framework is shown in Figure 1.

This study makes the following contributions to the body of knowledge.

(a) Since the hazards are different between phases of a tower crane on construction site, we analyze the hazards of a tower crane in different phases and compare them.

(b) This research points out that the consequence of the previous phase may influence the safety of the subsequent phase. It is helpful to dynamic risk management.

(c) The combination of IDEF0 and STAMP is applied on the tower crane for hazards analysis. This method is useful to analyze the hazard transition in a process.

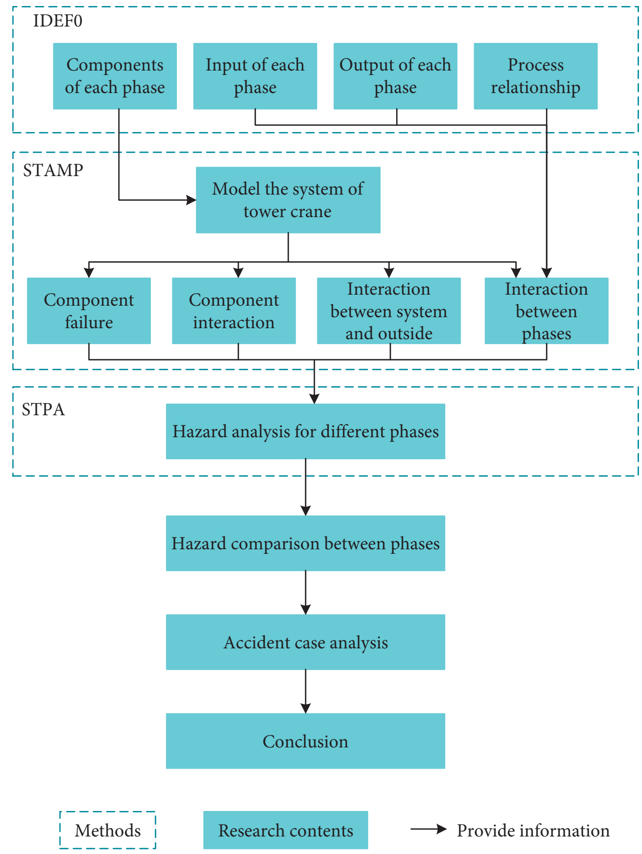


Figure 1: Research structure.

2. Literature Review

The literature review is summarized based on previous studies that primarily investigated tower crane safety management and different research methods, namely hazard analysis.

2.1. Tower Crane Safety Management. The safety management of tower cranes and the analysis of the contributing factors that influence tower crane safety have been previously reported based on multiple perspectives. Based on literature reviews and site visits, Shapira and Lyachin [4] identified several safety factors including the project conditions, the environment, the human factor, and the safety management procedures. Beavers et al. [5] investigated crane incidents based on OSHA (Occupational Safety and Health Act) incident data and highlighted the importance of safety training for managers and operators. Raviv et al. [6] investigated 51 crane accidents, as well as 161 near-misses. They also investigated the importance of crane safety risk factors and the relationship between human and technical factors [7]. According to the literature review, the human factor, the environment, the safety management procedures, and the equipment quality are all associated with tower crane safety [8].

Furthermore, although different hazards may occur during different phases, previous works often focused on the usage phase [9, 10]. Some researchers have investigated dynamic structural performance, the interaction effects of multitower crane operation, the load, and the environment of the tower crane in the usage phase [11–13]. In addition, the factors that impact safety during the installation (including climbing) and dismantling phases have been analyzed [14]. However, there are few comparative studies on the multiple phases of tower cranes on the construction site. Equally important are the interrelationships between the hazards associated with different phases, which have not been investigated to date. In this paper, we address the aforementioned limitations in the literature.

2.2. Hazard Analysis. The conventional hazard analysis methods include preliminary hazard analysis (PHA), system hazard analysis (SHA), fault tree analysis (FTA), event tree analysis (ETA), failure mode and effects analysis (FMEA), and failure mode effects and criticality analysis (FMECA) [15–17]. With the development of system thinking, system analysis methods such as AcciMap, STAMP, FRAM, and the 2–4 Model have been increasingly utilized in contemporary studies to analyze hazards [18]. According to one of the main tenets of system thinking, accidents are not caused by a series of linear events. Moreover, the relationships and interactions among the system elements should be considered [19]. A complex system of accidents may be analyzed in detail to define the relationship between several factors at different organizational levels based on the system thinking principle [20, 21]. It is an important method for the analysis of the cause of accidents and safety hazard identification.

These system thinking methods have different objectives. A summary of each method is presented in Table 1. These methods have also been compared in several investigations and it was concluded that the STAMP model results in a more comprehensive set of conclusions and is more reliable than other accident system analysis methods [26–28]. The STAMP model involves various elements of a system, such as the individuals, the objects, the organizations, and the environment [29]. The most important is that the STAMP model concerns the interactions of components and systems. As the tower crane safety system is a complex system

Table 1: System thinking method.

Method	Main idea
AcciMap	AcciMap analyzes accidents concerning six organizational levels, including government policy and budgeting, regulatory bodies and associations, local area government planning and budgeting (including company management), technical and operational management, physical processes and actor activities, and equipment and surroundings [22].
STAMP	Accidents are not due to independent component failures but occur when external disturbances, component failures, or interactions between system components cannot be controlled appropriately [23].
FRAM	Functional resonance theory is the theoretical basis of FRAM model construction and states that there are many functions with normal fluctuations in the system, and when the normal fluctuations of a particular function are abrupt, an accident occurs [24].
2-4 model	The model indicates that the occurrence of accidents is the result of the development of individuals and organizations in four stages: one-off behavior, habitual behavior, operational behavior, and guide behavior. The model considers the direct cause of an accident to be the unsafe behavior of humans or unsafe conditions of equipment and the environment. The root cause is a weak organizational safety culture [25].

with different components and phases, the STAMP model can contribute to the safety system analysis of the tower crane during different construction phases in this study.

Based on STAMP, two techniques have been developed by researchers. One is System Theoretic Process Analysis (STPA) and the other is Causal Analysis based on STAMP (CAST) [30, 31]. STPA is utilized for system hazard analysis, whereas CAST is utilized for accident cause analysis [32]. Since this research is focused on system hazard analysis, STPA technology is utilized.

3. Methodology

3.1. IDEF0. IDEF0 is one of the IDEF (ICAM Definition method) developed by the US Air Force's ICAM (Integrated computer-aided manufacturing) to describe the system manufacturing process using structured graphics [33, 34]. This approach utilizes boxes that represent activities and arrows that represent interfaces that affect the activities and mainly includes the following four interfaces:

(i) *Input interface*: Resources required to perform or complete specific activities, placed on the left side of the box diagram.

(ii) *Output interface*: Processed or modified output by the activities, placed on the right side of the box diagram.

(iii) *Control interface*: The conditions and restrictions required by the activities, placed above the box diagram.

(iv) *Mechanism interface*: The tools needed to complete the activities, including personnel, facilities, and equipment, are placed below the box diagram. The basic structure of IDEF0 is shown in Figure 2.

The output of the previous activity may be utilized as the input of the next activity when IDEF0 is used to analyze a series of process activities. In this research, the construction process of the tower crane is analyzed via this method.

3.2. STAMP. For accident analysis based on system theory, Leveson proposed STAMP (Systems-Theoretic Accident Model and Processes) that considers safety as a control problem and asserts that accidents occur when the control system cannot adequately address system component failures, external disturbances, or dysfunctional interactions among the system components.

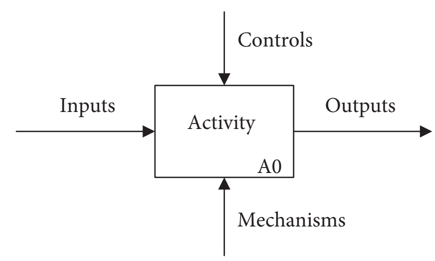


Figure 2: Basic structure of IDEF0.

The STAMP model was compared to other accident analysis methods in several previous works, including AcciMap, FRAM, HFACS, and 2-4 model [35]. The results of these studies also suggest that STAMP has better performance on hazard analysis for complex systems. Based on our literature review, the STAMP model can reflect both the impact of system components and process interactions [36]. As the tower crane safety system is a complex system with different components and phases, the STAMP model can contribute to the improvement of the safety system analysis of tower cranes during different construction phases in this study.

3.3. STPA. System Theoretic Process Analysis (STPA) is a system hazard analysis based on the STAMP model. It identifies hazards by analyzing unsafe behaviors in the STAMP control model [37–40]. The STPA Handbook defines the steps of STAMP and STPA as follows [41]:

(1) Define the purpose of the analysis

(2) Model the control structure

(3) Identify loss scenarios

(4) Identify unsafe control actions

According to STPA Handbook, the steps involved in STAMP and STPA are shown in Figure 3.

4. Hazards of Tower Crane in Different Phases

4.1. Process Analysis of Tower Crane with IDEF0. In principle, the installation, usage, climbing, and dismantling phases of

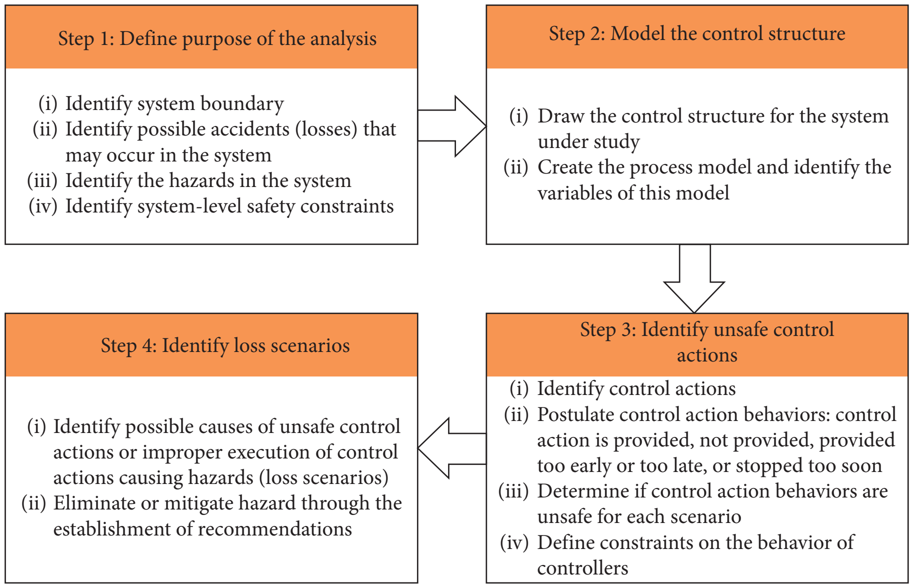


Figure 3: STAMP and STPA steps.

the tower crane occur at construction sites. Once the tower crane is installed, it is frequently used and climbed until it is removed at the end of the service cycle. A structured flowchart is generated via IDEF0 as shown in Figure 4. This figure shows the ordinal relations and involved components of tower crane installation (A1), usage (A2), climbing (A3), and dismantling (A4). In order to analyze the system input of installation (A1), the preparation for tower crane installation (A0) is also considered in the workflow.

According to the site investigation, the personnel, equipment, and task of each phase are listed in Table 2.

The personnel involved in the installation, climbing, and dismantling phases of the tower crane are primarily the same. The individuals and components involved in the climbing and dismantling phases are mostly the same as those of the installation phase. The differences are the system input and the working activities. The climbing process involves repeating certain steps of the installation process, namely the installation of the mast section. The dismantling process entails the inverse of the installation process. In consideration of the similar components and interactions in installation, climbing, and dismantling, the installation phase is selected to represent others to analyze internal system hazards. In the usage phase, the lifting system that consists of the tower crane and the lifting object is considered as the controlled object. The personnel in the usage phases mainly include the operator, rigger, and signalman. This is the process in which the operator uses the tower crane to lift the objects and is relatively different from the installation phase. Hazard analysis of the usage phase is therefore performed separately. Moreover, the hazards caused by the interaction among the phases are also analyzed separately.

4.2. System Analysis of Tower Crane with STAMP. The STAMP model has good performance for system modeling and safety analysis and is broadly applied to accident analysis in astronautics, fire disasters, traffic incidents, and other industries [42–44]. However, it is seldom applied to system hazard analysis in the construction industry, and the tower crane in particular. In the following, the STAMP method is adapted to model the installation and usage phases of the tower crane. Moreover, the proposed STPA method based on STAMP is applied to analyze hazards, namely, the unsafe behavior of humans and the unsafe state of the objects.

Since the STAMP model is proposed in the context of system theory, the system model is considered as a hierarchical structure in which each layer imposes constraints on its lower layers. In the complete STAMP, several superstructures are involved, including Congress and Legislatures, Government Regulatory Agencies, and Companies. However, in this investigation, only hazards at the construction site are analyzed and superstructures such as government and enterprise are not considered. Thus, the core content of the STAMP model, i.e., the control loop and the process model, is utilized in this work (Figure 5).

In the control loop and process model of STAMP, the boxes represent components, and the arrows represent the interactions between the components, the system, and the outside world. The components are listed as follows:

(i) *Controlled process*: The object of information perception, control decision, and instruction execution in the system process.

(ii) *Sensors*: Collect information during the controlled process and feedback for other components.

(iii) *Controller*: Provide control decisions based on system feedback, including feedback from human supervisors and automation controllers.

(iv) *Actuators*: According to the instructions issued by the controller, the operation is then conducted on the controlled object.

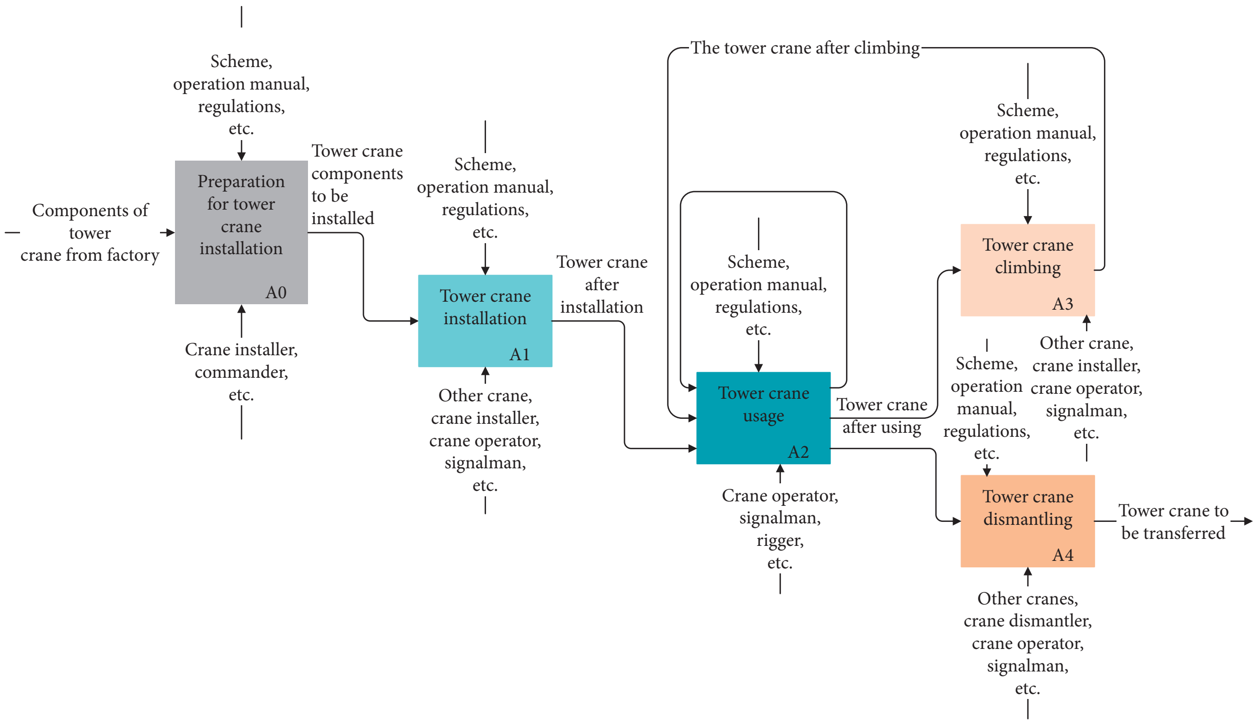


Figure 4: Tower crane phases on-site (IDEF0).

Table 2: Features of tower crane phases.

Phase	Task	Personnel	Equipment
Installation	The workers assemble the components to install a tower crane.	Installers, operator, rigger, signalman, supervisor, and manager	Truck crane and other tower cranes
Usage	The workers use a tower crane to lift materials.	Operator, rigger, and signalman	Tower crane
Climbing	The workers install a subassembly of the tower crane mast to add the height of the tower crane.	Installers, operator, rigger, signalman, supervisor, and manager	Truck crane and other tower cranes
Dismantling	The workers dismantle the tower crane to components.	Installers, operator, rigger, signalman, supervisor, and manager	Truck crane and other tower cranes

The interaction between components consists of the feedback of information and the control loops. A dynamic balance is also maintained by the system via the feedback and control of the components. The interactions between the system and the outside world include the process input, the process output, and the disturbance due to the outside world. Generally, the STAMP model is applied to system security analysis related to three aspects: component failure, component interaction failure, and external influence.

There are few safety analysis methods that consider system inputs and outputs. They usually consider factors within the system. STAMP can analyze the interaction between phases via the input and output analysis. It is the main reason to choose this method in our research. The process input and output of STAMP can correspond to the IDEF0 interface. Meanwhile, the controls and mechanisms of IDEF0 can help establish the control model of STAMP. Thus, it is feasible to combine IDEF0 and STAMP in this study. This method can analyze the hazard transition between different phases.

4.2.1. Tower Crane STAMP Model for the Installation Phase. Tower crane installation is a process that involves rigorous operation steps, short operation time, complicated procedures, and high professional requirements of the workers. Younes and Marzouk [13] analyzed and listed the components required for the installation of the tower crane as the foundation, basic mast, main jib, counter jib, winding gear, and operating room. All these components constitute the tower crane and form the controlled process of the system. The installation processes include sensing, controlling, and execution in the vicinity of the tower crane and its components. The supervisor acts as a sensor and collects on-site information, including the status of the tower crane and the behavior of the operators, which is then fed back to the manager. The manager acts as a controller, which involves making decisions and sending out operational commands based on the installation scheme and the information received from the construction site. Based on the directives of the supervisor, the workers install the tower crane according to the installation scheme and the operational commands

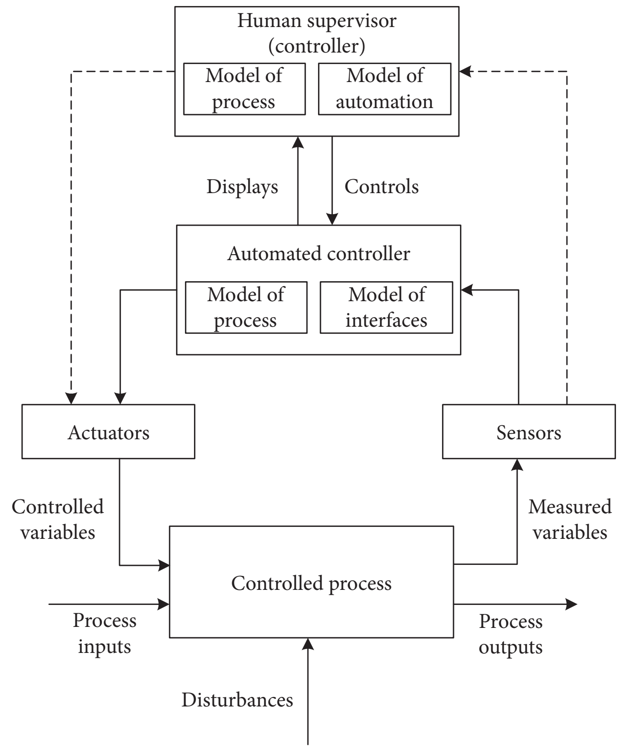


Figure 5: The control model of STAMP.

from the manager. The workers consist of an installer, operator, signalman, and rigger. The latter three can be the individuals that also operate the tower crane or those who use other lifting machinery to lift the tower crane components. Moreover, the completion of the previous phase, as the process input, affects the installation process. The external disturbance affects the system components, including the construction environment and the weather conditions. Likewise, the completion of the installation phase as the process output also affects the next phase. According to the previous analysis, the system control loop and the process model for the tower crane installation process are constructed using the STAMP method, as illustrated in Figure 6.

4.2.2. Tower Crane STAMP Model for the Usage Phase. The usage phase of the tower crane consists of several work components and participants different from the installation, climbing, and dismantling phases. Therefore, the analysis is performed separately. In the usage phase, the operators, riggers, and signalmen lift objects by operating the tower crane. Hence, the lifting system that consists of the tower crane and the lifting objects is considered as the controlled process. The tower crane monitoring system acts as a sensor to monitor the status of the lifting system. If the monitoring system identifies abnormal data, the security system, including lifting limiters, lifting height limiters, and other functional systems, limits the operation of the tower crane to ensure safety. The signalman acts as a human sensor to observe the state of the lifting system and to transmit signals to the operator and riggers. The operator evaluates the status of the lifting system by observing and monitoring system data and the information provided by the signalman. The operator then informs the signalman to command the riggers to cooperate with the operation. According to the command of the signalman, the riggers operate the hook and the lifting objects and cooperate to complete the lifting task. Figure 7 shows the STAMP system model of the tower crane in the usage phase.

4.3. Hazards Analysis of Tower Crane with STPA. In the STAMP model, hazard analysis involves three components: component failure, component interaction failure, and external influence. In this research, the system input and output at the installation, climbing, and dismantling phases are different, whereas the other internal components and external disturbance of the system are almost the same. Therefore, system interactions that involve system input and output are analyzed separately. The hazard analysis is conducted based on four aspects: component failure, component interaction failure, external disturbance, and system interaction. The first three components are analyzed in this section. Referring to the STAMP model diagram, the relevant components and processes of the installation are also listed, and the hazards are analyzed using the STPA method. STPA defines the following four unsafe control actions:

(1) Action required but not provided;
(2) Unsafe action provided;
(3) Incorrect timing/order;
(4) Terminated too soon/applied too long.

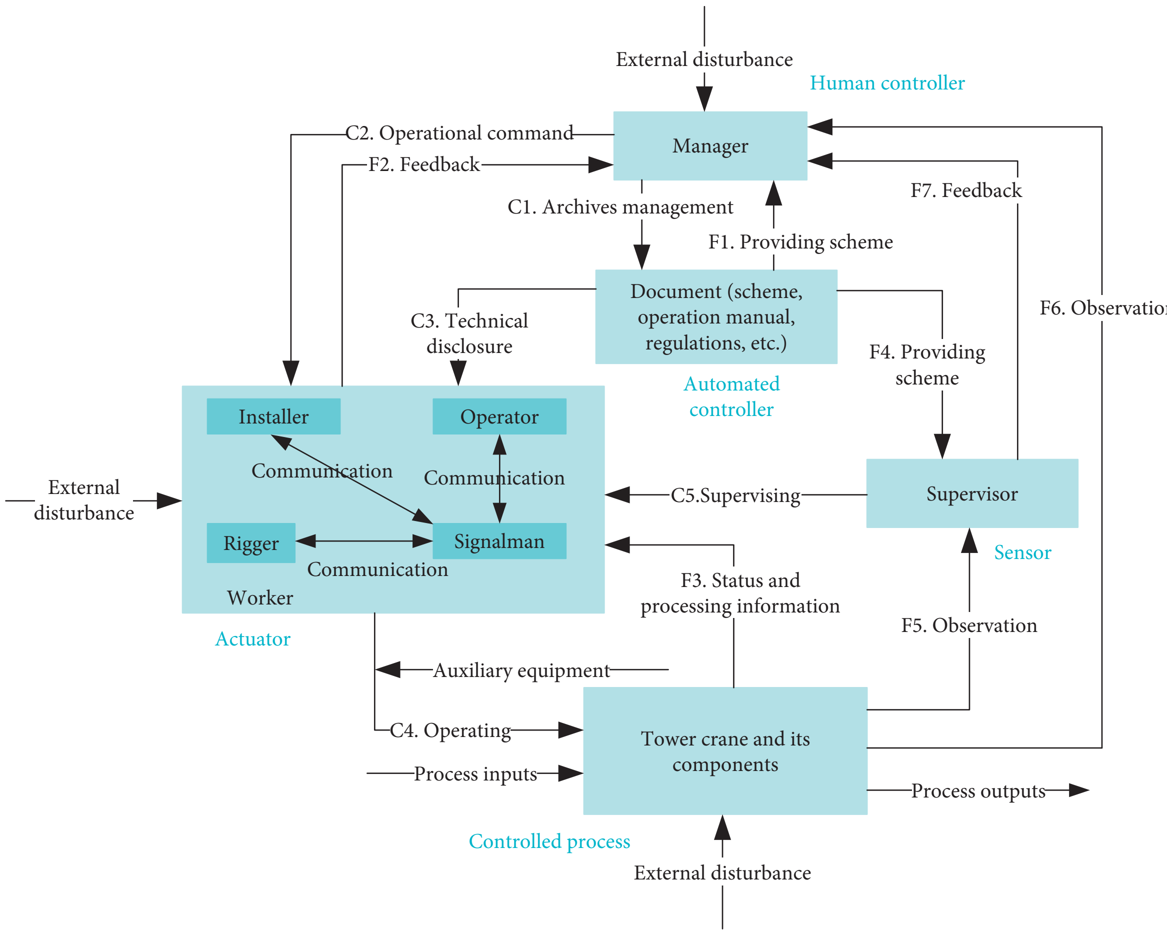


Figure 6: STAMP model in installation.

The specific descriptions of the hazards are provided based on the analysis of 149 tower crane accident reports and construction site investigations. In China, once an accident occurs, the government will organize an expert group to investigate the accident site and disclose the accident report to the public. The accident report will specify the course of the accident, the causes, and the person responsible for the accident. The tower crane accident reports can be obtained from the website of the Ministry of Housing and Urban-Rural Development of the People's Republic of China. We collected 149 tower crane accidents that happened in the period from 2015 to 2019. According to the analysis and statistics of the accidents, 27 occurred during installation, 19 during climbing, 11 during dismantling, and 92 during usage. Figure 8 shows the information of the accident reports collected in this research.

Among all the phases, the number of accidents in the usage is the largest. In the service cycle of the tower crane, the time in the usage phase is the longest. The time for installation, climbing, and dismantling is only a few days. Table 3 shows the number of casualties at each phase. According to the statistic table, the average number of casualties in the usage phase is lower than the other three phases. It indicates that the consequences of the accident during the installation, climbing, and dismantling phases are serious. Therefore, the safety of the tower crane in these phases is also worthy of attention.

Throughout this investigation, from November 2017 to December 2019, the research team conducted field studies at least twice a month at the construction sites of three high-rise building projects and a bridge project in China. The three high-rise building projects included at least two large tower cranes. In the case of the bridge project, each pier of the bridge was equipped with a small tower crane. Thus, several tower cranes were simultaneously in different phases. Fifty-two research reports were generated based on the observation of each phase during the service cycle of the tower cranes.

4.3.1. System Hazard Analysis for Installation Phase. According to the accident reports from the government and research reports from the construction site, the hazard descriptions associated with the tower crane can be extracted. Using this information, the hazards analysis for the tower crane can be conducted by STPA.

(1) Component failure. This refers to the possible unsafe states of the system components, including the tower crane and its elements, the relevant personnel, and the documents. The unsafe state of the components is an absent and

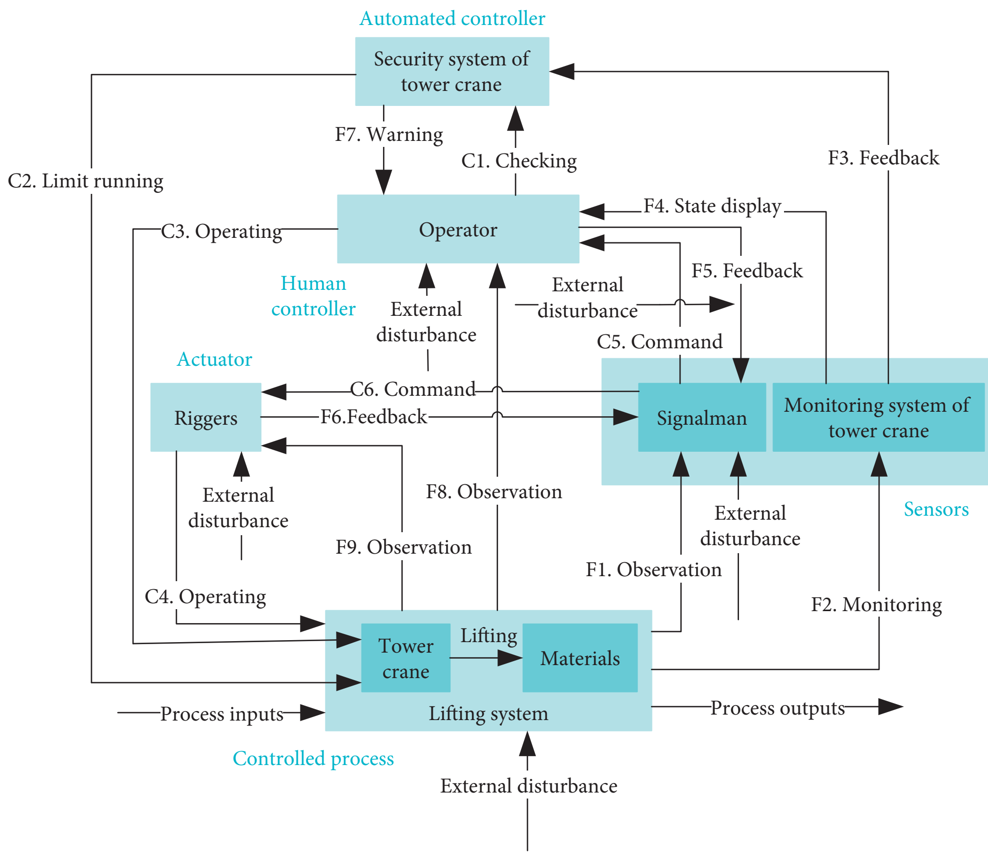
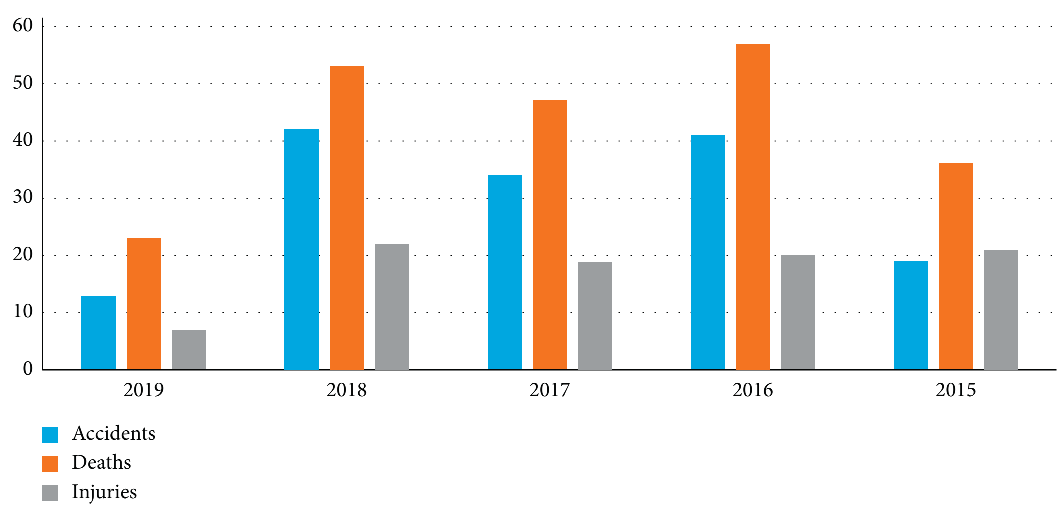


Figure 7: STAMP model in the usage phase.



(a)

Figure 8: Continued.

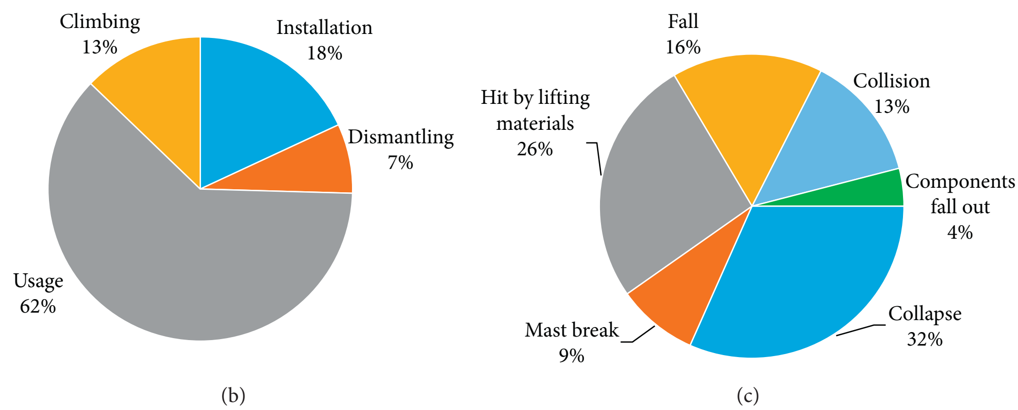


Figure 8: Information of accident reports: (a) Accident consequence; (b) Accident phase; (c) Accident type.

Table 3: Casualties of tower crane accidents.

Phase	Accidents	Deaths	Injuries	Average casualties
Installation	27	42	32	2.74
Usage	92	110	30	1.54
Climbing	19	41	18	3.10
Dismantling	11	23	9	2.91

unqualified component. The hazards associated with the installation phase (HIP) due to component failure are gained via the analysis of each component in the STAMP model, as presented in Table 4.

(2) Component Interaction. In the STAMP model, the component interaction is divided into the control and feedback processes. The difference between them is that the feedback process only yields data and not the decision commands. The control process also yields decision results and commands. The interaction between the components includes the control and feedback process. According to the four unsafe constraints of the STPA, the component interaction hazards associated with the installation phase are analyzed, and the analysis results are shown in Table 5.

(3) External Disturbance. Disturbances from the outside may influence components and interactions. The hazard analysis results are shown in Table 6.

4.3.2. System Hazard Analysis for Usage Phase. According to the accident reports and construction site investigations, the hazards associated with the usage phase (HUP) are analyzed using similar methods to the aforementioned approach. Table 7 lists the component failure associated with the usage phase and analyzes the corresponding hazards. Table 8 shows the hazards caused by components interaction. The hazards caused by external disturbances are presented in Table 9.

4.3.3. Hazards of System Interactions during the Four Phases. The system interactions include the inputs and outputs, which differ for the different phases based on the state of the construction process of the tower cranes on-site. According to the IDEF0 map of the tower crane, the outputs of previous phases are the inputs of the next phase. The inputs and outputs of each phase are shown in Figure 9. The hazards of system interactions mean the negative effects of the previous process. The arrows show the propagation path of hazards. According to the accident reports and research reports, some descriptions of the hazards associated with system interactions during the four phases can be found. Table 10 lists the hazards of system interactions, including hazards associated with the installation phase (HIP), hazards associated with the usage phase (HUP), hazards associated with the climbing phase (HCP), and hazards associated with the dismantling phase (HDP).

5. Case Study

To verify and explain the practical significance of the preceding results, a case study was conducted based on random selection from the available 149 accident cases. The selected tower crane collapse incident resulted in 3 deaths and occurred on December 10, 2018, in Shanxi, China. The tower crane was lifting 1.7 t of cement when it leaned, and the mast was fractured. The main jib then fell, causing the death of the operator. The counter jib also fell and killed two workers. The on-site sceneries of the accident are shown in Figure 10. After the accident, the Shanxi province government organized an expert group to conduct an investigation on the scene immediately. Then, the accident investigation report was disclosed on April 16, 2019. According to the accident investigation report, all the on-site hazards that caused this accident can be found in the hazard list in this research. The hazards and their propagations in this accident are shown in Figure 11.

Although this accident occurred during the usage phase, the hazards involved A0, A1, A2 phases. The inadequate preparation caused a hazard in installation (HIP55). Based on the presented research results, the hazards associated with the installation phase were propagated to the usage phase, resulting in hazards of the usage phase: unqualified installation of the tower crane (HUP63). With the use of the tower crane, the tower crane was gradually ageing. The tower crane was assembled on-site, which was mainly connected

Table 4: Component failure of installation phase.

Component	Hazard
Tower crane and its components	HIP1 defective foundation of tower crane HIP2 unstable integral structure of tower crane HIP3 nonconforming member of tower crane HIP4 deletion of tower crane member HIP5 unstable fastenings
Manager/supervisor/worker	HIP6 lack of staff HIP7 lack of ability or qualification HIP8 mental and physical distress HIP9 weak safety concept HIP10 failure to wear protective equipment as required
Document	HIP11 lack of document HIP12 incomplete scheme HIP13 design error

Table 5: Unsafe control action behaviors in the installation phase (STPA).

Interactions	Action required but not provided	Unsafe action provided	Incorrect timing/order	Terminated too soon/ applied too long
C1. Archives management	HIP14 scheme has not been inspected	HIP15 wrong scheme has been provided	HIP16 scheme inspection has not been conducted before installation	—
C2. Operational command	HIP17 manager has not provided operational command	HIP18 manager command error	HIP19 operational command delay	HIP20 command behavior last too long
C3. Technical disclosure	HIP21 worker has not participated in the technical disclosure	HIP22 incorrect technical disclosure	HIP23 technical disclosure has not been conducted before installation	—
C4. Operating	HIP24 necessary operations have not been conducted	HIP25 missing operation	HIP26 sequence of operations error	HIP27 operations last too long
C5. Supervise	HIP28 supervisors have not observed the behavior of the workers	HIP29 supervisor has not stopped the unsafe behavior of the workers	HIP30 cessation of the unsafe behavior was too late	HIP31 supervisor has not supervised the whole process
F1. Provide scheme	HIP32 manager has not participated in the technical disclosure	HIP22 incorrect technical disclosure	HIP23 technical disclosure has not been conducted before installation	—
F2. Feedback	HIP33 workers have not reported to the manager	HIP34 workers have misreported	HIP35 workers have reported too late	—
F3. Status and process information	HIP36 workers have not observed the status of the tower crane	HIP37 workers have misjudged the status of the tower crane	—	—
F4. Provide scheme	HIP38 supervisor has not participated in the technical disclosure	HIP22 incorrect technical disclosure	HIP23 technical disclosure has not been conducted before installation	—
F5. Observation	HIP39 supervisor has not observed the status of the tower crane	HIP40 supervisor has misjudged the status of the tower crane	—	HIP31 supervisor has not supervised the whole process
F6. Observation	HIP41 manager has not observed the status of tower crane	HIP42 manager has misjudged the status of tower crane	—	—
F7. Feedback information	HIP43 supervisor has not reported information to the manager	HIP44 supervisor provided wrong information to manager	HIP45 supervisor provided feedback too late	—

by bolts. After long-term work, the tower crane was rusty and the connections were loose. These aging phenomena affected the safety of the tower crane because there was no maintenance, which caused a hazard of usage (HIP64). This accident case suggests that the hazards associated with previous phases can transmit and adversely affect the safety of subsequent phases, which is consistent with the results of this research.

Table 6: External disturbance of installation.

Components and interactions	External disturbance
Worker	HIP46 The pressure of reward and punishment mechanism HIP47 short of safety education and training HIP48 schedule pressure
C4. Operating	HIP49 auxiliary equipment failure
Tower crane and its components	HIP50 bad weather HIP51 complex operating environment HIP52 lack of warning signs
Manager	HIP48 schedule pressure
Communication	HIP53 noise HIP54 failure or interference of communication tools

Table 7: Component failure of usage phase.

Component	Unsafe state
Lifting system	HUP1 defective foundation of tower crane HUP2 unstable integral structure of tower crane HUP3 nonconforming member of tower crane HUP4 deletion of tower crane member HUP5 unstable fastenings HUP6 tower crane over the service life HUP7 tower crane operating system malfunction HUP8 materials too large or too heavy
Monitoring system of tower crane	HUP9 lack of monitoring system HUP10 sensors failure
Security system of tower crane	HUP11 lack of security system HUP12 security device failure
Signalman/operator/rigger	HUP13 lack of staff HUP14 without ability or qualification HUP15 mental and physical distress HUP16 weak safety concept HUP17 failure to wear protective equipment as required

Table 8: Unsafe control action behaviors of usage phase (STPA).

Interactions	Action required but not provided	Unsafe action provided	Incorrect timing/order	Terminated too soon/applied too long
C1. Check	HUP18 operator has not routinely checked	HUP19 illegal shut down or destroy the security system	—	—
C2. Limit running	Same as "component failure."	HUP20 security device setting error or fault	HUP21 security device is not sensitive	—
C3. Operating	HUP22, the operator has not performed the operation	HUP23 misoperation of operator	HUP24 Operator's operation is not timely	HUP25 insufficient or excessive lifting height and swivel angle
C4. Operating	HUP26 rigger has not checked the lifting system	HUP27 rigger illegally has bound or placed the lifting object	HUP28 rigger has not escaped to a safe place when lifting	—
C5. Command	HUP29 signalman has not provided command	HUP30 command error	HUP31 command not timely	—
C6. Command	HUP29 signalman has not provided command	HUP30 command error	HUP31 command not timely	—
F1. Observation	HUP32 signalman has not observed the status of tower crane	HUP33 signalman has misjudged the status of tower crane	—	—
F2. Monitor	HUP34 the tower crane monitoring system is not open	HUP35 sensors are not sensitive	—	—

Table 8: Continued.

Interactions	Action required but not provided	Unsafe action provided	Incorrect timing/order	Terminated too soon/applied too long
F3. Feedback	HUP36 monitoring data have not uploaded	HUP37 data missing or error	HUP38 data is not uploaded timely	—
F4. State display	HUP39 monitoring data is not visual	HUP40 wrong data have been displayed to the operator	—	—
F5. Feedback	HUP41 operator has not submitted feedback to the signalman	HUP42 feedback information missing or error	HUP43 feedback is not timely	—
F6. Feedback	HUP44 rigger has not sent a signal	HUP45 signal sending error	HUP46 the signal is not sent in time	—
F7. Warning	HUP47 lack of alarm	HUP48 false alarm	—	HUP49 alarm ringing after trouble removal
F8. Observation	HUP50 operator has not observed the status of tower crane	HUP51 operator has misjudged the status of tower crane	—	—
F9. Observation	HUP52 rigger has not observed the status of tower crane	HUP53 rigger has misjudged the status of tower crane	—	—

Table 9: External disturbance of usage phase.

Components and interactions	External disturbance
Worker	HUP54 the pressure of reward and punishment mechanism HUP55 short of safety education and training HUP56 schedule pressure
Lifting system	HUP57 bad weather HUP58 complex operating environment HUP59 lack of warning signs HUP60 multitower crane interaction
Command and feedback	HUP61 noise HUP62 failure or interference of communication tools

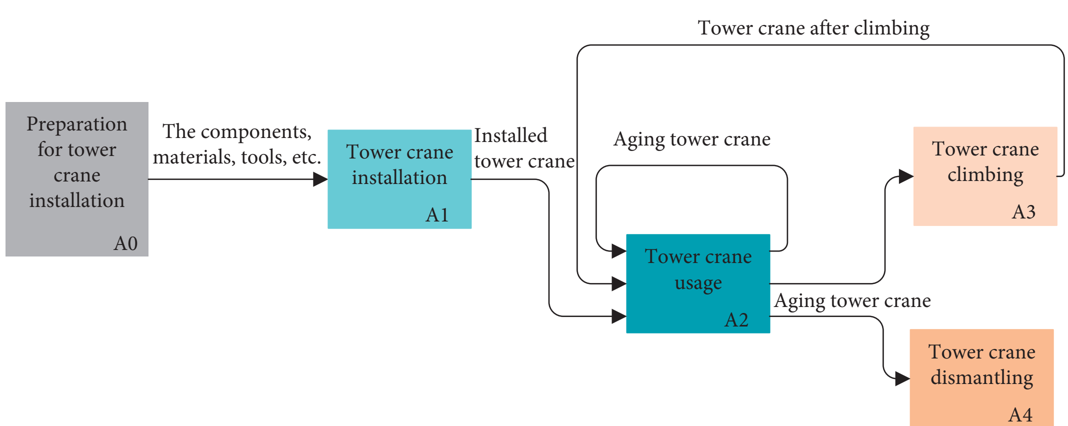


Figure 9: System inputs and outputs of each phase.

6. Discussion

To facilitate comparative analysis, repetitive or similar hazards in Section 4 are merged. Considering the described scenarios, these hazards were classified into seven categories: Document (X1), Structure (X2), Equipment (X3), People (X4), Management (X5), External environment (X6), and Procedure (X7). Among them, Procedure (X7) is the result of hazard propagation between phases. The integration results are presented in Table 11.

Comparing the hazard analysis results for different phases, it was determined that although there are similar hazards in these phases, there are also many differences between their hazards. This is because although an object in different phases is the same, the work content and requirements are different. In addition, each phase is in

Table 10: Hazards of system interactions.

Current phase	Previous phase	Hazards of system interaction
A1	A0	HIP55 insufficiency of preparation for tower crane installation
A2	A1	HUP63 unqualified installation of tower crane
	A2	HUP64 without maintenance
	A3	HUP65 unqualified climbing of tower crane
A3	A2	HCP55 overuse causes breakdown
A4	A2	HDP55 overuse causes breakdown

Note: A0-Preparation for installation, A1-Installation, A2-Usage, A3-Climbing, A4-Dismantling, as in Figure 3.

Figure 10: On-site sceneries of Shanxi tower crane accident.

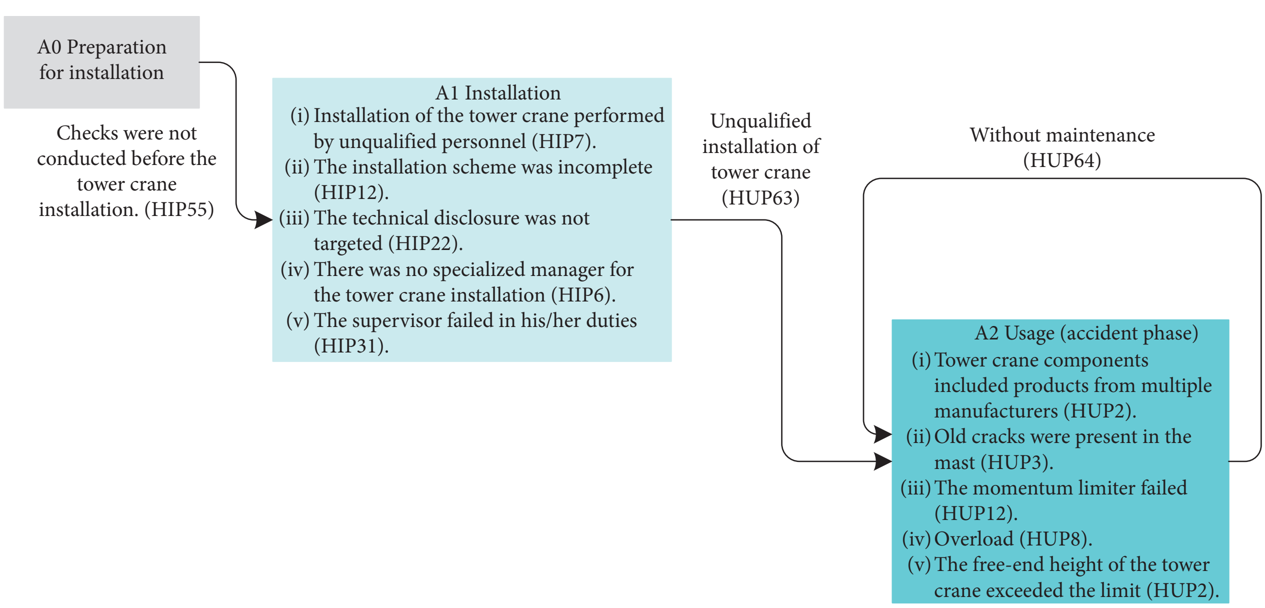


Figure 11: Hazards associate with the accident.

Table 11: Integration of hazards.

Aspect		Installation/climbing/dismantling phase	Usage phase
Document X1		Lack of document HIP(11)	—
		Scheme error HIP(12, 15)	—
		Design error HIP(13)	—
		The scheme has not been inspected as required HIP(14, 16)	—
Structure X2		The defective foundation of tower crane HIP(1)	The defective foundation of tower crane HUP(1)
		Unstable integral structure of tower crane HIP(2)	Unstable integral structure of tower crane HUP(2)
		Nonconforming member of tower crane HIP(3)	Nonconforming member of tower crane HUP(3)
		Deletion of tower crane member HIP(4)	Deletion of tower crane member HUP(4)
		Rickety fastenings HIP(5)	Rickety fastenings HUP(5)
			Tower crane over service life HUP(6)
			Materials too large or too heavy HUP(8)
Equipment X3		Auxiliary equipment failure HIP(49)	Tower crane operating system malfunction HUP(7)
			Lack or failure of monitoring system HUP(9, 10, 34, 35, 36, 37, 38, 39, 40)
			Lack or failure of security system HUP(11, 12, 19, 20, 21, 47, 48, 49)
People X4	Personnel status	Lack of staff HIP(6)	Lack of staff HUP(13)
		Without the ability or qualification HIP(7)	Without the ability or qualification HUP(14)
		Mental and physical distress HIP(8)	Mental and physical distress HUP(15)
		Weak safety concept HIP(9)	Weak safety concept HUP(16)
		Failure to wear protective equipment as required HIP(10)	Failure to wear protective equipment as required HUP(17)
	Personnel behavior	Command missing or error HIP(17, 18, 19, 20)	Command missing or error HUP(29, 30, 31)
		Operational error or failure to conduct HIP(24, 25, 27)	Operational error or failure to conduct HUP(18, 22, 23, 24, 25, 26, 27, 28)
		Failure to observe the status of tower crane as required HIP(36, 37, 39, 40, 41, 42)	Failure to observe the status of tower crane as required HUP(32, 33, 50, 51, 52, 53)
		Failure to monitor worker behavior as required HIP(28, 29, 30, 31)	—
		The sequence of operations error HIP(26)	—
	Communication	Communication barriers between workers HIP(53, 54)	Communication barriers between workers HUP(61,62)
		Failure to report as required HIP(33, 34, 35, 43, 44, 45)	Failure to report as required HUP(41, 42, 43, 44, 45, 46)
Management X5		Failure to carry out the technical disclosure as required HIP(21, 22, 23, 32, 38)	—
		Unreasonable reward and punishment mechanism HIP(46)	Unreasonable reward and punishment mechanism HUP(54)
		Short of safety education and training HIP(47)	Short of safety education and training HUP(55)
		Schedule pressure HIP(48)	Schedule pressure HUP(56)
External environment X6		Severe weather HIP(50)	Severe weather HUP(57)
		Complex operating environment HIP(51)	Complex operating environment HUP(58)
		Lack of warning signs HIP(52)	Lack of warning signs HUP(59)
		—	Multitower crane interaction HUP(60)
Procedure X7	Installation	Insufficiency of preparation for tower crane installation HIP(55)	—
	Climbing	Overuse cause breakdown HCP(55)	—
	Dismantling	Overuse cause breakdown HDP(55)	—
	Usage	—	Unqualified installation or climbing of tower crane HUP(63, 65)
			Without maintenance HUP (64)

different positions along the tower crane workflow, with different previous and subsequent phases. Thus, the hazards associated with system interactions during the phases are different. In order to avoid the accident caused by hazards propagation, the following precautionary measures can be taken:

(i) For the installation phase, the quality and integrity of the tower crane components should be checked carefully before installation. In addition, the auxiliary equipment and tools should be prepared in advance. After the installation, the acceptance inspection should also be performed by following strict standards.

(ii) During the usage phase, the overall quality and stability of the tower crane equipment should be examined before use to ensure that quality defects are not present. Regular maintenance should also be performed during use.

(iii) During the climbing and dismantling phases, the tower crane equipment should be repaired in advance to potentially detect the unstable structure of an aging tower crane, which may cause accidents. After climbing, the acceptance inspection should be conducted by adhering to strict standards.

7. Conclusion

This paper analyzes the whole process of the tower crane on the construction site. The hazards of each phase are identified through a systematic analysis method. The results show the differences and relations between the hazards of phases. The results can provide a reference for tower crane accident prevention. The main conclusions and contribution of this research are as follows:

(a) The research found that STAMP combined with IDEF0 is an effective method for hazard analysis during the different phases. IDEF0 can provide system input, output, and relevant elements for STAMP. STAMP can model the system based on components and processes. As an analysis tool derived from STAMP, STPA can identify the hazards of a system. Using these methods, the hazards of a tower crane can be identified and its propagation path can be found.

(b) Based on comparisons, it was determined that the personnel, equipment, and work content of the different phases of the tower crane service cycle are different. Moreover, the hazards that may occur in different phases are also different. Thus, this research provides a hazard list for different tower crane phases. This list can help to carry out formulate emergency measures according to the phase of the tower crane.

(c) Since various phases of tower cranes are interrelated, the adverse consequences associated with each phase can also affect the next phase. Therefore, the safety management of the subsequent phase is predicated on the construction results of the previous phase to achieve the desired safety level. The research analyzes the propagation path of hazards about the tower crane. Accordingly, it is crucial to improve the inspection and maintenance of the tower crane before and after each phase to reduce the possibility of accidents caused by the propagation of hazards between phases.

Generally, in this investigation, the tower crane hazards that can arise at the construction site during different phases were analyzed. The hazard identification and classification procedures used in this investigation are qualitative and are primarily suitable for comparative and process analysis of different phases. In subsequent research, quantitative calculations will be investigated for further classification of these hazards.

Data Availability

Some or all data and materials generated or used during the study are available from the corresponding author by request (accident data).

Conflicts of Interest

The authors have no conflicts of interest to declare.

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