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Optimizing Tower Crane Risk Management and Accident Prevention Through Systematic Event Tree Analysis

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ABSTRACT. Today, due to increasing technology and population density, the number of skyscraper constructions and residences is increasing rapidly. Tower cranes help in the rapid construction of constructions in terms of the ease of service of the machinery and equipment they provide during the construction. Accidents occurring in the construction sector in Turkey and around the world show that 30% of them take place in this type of construction. For this reason, analyzing the risky situations created by tower cranes regarding their positive aspects is very important in preventing and controlling serious and catastrophic accidents. In the study, the risks that may occur in tower crane environments were determined from accident records, obtained accident analyses, risk analysis reports, and literature studies. The motivation of the study is to analyze and manage the risks associated with tower cranes to prevent serious accidents in rapidly growing high-rise construction. The identified risk sources were evaluated with event tree analysis and scenarios. Lack of maintenance and checks, incorrect installation and assembly, and electric initiating events are analyzed in detail. As a result of the analysis, the probability of a catastrophic event was found to be 2.1% for the Lack of maintenance and checks starting event, 0.8% for the incorrect installation and assembly starting event, and 0.4% for the electric starting event. If serious events are taken into account, the probability increases to %33.04. Therefore, after risk analysis is done, it should be managed well and significant risks should be prevented from increasing by using the Plan-Do-Control-Act (PDCA) standard.

Keywords: Tower crane; event tree analysis; risk analysis; measurement; control.

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Introduction

Any device designed to raise or lower a load and move it horizontally, including the crane's foundations and supporting structure, is referred to as a crane. A tower crane is a crane with a boom or jib fixed atop a tower frame. Tower cranes have a tower-like shape and are made of high-strength iron. Typically, they are employed in building construction and industrial operations. A tower crane's slewing platform, lifting apparatus, boom, and other components are situated atop the tower, which is supported by piles and mounted on a concrete base (Occupational Safety and Health Department [OSH], 2017; Safe Work Australia, 2023). Images of tower cranes, which are frequently used in building constructions, are provided in Figure 1.

Tower cranes play a crucial role in construction sites where working at heights or transporting otherwise immobile building materials is necessary (Coral-Enriquez et al., 2019). They are essential for lifting and transferring huge loads. On building projects, tower cranes are used to lift large materials like steel and concrete. Tower cranes are another tool used for moving large objects. Tower cranes can have an underestimated lifting capability due to their slimmer design when compared to high-rise buildings. After the tower crane's parts are shipped from the factory, they usually need to be put back together on the construction site. Tower cranes are required for construction projects that get higher, and eventually; these cranes have to be climbed. In addition, disassembly and maintenance have to be done. As a result, a tower crane is both a construction object with intricate operations and an auxiliary piece of equipment (Zhou et al., 2018). Accidents involving tower cranes have the potential to result in fatalities, severe injuries, and costly damage to materials and buildings. It will also result in significant time and money expenses. This implies that the way tower cranes are used should be determined by their designs (Al Hattab et al., 2017). Tower crane overloading, sliding, operator incompetence, and mechanical failure can all cause loads to fall from the crane (Sadeghi et al., 2021). Although it is possible to prevent overloading by combining at least two tower cranes, the choice of tower crane should respect its operational limitations. In any other case, they risk permanent damage and structural strains (Olugboyega et al., 2022).

Figure 1. Tower crane in building construction.

The phases of tower cranes on building sites are installation, climbing, usage, and dismantling. Because of the weight of the objects and the heights to which they are carried, tower crane accidents are likely to be lethal (Beavers et al., 2006). The examined accidents indicate that different construction phases use different techniques and contractors. This leads to the occurrence of various accident kinds at various stages. Furthermore, dangers spread throughout each stage, and this spreading has an impact on the tower crane's safety (Jiang et al., 2021). As a result, it's important to examine the risks connected to each stage of construction as well as their variations and interactions. The view of the two tower cranes in different building areas is presented in Figure 2.

Figure 2. Installed tower cranes in different building areas.

Accidents are mostly caused by the existence of dangers in a work system. Anything that poses a risk of harm or danger is considered a hazard (Webster, 1970). An accident occurs when a hazard turns into a dangerous occurrence. Hazard identification and removal are consequently crucial. The first step in the well-established risk assessment process is hazard identification. Numerous techniques for danger identification have been developed over time (Guymer et al., 1987; Kletz, 1997; Lambert, 1991; M.I.L.-S.T.D.-882D, n.d.; Montague, 1990; Smith et al., 2006; Stamatelatos et al., 2011; Tixier et al., 2002; U.S. Bureau of Labor Statistics, 2008). 40 hazard identification strategies have been identified, which they categorized into four categories: process, equipment, software, and human (hazard identification techniques) by Glossop et al. (Glossop et al., 2000). What-if analysis, preliminary hazard analysis (PHA), checklists, hazard and operability (HAZOP) studies, reliability block diagram (RBD), failure mode and effect analysis (FMEA), fault tree analysis (FTA), and task analysis are the most often used hazard identification techniques. Ericson (Ericson, 2015) provides a detailed explanation of the methods used in danger identification.

Many nations have enacted pertinent laws, rules, and standards to lower the safety risk and guarantee the safe condition of tower cranes throughout installation, operation, and dismantling. Among these are the Construction Tower Cranes, ANSI/ASME B30.3 (American National Standards Institute [ANSI], 2004) issued by the United States as early as 2004, the Safety Code for Tower Cranes GB 5144 (China, 2006) in 2006 by China, the Crane-Safety-Tower Cranes DIN EN 14439 (Deutsches Institut für Normung [DIN], 2007) introduced by Germany in 2007, the Cranes - Safety - Tower cranes TS EN 14439+A2 (Turkish Standards Institution, 2010) issued by Turkey in 2010 and the Technical Specification for Safety Installation Operation and Dismantlement of Tower Crane in Construction JGJ 196 (Ministry of Housing and Urban-Rural Development of the People's Republic of China [MOHURD], 2010) issued by China. Although the implementation of these laws, rules, and standards has given rise to a strong foundation for preventing and minimizing tower crane accidents, it does not systematically ascertain the frequency of tower crane accidents or the variables that contribute to them.

As a result, some researchers have conducted studies on the variables that affect tower crane safety as well as the reasons behind tower crane mishaps. To investigate the risk variables influencing tower crane operations, Shapira and Lyachin (Shapira & Lyachin, 2009) provided questions to an expert team. These questions were divided into 21 categories based on four aspects: safety management, human factors, environment, and project circumstances. Tam and Fung (Tam & Fung, 2011) investigated tower crane safety using a questionnaire survey and structured interviews based on prior research. They discovered that four major risk factors during tower crane operations were participant negligence or misjudgment, inadequate training, illegal subcontracting practices, and time constraints. Häkkinen (Häkkinen, 1993) concluded that the primary reason for tower crane accidents was a lack of safety education and training for workers. After thoroughly examining the failures of two tower cranes with dissimilar designs, Marquez et al. (Marquez et al., 2014) discovered that one of the primary reasons for accidents was likewise a lack of foundation stability. These studies, however, did not take into account the assembly or breakdown of the tower cranes-only their functioning. To account for this, Skinner et al. (Skinner et al., 2006) divided the primary causes of tower crane accidents into three groups: incorrect installation, wrong operation (such as overloading), and structural deterioration. (He et al., 2022; Hu et al., 2023; Jiang & Jiang, 2023; Jiang, 2020; Milazzo et al., 2017; Nazlıoğlu et al., 2018; Ni et al., 2023; Pazari et al., 2023; Radlov & Ivanov, 2020; Sadeghi & Zhang, 2024; Sadeghi et al., 2021; Shin, 2015; Wu et al., 2022) employed accident analysis and focus group interviews to provide an overview of the elements that led to accidents during the installation and disassembly of tower cranes in Korea. The most significant cause of accidents was determined to be human factors. In their study, Zhou et al. (Zhou et al., 2018)examined tower crane safety from the standpoint of a complex socio-technical system. They identified 56 elements associated with tower crane safety and used factor analysis to categorize them into nine primary dimensions and pinpoint 25 crucial factors. In general, the earlier studies offer a solid framework for examining the reasons behind tower crane mishaps. Core components of tower crane safety have been determined using surveys, interviews with experts, and further research techniques. However, there hasn't been much focus on using quantitative approaches to investigate the intricate relationships between the causes of tower crane accidents and identify the key factors. Zhang et al. (Zhang et al., 2020) determined the crucial elements from these foundational components, investigated the relationships between various parameters, and offered a practical guide for safety control and accident prevention.

There is a dearth of literature on crane safety that specifically mentions risk factors or safety risks connected to tower cranes (Salihu et al., 2020). Thus, it is necessary to carefully consider safety concerns about the installation and disassembly of tower cranes.

In the study where EU-OSHA (Occupational Safety and Health Administration [OSHA], 2012) data were evaluated, the main causes of occupational accidents that occurred in the use of lifting machines were the contact of lifting machines with power lines, standing under the lifting vehicle, tipping of the lifting machine, falling of the load, failure to perform periodic checks, collapse of the boom, damage to the system by the counterweight, misuse of support legs, falls and fastener errors.

Aim of the study

Accidents involving tower cranes in construction sites highlight the need to take proactive measures in tower crane operations. Occupational accidents in tower cranes occur for various reasons. When the occupational accidents were examined, it was determined that the important reasons were lack of machine maintenance and checks, incorrect installation and assembly, and electrical accidents. It is to prevent tower crane accidents by identifying the sources of danger that cause accidents and through risk analysis. According to SSI of Türkiye 2022 (CSGB, 2022) data, a total of 422 fatal accidents occurred, including 248 fatal accidents in building construction, 91 fatal accidents in the construction of non-building structures, and 83 fatal accidents in private construction activities (CSGB, 2022). U.S. Labor statistics record 632 crane-related construction worker deaths from 611 crane incidents and 17 multiple death incidents resulting in 38 deaths from 1992 to 2006 (Labor Statistics, 2008). The most dangerous process that can lead to fatalities at construction sites is the installation/dismantling of tower cranes; for example, in 2012, the collapse of a tower Crane during dismantling at the University of Texas, USA claimed the lives of two workers ([OSHA], 2012).

Work accidents related to tower cranes in construction work highlight the need to take proactive measures in the tower crane environment. Work accidents in tower cranes occur for various reasons. When the occupational accidents were examined, it was determined that the important reasons were lack of machine maintenance, incorrect installation and assembly, and electrical accidents. The aim is to prevent tower crane accidents by identifying the factors that cause them. According to SSI of Türkiye 2022 data (CSGB, 2022), a total of 422 fatal accidents occurred, including 248 fatal accidents in building construction, 91 fatal accidents in the construction of non-building structures, and 83 fatal accidents in private construction activities. The total number of fatal accidents in all business lines is 1517. Therefore, 27.81% of total accidents belong to the construction sector. In the incident that took place in December 2023, 6 employees lost their lives when the tower crane collapsed. The purpose and motivation of the study are to establish and analyze event tree scenarios to develop proactive measures by creating accident causes from all events and studies in the literature.

Event Tree Analysis Method (ETA)

The ETA method is a useful technique that helps to identify all potential outcomes resulting from an initiating accidental event. It takes into account whether installed safety barriers are functioning or not, as well as additional events and factors. By examining all relevant accidental events that have been identified through a preliminary hazard analysis, a HAZOP, or another technique, the ETA can identify all possible accident scenarios and sequences in a complex system. The ETA method can also identify design and procedural weaknesses and determine the probabilities of various outcomes resulting from an accidental event (Rausand & Høyland, 2004).

Event tree modeling begins with the initial event and ends with the number of barrier prevention scenarios and risk classification (Aghajani et al., 2015; Alileche et al., 2016; Bahr, 1997; Clemens, 1990; Karanki et al., 2015; Karanki & Dang, 2016; Lower et al., 2016; Mizrak Ozfirat, 2014; Özfirat et al., 2017; Ozkilic, 2014; Ramzali et al., 2015; Rosqvist et al., 2013; Stapelberg, 2009). Most well-designed systems have one or more barriers that are implemented to stop or decrease the consequences of potential accidental events. It aims to reduce the consequences of accidents to an insignificant and minimum level by modeling the number of barriers and prevention techniques. Risk levels are calculated according to tree branches, depending on whether the barriers are prevented or not.

To build an event tree, we begin with an initiating event and consider each event in a chain. Depending on whether the next event occurs or not, the main branch splits into two branches. This process continues until all events from the chain have been considered. For a chain of n events, there will be 2^n possible final scenarios.

The probability of each final scenario is equal to the probability of the path leading to that scenario. This probability is determined by multiplying the probabilities of the branches that compose the path and the probability or frequency of the initiating event.

Barrier prevention probability;

The prevention probabilities of accidents for technical personnel to perform maintenance and checks (B1), the machine operator and maintenance team control the wire ropes and chains (B2) and the operator controls daily checks (B3) barriers, with the measures taken, were determined from the FMEA probability chart. Since the scale has 10 points, accident probabilities and prevention percentages from accident probabilities after precautions were calculated and are given in Table 2.

Lack of maintenance and checks, incorrect installation and assembly, and electricity. Lack of Maintenance and checks initiating events barriers are grouped as technical personnel to perform maintenance and checks (B1), the machine operator and maintenance team control the wire ropes and chains (B2) and the operator controls daily checks (B3). Tower crane maintenance cards must be prepared and recorded before, during, and after work. The maintenance team should check the ropes and chains before each work. In case of any adverse event, operation should not be allowed without maintenance. The operator should check the machine engine and other indicators before daily work and inform the maintenance team after all checks have been made. After all maintenance and checklists are recorded in the checklist, work should be started after positive scores occurred (Nazlıoğlu et al., 2018). In addition to tower crane operators, to ensure the safety of other people in the work area by taking all necessary precautions is signalmen's duty too, apart from the occupational safety expert or field manager. Necessary occupational safety training should be given to both the operator and the signalman. Periodic maintenance of tower cranes should not be interrupted, inspections should be carried out, deficiencies in control should be completed immediately and the tower crane should not be used during this process. It is important to calculate the static test load to check the structural adequacy of the crane and the elements that make up the crane, and the dynamic test load to check the safe operation of the crane mechanisms and brake systems.

According to BS ISO 4309 (Özfırat et al., 2019), crane ropes must be replaced in case of breaking of a rope wire, the emergence of broken wire slots, reaching the maximum allowed number of broken wires, spiral-shaped deformations being more than 1/3 of the rope diameter, occurrence of wire rope deformation (basket shape deformation), wire or wire groups coming out of the rope in the form of pinning deformation, immediate corrosion, abrasion, a decrease of 15% of the rope diameter compared to its nominal diameter, breakage or crushing, lint or permanent deformations.

Based on this data; all barriers prevention probability is calculated from Table 1 as shown in Table 2.

For B1;

- Before measurement of accident probability 8,
- After measurement of accident probability 2 from Table 1
- The probability of the accident occurrence is 2/8 = 0.25
- The probability of barrier B1 preventing an accident is 1-0.25 = 0.75 (Table 2).

Table 1. Probability and degree of error occurrence (Özfırat et al., 2019; Ozkilic, 2014).

Probability of Failure	Degree (P)
Extremely high	10
Failure almost inevitable	9
High failures	8
Repeated failures	7
Moderately high	6
Moderately average	5
Low Relatively failure	4
Rarely failure	3
Very low failure	2
Unlikely failure	1

Table 2. Initiating events and prevention probabilities of barriers.

Initiating Events	Before measurement	After measurement	Barriers	%
Lack of Maintenance and checks	8 points for 1/8	2 points for 1/150000	Technical personnel to perform maintenance and checks (B1)	75
	9 points for 1/3	3 points for 1/15000	The machine operator and maintenance team control the wire ropes and chains (B2)	67
	8 points for 1/8	2 points for 1/150000	The operator controls daily checks (B3)	75

	10 points for > 1/2	1 point for < 1/150000	Supporting the roof of the tower crane with concrete weights (B4)	90
Incorrect Installation and Assembling	10 points for > 1/2	2 points for 1/150000	Checking the connections of fixing the pins (B5)	80
	10 points for > 1/2	1 point for < 1/150000	Proper design of counterweights (B6)	90
	10 points for > 1/2	2 points for 1/150000	Making final checks (B7)	80
	10 points for > 1/2	2 points for 1/150000	Control of power lines (B8)	80
Electric	10 points for > 1/2	1 point for < 1/150000	Checking the grounding and fuse lines, ensuring insulation (B9)	90
	10 points for > 1/2	2 points for 1/150000	Electrical fire control (B10)	80

According to some researchers, crane collapses are the primary cause of accidents, accounting for 38% of incidents. These collapses are primarily attributed to factors such as bad weather conditions (strong winds), structural failures, mechanical malfunctions, broken cables, overloading, and insecure load handling. 16% of accidents occur due to the crane's overturning. Another 16% result from individuals being struck by the boom or load, leading to falls. Boom buckling and jib collapses contribute 11% to the overall accident rate. Additional relevant factors include crane crashes (6%), electrocution (2.4%), fires and explosions (1%), and drops of load or heavy load handling (2%).(Milazzo et al., 2017; Radlov & Ivanov, 2020).

Supporting the roof of the tower crane with concrete weights (B4), Checking the connections of fixing the pins (B5) and Proper design of barriers (B6) prevents from collapse of tower cranes respectively 90, 80, and 90%. When tightening bolts, it is important to mount them tightly using appropriate machinery and equipment, using appropriate screw steps. It is very important that the tightening load of the bolts is known and that the assembly workers do it consciously. Correct assembly and correct tower infrastructure will prevent tower crane ruptures and collapses. Counterweights must be calculated and installed properly. The placement of counterweights during the design and installation phase must be done by all rules. Counterweight design and calculations in tower cranes are very important in terms of maintaining the stability of the tower crane while operating. Causes of occupational accidents that occur while working with tower cranes are overloading, breakage of outriggers, the impact of hooks, breakage of the crane arm, crane tipping over, contact of the crane with power lines, improper installation and dismantling of the crane, inadequate equipment in lifting equipment, the impact of the load or crane on employees, and bad weather conditions. According to the study 'Analysis of 85 large tower crane accidents that occurred around the world from 1989 to 2009' prepared by the UK Health and Safety Executive (HSE) and the Health and Safety Laboratory (HSL) in 2010; accidents occurred during 'Installation/Dismantling/Upgrading' with a rate of 34%.

The operator must stop working with the tower crane when the wind speed exceeds 50 km h^{-1}. If the wind speed exceeds 72 km h^{-1}, the wind brake must be disabled and the crane must be left, allowing free rotation. Ropes are important elements that play a role in pulling and lifting operations in tower cranes.

Control of power lines (B7), Checking the grounding and fuse lines, ensuring insulation (B8), and Electrical fire control (B9) prevents collapses of tower cranes respectively 80, 90, and 80%. Contact of the crane with power lines is one of the most important causes of accidents for tower cranes. According to EU-OSHA's 2010 analysis of occupational accidents resulting in death caused by cranes, 39% of the accidents are electric shocks. In the area where the tower crane is installed, lines such as power, gas, and steam should be identified and the crane working area should be arranged. Workers and operators must be informed about the risks of power lines. All electrical sockets must be grounded. There should be no damaged plugs or sockets. There should be a residual current device in electrical panels and periodic checks should be made. It should be ensured that all fuses are in protected places. Conduit/fuse boxes must be protected and access by unauthorized persons must be prevented. Stripped, damaged, or worn electrical cables should not be used. There should be no objects in front of the panels so that the electrical power can be easily cut off in case of emergency.

To prevent damage to the operator and electronic components in the event of a lightning strike, tower cranes without a grounding line should not be operated. Lightning is a high-voltage electrical discharge and is one of the deadliest natural disasters. Protection of tower cranes from lightning is provided primarily by using lightning rods and secondarily by using a correct grounding system. Another piece of equipment that plays an active role in protecting tower cranes from lightning is low voltage surge arrester systems. In addition to the mentioned protection devices, lightning detectors also indirectly contribute to the protection of tower cranes. Lightning detectors measure the surrounding electric field with the detector antenna, thus detecting an approaching lightning storm in advance and helping to activate other lightning protection measures such as surge arrester devices or grounding systems promptly.

Modelling and discussion of the model scenarios

Event tree analysis started with determining the initial events. Three different events were examined in this study. In the cases examined, studies, risk analysis projects in the literature, and real-life events were taken into consideration. The three accident initiation events examined are lack of maintenance and checks, incorrect installation and assembly, and electric events.

Lack of maintenance and checks

Lack of maintenance and checks initiating event (ie#1) barriers are grouped as technical personnel to perform maintenance and checks (B1), the machine operator and maintenance team control the wire ropes and chains (B2) and the operator controls daily checks (B3). The event tree modeled as three barriers was examined with 8 scenarios with the 2^n formula. When B1, B2, and B3 measures are taken, no accidents are expected with 37.7%, as seen in Figure 3. However, if one of B3, B2, or B1 is neglected, the marginal accident probability is 43.6%. If two of the measures are neglected, there is a risk of serious accident probability, and the rate is 16.6%. If three measures are not taken, a catastrophic accident is 2.1% likely. Therefore, in an operation where all the above-mentioned measures are taken and controlled, the probability of an accident is reduced by 37.7%. If the marginal accident probability is taken carefully and the measures are controlled without turning it into an accident probability, safe operation can be achieved with a rate of 81.7% (Table 3). In previous studies, the effects of maintenance and checks on minimizing risks have also been investigated, and it has been observed that these precautions significantly reduce the risks (Al Hattab et al., 2017; Coral-Enriquez et al., 2019; T. Jiang, 2020).

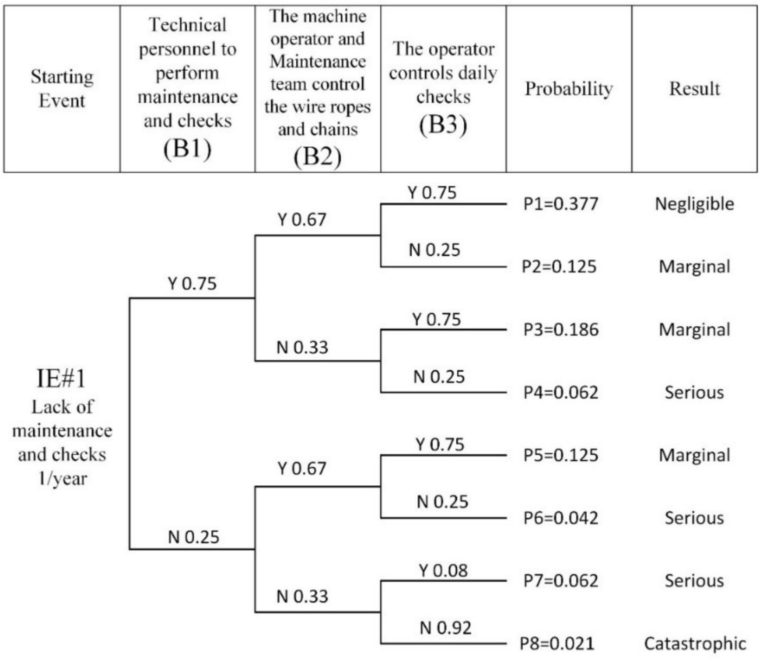

Figure 3. Event tree analysis for lack of maintenance and checks.

Periodic maintenance and inspection of cranes are important to prevent accidents such as material falling and tipping over. Maintenance and checks must be carried out by authorized technical personnel, machine unit, operator, and slingers.

The machine maintenance unit should check the chains and wire ropes. Periodic checks should be made for chains. Chains must be attached with elements that comply with standards. Loads should not be lifted with wire ropes that are not suitable for the load and are not found suitable during inspection. Ropes with breaks, basket shape deformation, or twists in the wires should not be used. When working with ropes, care should be taken to ensure that the wire rope is suitable for the work done and the load to be lifted, that it is lubricated at certain periods, and that it is not exposed to welding flames and heat. If there is a reduction of more than 5% of the nominal diameter of the rope, the rope should not be used.

The tower crane operator carries out his work inside or outside the crane control cabin. The working environment may be extremely cold or hot, dusty, muddy, windy, noisy, and humid depending on seasonal conditions. The tower crane operator should be in communication with managers, other employees, and machine maintainers before and after work and should know the maintenance and repairs performed on the machine (Nazlıoğlu et al., 2018).

Table 3. Risk Classification of IE#1.

Risk Class	Probability
Negligible	0.377
Marginal	0.436
Serious	0.166
Catastrophic	0.021
Total	1

Incorrect installation and assembly

Supporting the roof of the tower crane with concrete weights (B4), Checking the connections of fixing the pins (B5) and Proper design of barriers (B6), and Making final checks (B7) prevent from collapse of tower cranes respectively 90, 80, 90, 80%. 16 scenarios were examined with the formula 2n in the event tree modeled as four barriers. When B1, B2, B3, and B4 precautions are taken, no accidents are expected with 51.8%, as seen in Figure 4. However, if one of B1, B2, B3, or B4 is neglected, the marginal accident probability is 38% possible. If two of the measures are neglected, there is a risk of serious accident probability and the rate is 9.4%. If three measures are not taken, a catastrophic accident is possible with a probability of 0.8%. Therefore, in a controlled operation where all the above-mentioned measures are taken, the probability of an accident is reduced by 51.8%. If the marginal accident probability is taken carefully and the precautions are controlled without turning it into an accident probability, safe operation can be achieved with a rate of 89.8% (Table 4).

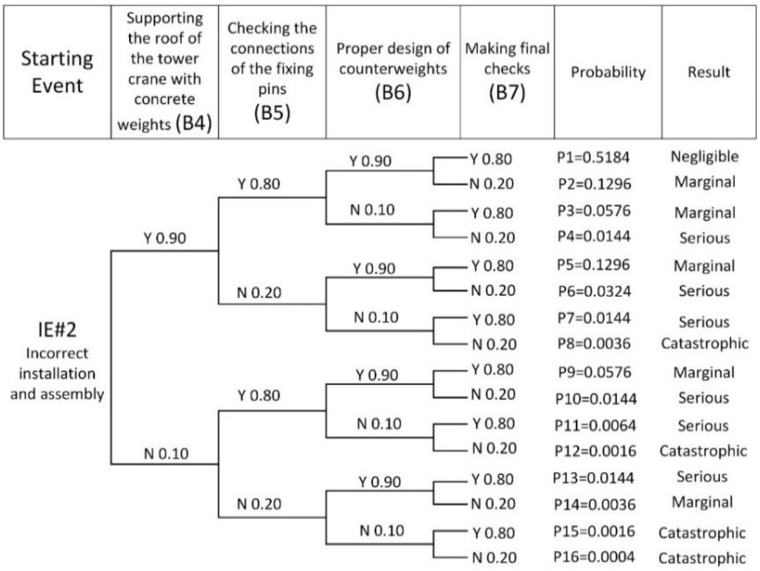

Figure 4. Event tree analysis for incorrect installation and assembly.

Table 4. Risk Classification of IE#2.

Risk Class	Probability
Negligible	0.5184
Marginal	0.378
Serious	0.0964
Catastrophic	0.002
Total	1

According to the study prepared in 2010 by the UK Health and Safety Executive (HSE) (British Standards Institution, 2017; Military standard, 2000) and the Health and Safety Laboratory (HSL) 34% of the 85 large tower crane accidents that occurred worldwide from 1989 to 2009 occurred during Erection/ Disassembly/Elevation. That's why; when tightening bolts, it is important to mount them tightly using appropriate machinery and equipment, using appropriate screw steps. It is very important that the tightening load of the bolts is known and that the assembly workers do it consciously. Correct assembly and correct tower infrastructure will prevent tower crane ruptures and collapses. Counterweight design and calculations in tower cranes are very important in terms of maintaining the stability of the tower crane while operating. Therefore, counterweights designed and positioned should be safe after work. The placement of counterweights during the design and installation phase must be done by all rules.

Weather forecasts should be monitored in advance. In windy weather, work should be postponed and the operator should not be taken to the tower crane cabin. In addition, a safe zone must be provided in the areas within the tower crane's area of influence. Previous occupational safety and risk analysis studies on installation and assembly have shown that the precautions to be taken in this area significantly reduce risk levels and can effectively prevent potential accidents to a great extent (Radlov & Ivanov, 2020; Sadeghi et al., 2023; Salihu et al., 2020)

Electric

Electric initiating event (IE#3) barriers are grouped as Control of power lines (B8), checking the grounding and fuse lines, ensuring insulation (B9), and electrical fire control (B10). In case of an electrical incident, control of power lines, checking the grounding and fuse lines, and electrical fire control prevent the accident by 80%, 90%, and 80%, respectively. The event tree modeled as three barriers was examined with 8 scenarios created with the 2^n formula. When B8, B9, and B10 measures are taken, no accidents are expected with 57.6%, as seen in Figure 5. However, if one of B8, B9, or B11 is neglected, the marginal accident probability is possible at 35.2%. If two of the precautions are neglected, there is a risk of serious accident probability and the rate is 6.8%. If three measures are not taken, a catastrophic accident is possible with a probability of 0.4%. Therefore, in a controlled study where all the above-mentioned measures are taken, the probability of an accident is reduced by 57.6%. If the marginal accident probability is controlled without turning it into an accident probability, if measures are taken carefully, safe operation can be achieved with a rate of 92.8%. If all measures are ignored, there is a 0.4% probability of a catastrophic accident (Table 5). Previous scientific studies on electrical hazards have shown that implementing appropriate safety measures in the work area provides substantial benefits in minimizing this risk (He et al., 2022; Milazzo et al., 2017; Özfirat et al., 2017).

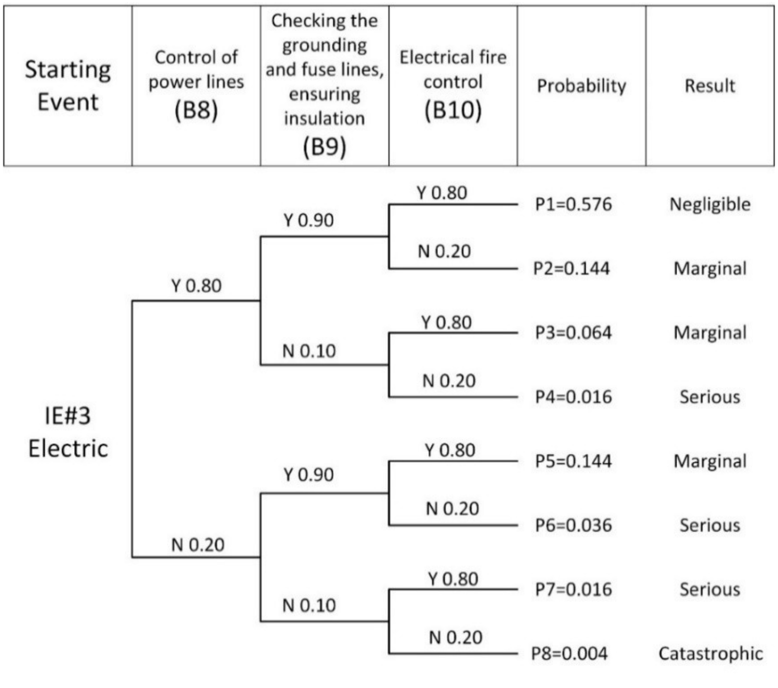

Figure 5. Event tree analysis for electric.

The locations of power lines in and around the work area should be determined and these lines should be paid attention to. The insulation of the tower crane from the power lines should be checked. Insulation etc.

to prevent possible fires caused by electrical lines should be checked. All sockets must be grounded, and cables must be intact and used regularly in the working environment. There must be a residual current device in electrical panels. In the area where the tower crane is installed, necessary measures are taken by detecting the power lines in the area where the tower crane is installed. Employees should be informed about the risks of the power lines. A lightning rod and ground line must be installed for lightning.

Table 5. Risk Classification of IE#3.

Risk Class	Probability
Negligible	0.576
Marginal	0.352
Serious	0.068
Catastrophic	0.004
Total	1

Conclusion

The use of tower cranes has become essential with advancing technology and the rise of high-rise construction. In this context, the three most critical risk sources identified through accident analyses, risk reports, and studies related to tower cranes were evaluated using event tree analysis and various scenarios. These risk sources include inadequate maintenance and inspection, improper installation and assembly, and electrical initiation events—all of which were examined in detail. The analysis revealed that the probability of a catastrophic event is 2.1% for inadequate maintenance and inspections, 0.8% for improper installation and assembly, and 0.4% for electrical initiation events. When serious (but not catastrophic) incidents are also considered, the total probability rises to 33.04%, with individual probabilities of 16.6% for maintenance-related failures, 9.64% for installation errors, and 6.8% for electrical faults. However, if all safety barriers are effectively managed, the probability of avoiding an accident entirely increases significantly: 37.7% for maintenance-related issues, 51.84% for installation problems, and 57.6% for electrical sources. These findings highlight the importance of not only conducting thorough risk analyses but also ensuring robust risk management practices. Implementing the PDCA (Plan–Do–Check–Act) cycle is crucial to keeping critical risks under control and enhancing overall safety.

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