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Load Cell Failure Risk in Tandem Mobile Crane Lifting: A Fuzzy Fault Tree Analysis Approach

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Abstract— **Mobile crane lifting activities carry a significant accident risk, especially when performed in tandem configurations. The main risk comes from the possibility of failure of the load cell component which plays an important role in actual load measurement. This research aims to analyze the potential failure of the load cell function in tandem lifting operations using the Fuzzy Fault Tree Analysis (FFTA) method. Data were collected through literature studies, field observations, and interviews. The FFTA method is used to identify factors that cause failure and calculate the probability of failure quantitatively. The investigation identified that the primary variables leading to load cell failure include overload situations, internal component damage, and external impacts. The highest probability of failure was recorded in the material fatigue scenario due to damage to the cable. These findings highlight the need of instituting preventative maintenance programs and conducting frequent inspections of load cell components to reduce the risk of workplace accidents.**

Keywords— fuzzy, mobile crane, load cell, risk analysis, tandem lifting

I. INTRODUCTION

Lifting operations using mobile cranes represent one of the most critical activities in the construction sector. The use of mobile cranes in construction projects offers numerous advantages, including reduced execution time, minimized manpower requirements, and enhanced cost efficiency [1], [2], [3]. However, mobile crane operations also entail inherent safety risks that cannot be overlooked, such as dropped loads, collisions with personnel or property, and crane overturning incidents [4], [5], [6], [7]. These hazards can lead to a range of adverse outcomes, including equipment damage, property destruction, personal injuries, and even fatalities.

According to the Census of Fatal Occupational Injuries (CFOI), based on data from the U.S. Bureau of Labor Statistics, there were 297 reported occupational accidents involving mobile cranes between 2011 and 2017. Similarly, in Malaysia, 18 fatal crane-related accidents were recorded between 2015 and 2018 [8].

Mobile crane lifting operations can vary significantly in configuration depending on specific project requirements. These operations may involve a single mobile crane or multiple cranes operating simultaneously. The latter is commonly referred to as tandem lifting (see Figure 1). Various studies suggest that tandem lifting poses higher levels of risk compared to single-crane operations due to its increased complexity and the critical need for precise coordination among all involved parties [9]. Additionally, tandem lifting requires meticulous planning concerning boom length, optimal working radius, safe outreach relative to nearby structures or obstructions, and synchronized movements between cranes to ensure operational harmony.

This study was initiated based on the consideration that tandem lifting operations involving mobile cranes remain underexplored in the academic literature, despite their frequent implementation in actual construction activities. Therefore, this research aims to provide a detailed and comprehensive analysis of the dominant hazards that can potentially lead to failure in tandem mobile crane lifting operations. The findings are expected to contribute valuable insights for establishing effective preventive measures tailored to such operations.

The most severe hazard associated with tandem lifting is crane tipping. Tipping refers to the condition in which a mobile crane overturns due to structural failure, unstable ground conditions, or excessive loading [10]. Overloading is considered the most probable cause in lifting operations, often resulting from the malfunction of the overload detection system—specifically, the load cell (see Figure 2) [11].

This study was initiated based on reports of recurrent occupational accidents within a construction-focused company. The operation under investigation involves the use of two mobile cranes, each with a lifting capacity of 45 tons, to repeatedly lift a 24-meter-long pipe weighing 12 tons from the ground to a trailer truck. This lifting operation is classified as highly hazardous; however, it remains essential and unavoidable. As previously noted in the literature, one of the most critical potential hazards in such operations is crane tipping, which is highly likely to be caused by overloading due to the malfunction of the load cell component responsible for measuring actual loads during lifting.

To address this, the risk assessment for the tandem lifting operation is conducted using the Fuzzy Fault Tree Analysis (FFTA) method. Fault Tree Analysis (FTA) is an effective top-down approach for risk assessment,

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enabling in-depth analysis of potential hazardous events and their underlying causes [12]. Integrating FTA with fuzzy logic helps overcome fundamental limitations in decision-making under uncertainty. Fuzzy logic also offers the ability to compensate for vagueness and uncertainty in probability estimates found in conventional FTA. The FFTA approach was first applied in 1989 for nuclear power plant safety analysis [13] and has since been employed in various domains, including mining safety risk assessments [14] and lifting operations in the construction sector [15].

Previous studies have explored risk assessment in crane operations using different methodologies. For example, several studies employed Failure Mode and Effects Analysis (FMEA) in the construction sector [16], [17], [18], identifying general crane failure modes by ranking them using the Risk Priority Number (RPN). However, these studies lacked a detailed exploration of the root causes of specific component failures. Other studies applied fuzzy-based methods, such as integrating fuzzy logic with Bayesian Networks (BN) to assess tower crane safety [19] or evaluate hazards in bridge crane operations [20]. Nonetheless, these approaches mainly focused on comparing risk weightings across human, technical, managerial, and environmental factors, without providing in-depth causal analysis of specific failure mechanisms.

Furthermore, FTA has been employed in various engineering contexts, such as analyzing weld failure points on excavator buckets [21] and assessing risks in base-core bridge crane applications [22]. The novelty of the present research lies in its specific application of FFTA to the load cell component in tandem lifting operations—an essential element for monitoring safe load conditions during mobile crane activities.

Figure. 1. Tandem lifting operation using two mobile cranes

Figure. 2. Load cell components on a mobile crane

TABLE 1.
RESPONDENT DATA

Respondents	Category			
	Age	Experience	Position	Education
1	38	12	Senior Manager for Lifting Expert	BSc
2	44	10	Lifting Instructor	MSc
3	38	10	Operational Manager	BSc
4	31	8	HSE	BSc
5	26	7	Operator	BSc

TABLE 2.
LINGUISTIC VARIABLES

Linguistic Variables	Function
Very High (VH)	(0.75, 1.00, 1.00)
High (H)	(0.50, 0.75, 1.00)
Medium (M)	(0.25, 0.50, 0.75)
Low (L)	(0.00, 0.25, 0.50)
Very Low (VL)	(0.00, 0.00, 0.25)

In addition, most previous studies relied on deterministic approaches that assume the availability of accurate failure rate data. In practical field conditions, however, data is often limited or incomplete. This research addresses the gap in comprehensive studies focusing on FFTA-based risk analysis of load cell failure in the context of tandem lifting using mobile cranes. By applying FFTA, this study accommodates uncertainty in technical and operational data while identifying the critical root causes of load cell malfunction. The novel contribution of this research lies in the integration of fuzzy logic into FTA, thereby optimizing the accuracy of risk modeling under uncertain data conditions—a highly suitable approach for complex tandem lifting operations.

TABLE 3.
RESPONDENT WEIGHTING

No	Criteria (Code)	Ranking Criteria	Score
1	Organizational position (C1)	Senior Manager	4
		Manager	3
		Operations Supervisor	2
		Crane operator	1
2	Job experience (years) BEST (C2)	>30	4
		20-30	3
		10-19	2
		5-9	1
3	Age (year) Worst (C3)	>50	4
		41-50	3
		30-40	2
		<30	1
4	Education level (C4)	MSc	4
		BSc	3
		Associate	2
		Diploma	1

A. Problem Definition

Work accidents often occur in lifting work using mobile cranes. Unexpected events such as human error, equipment damage, and environmental factors often cause these accidents. In the company that the researcher used as the object of the study, it was recorded that from 2023 to 2024, there was 1 incident that resulted in injury to lifting workers and 5 incidents that resulted in property damage in tandem lifting work using mobile cranes. This condition needs to be addressed immediately so that it is followed as mandatory in the Ministry of Manpower Regulation No. 1 of 1970 concerning occupational safety in the workplace.

Tandem lifting operations with a mobile crane present significant dangers. Collected from several pieces of literature collected by researchers, several accidents that can be caused are loads falling from the crane that can hit personnel, to the most severe impact, namely tipping, which can damage the load and the mobile crane unit used. Untreated accidents will result in many losses, including those due to property damage and injury. Also, the decline in client trust, which is not visually apparent, will continue to decline and affect finances.

B. ProposedSolution

Fault Tree Analysis (FTA) is a very prominent method for analyzing risks related to safety and critical assets. The FTA method consists of various modeling and analysis techniques, supported by various software. Generally, the Fault Tree Analysis, or FTA, technique is used in the field of mechanical engineering, especially in industries where technical errors have a very significant impact, such as nuclear power and aviation. However, risk management practices can also utilize this technique.

In risk management practice, FTA is a technique for identifying and analyzing factors that may contribute to an adverse event ("peak event," short for "major risk event") [23]. Fault tree analysis is a suitable method for understanding how a system can fail or, in the context of risk management, how a risk can occur and what causes it. This technique helps determine the best way to reduce the level of risk and the factors that may influence the risk event. Risk factors are deductively identified, logically arranged, and presented in the form of a tree diagram that illustrates the logical relationship between the causal factors and the risk event. The addition of fuzzy analysis methods to FTA provides confirmation and strength in making more valid decisions.

II. Method

A. Data Collection

To facilitate the work of this study, the researcher collaborated with a company that does similar work in an oil and gas company. The researchers collect data using several methods, namely:

1) Collection of literature

In this study, researchers collected articles related to the topic of tandem lifting using a mobile crane. This information is crucial for constructing an analytical framework based on specific guidelines [24], [25], [26]. However, it turns out that not many other researchers have conducted research on the same topic. Therefore, researchers collected similar articles and developed them based on available handbooks related to load-lifting procedures using a mobile crane.

2) Interview with lifting personnel

To obtain accurate results related to tandem lifting operations using mobile cranes, researchers conducted interviews with several personnel who do the work every day. This approach is intended to obtain a more actual point of view and can later be compared with the results of the literature that has been collected [27], [28].

3) Collection of supporting documents

To support the analysis, researchers also collected supporting documents related to the history of the frequency of failure of tandem lifting work using mobile cranes. We successfully collected documents such as Job Safe Analysis (JSA) forms, mobile crane inspection summary data, and Standard Operating Procedures (SOP).

B. Method Analysis

The risk analysis method employed in this tandem lifting operation using mobile cranes is Fuzzy Fault Tree Analysis (FFTA). Based on literature reviews and interview findings, load cell malfunction was identified as the top event. This was further validated using inspection records of mobile cranes from 2022 to 2024. The fault tree structure was developed to determine the possible causes of load cell failure, identifying intermediate, undeveloped, and basic events. The construction of the fault tree and identification of Minimum Cut Sets (MCSs) were assisted by expert participants.

Following the establishment of the top event—load cell malfunction—the contributing factors were identified through an extensive literature review on related topics, field observations, and interviews with relevant personnel. In the subsequent stage, the risk factors contributing to the top event were classified into three categories: intermediate events, undeveloped events, and basic events, in collaboration with domain experts. Intermediate events are those triggered by one or more contributing events. Undeveloped events represent risk factors for which sufficient information is not available for further development. Basic events are the fundamental causes of the top event. Expert judgment is used to estimate the probability of each basic event occurring.

To conduct probability weighting of basic events, expert judgment was applied based on references [29], [30], and [31]. The first step involved identifying expert participants to provide probability ratings for each basic event Table 1. Experts were categorized by age, position, educational background, and work experience, following the approach used in previous studies [32]. Subsequently, linguistic variable weighting was carried out using the Fuzzy Best–Worst Method (FBWM) for prioritization Table 2 [33]. The final step involved assigning fuzzy weights based on the assessment criteria classification presented in Table 3.

In the initial stage, fuzzy numerical weights were assigned to estimate the likelihood of each basic event. The weighting process was based on the linguistic variables presented in Table 2, followed by calculations using Equation (1). Subsequently, the estimated likelihood values were computed using Equation (2), and then converted into probability values through Equation (3). For the expert-based weighting stage, linguistic variable scores were applied using Equation (4) to reflect expert judgment in evaluating the probability of occurrence for each basic event.

$$\mu_{\tilde{n}(x)} = \begin{cases} 0, & if\ x \leq 1 \\ \frac{x-1}{m-1} & if\ l < x < m \\ 1, & if\ x = m \\ \frac{u-x}{u-m} & if\ m < x < u \\ 0, & if\ x \geq \end{cases} \quad (1)$$

$$\begin{aligned} \tilde{M}_1 \oplus \tilde{M}_2 &= (l_1, m_1, u_1) \oplus (l_2, m_2, u_2) \\ &= (l_1 \oplus l_2, m_1 \oplus m_2, u_1 \oplus u_2) \\ \tilde{M}_1 \otimes \tilde{M}_2 &= (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) \\ &= (l_1 \otimes l_2, m_1 \oplus m_2, u_1 \otimes u_2) \\ \tilde{M}_1 \ominus \tilde{M}_2 &= (l_1, m_1, u_1) \ominus (l_2, m_2, u_2) \\ &= (l_1 \ominus l_2, m_1 \ominus m_2, u_1 \ominus u_2) \end{aligned} \quad (2)$$

$$FPr = \begin{cases} \frac{1}{10^K} & if\ FPs \neq 0 \\ 0 & if\ FPs = 0 \end{cases}$$

$$K = \left[\left(\frac{1-FPs}{FPs}\right)\right]^{1/3} \times 2.301 \quad (3)$$

$$M_i = \sum_{j=1}^{n} wjAij \quad (i = 1,2,3,\ldots,m) \quad (4)$$

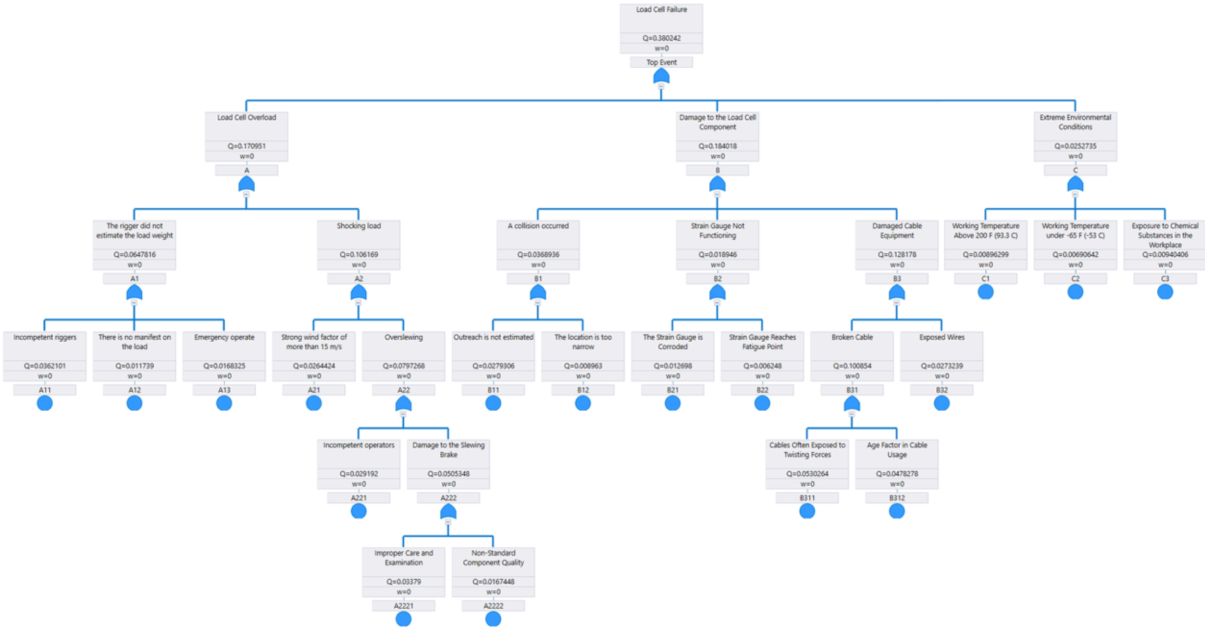

Figure. 3. FTA on Top Even if there is a failure of the load cell function

III. Results and Discussion

A. Result

The results presented in Table 4 represent the outcome of the Fault Tree Analysis (FTA), where the top event is defined as the failure of the load cell—identified as a critical point in load reading and a key reference for crane operators during mobile crane operations. The FTA results identified 11 intermediate events and 17 basic events associated with the potential failure of the load cell. Among the intermediate events, three primary categories were identified: (A) Load cell overload, (B) Load cell component damage, and (C) Extreme environmental conditions. These intermediate and basic events were assumed based on direct interviews with operational personnel regarding the top event—load cell malfunction.

The mapping of intermediate and basic events to the top event is illustrated in Figure 4. Based on discussions with expert contributors, it was determined that all intermediate events in the FTA structure are connected to their associated basic events through "OR" gates, indicating that the occurrence of any one basic event could trigger the corresponding intermediate event. Each basic event was evaluated in terms of its effects and likelihood of leading to an intermediate event.

The 17 basic events were further analyzed and validated through expert judgment, involving five experts with backgrounds and experience relevant to the subject of analysis. The experts assigned weights using the formulas previously described in the methodology section, and the results are presented in Table 5. The weighting was based on variables including age, position, work experience, and educational level.

The final result of the expert judgment weighting process involved calculating the Weight of Judgment (Wj), which serves as the basis for conducting fuzzy analysis of each basic event. The categorical values assigned by the expert panel produced varied analytical outcomes, thereby enriching the decision-making process by offering a wider range of options for selecting the most appropriate mitigation strategies.

The next stage involved computing the fuzzy numbers for all predetermined basic events. Prior to this, the expert weighting was calculated by considering four key criteria: age, work experience, professional position, and educational level. The results of this calculation are presented in Table 6.

The process began by determining the Fuzzy Possibility Scores (FPs) for each basic event. The FPs were derived from expert opinions using linguistic variables ranging from low to very high to represent the likelihood of each of the 17 basic events. These linguistic assessments were subsequently converted into Fuzzy Probability values (FPr) for further quantitative analysis.

The results revealed that the highest likelihood score was associated with code A221 – "Incompetent Operator", which ultimately leads to load cell damage due to overloading. These probability values for each basic event were then input into the FTA software to calculate the overall probability of the top event.

The final output of the analysis yielded a probability value of 0.380 for the top event (load cell failure), with detailed contributions as follows: Intermediate A: Load cell overload – 0.1709 (45%), Intermediate B: Load cell component damage – 0.1840 (47%) and Intermediate C: Extreme environmental conditions – 0.02527 (7%) These percentages provide a quantitative basis for identifying the most probable causes of load cell malfunction, serving as valuable input for developing preventive measures in tendem lifting operations.

TABLE 4.
LIST OF FTA

No	Code	Top Event
1	TE	Load cell failure
No	**Code**	**Intermediate Event**
1	A	Load cell overloaded
2	A1	The rigger does not estimate the load weight
3	A2	Shocking load
4	A22	Overswing
5	A222	Damage to the slewing break
6	B	Damage to the load cell components
7	B1	A collision occurred
8	B2	Stain gauge not function
9	B3	Damaged cable equipment
10	B31	Broken wires
11	C	Extreme environmental conditions
No	**Code**	**Basic Event**
1	A11	Incompetent rigger
2	A12	There is no manifest on the load
3	A13	Emergency operation
4	A21	Strong wind factor more than 15 m/s
5	A221	Incompetent operator
6	A2221	Improper care and examination
7	A2222	Non-Standard component quality
8	B11	Outreach is not estimate
9	B12	The location is too narrow
10	B21	Strain gauge is corroded
11	B22	Stain gauge reaches fatigue point
12	B311	Cables are often exposed to twisting forces
13	B312	Age factor of cable usage
14	B32	Expose cable
15	C1	Working temperature above 200 F (93.9 C)
16	C2	Working temperature below -65 F (-53 C)
17	C3	Exposure to chemicals substance in the workplace environment

B. Discussion

Based on the results of the fuzzy FTA analysis, it was found that the likelihood of load cell malfunction is considerably high, with a calculated probability of 0.380. This value comprises three intermediate events: Intermediate A – Load cell overload (0.1709 or 45%), Intermediate B – Load cell component damage (0.1840 or 47%), and Intermediate C – Load cell failure due to extreme environmental factors (0.02527 or 7%). These intermediate events represent the major contributing factors to potential accidents.

TABLE 5.
RESULTS OF RESPONDENT WEIGHTING CALCULATIONS

Resp-Onions	Category				Category Value				Total	Wj
	Age	Experience	Position	Education	A	ET	PP	EL		
1	38	17	Senior Manager for Lifting Expert	BSc	2	2	4	3	11	0.23404
2	44	12	Lifting Instructor	MSc	3	2	3	4	12	0.25532
3	38	10	Operational Manager	BSc	2	2	2	3	9	0.19149
4	31	8	HSE	BSc	2	1	2	3	8	0.17021
5	26	7	Operator	BSc	2	1	1	3	7	0.14894

Intermediate A, load cell overload, is predominantly associated with inaccurate weight estimations of the lifted object. It may also be triggered by abrupt crane movements that cause dynamic shock loads, increasing the effective load due to potential energy conversion. Previous studies have highlighted that such overloads may be caused by miscalculations in the load moment within the Load Moment Indicator (LMI) system [34]. In response, this study recommends implementing comprehensive training programs aimed at enhancing operator awareness and competency in adhering to standard operating procedures and safety guidelines.

Intermediate B, damage to load cell components, may result from various technical issues. One key factor is deterioration of the strain gauge, which plays a crucial role in load tension measurement. This degradation may arise due to component aging and inadequate maintenance. In addition, damaged or disconnected power supply cables may interrupt energy transmission, rendering the load cell non-functional. Signal cables transmitting voltage readings to the display unit may also suffer wear, compromising reading validity. Furthermore, selection of an inappropriate load cell specification for a specific mobile crane model may contribute to such failures. A related study stresses the vulnerability of load cells in weight measurement applications, thereby recommending a tailored design and environmental compatibility assessment for each load cell type [35]. These issues can be mitigated by replacing load cells based on their service life and redesigning their installation to ensure physical protection.

Intermediate C, involving extreme environmental conditions, primarily relates to temperature exposure. Load cell strain gauges are sensitive to high temperatures and may deform if exposed to heat exceeding 200°F. Preventive measures include avoiding high-temperature environments or employing specialized thermal insulation covers to shield the load cell.

The findings of this study have broader implications, as load cells are not only used in mobile cranes but also in various other crane types. For instance, overhead cranes often incorporate load cells with artificial neural networks (ANNs) to detect overloads due to dynamic mass movements, which may compromise structural stability [36]. Beyond cranes, load cells are increasingly applied in heavy-duty vehicles to monitor load distribution and maintain unit stability [37]. This underscores the critical role of load cells in load-bearing equipment, highlighting the need for routine inspection, failure analysis, and comprehensive evaluation of influencing factors [38].

Compared to previous studies such as Halme et al. (2012) [39], which used conventional FTA to determine maintenance needs for mobile cranes by identifying the failure probabilities of components like bearings and hooks, the deterministic nature of classical FTA limits its flexibility in handling data quality variations—especially in complex tandem lifting operations.

Zuang et al. (2023) [40] examined load cell effectiveness in relation to strain gauge performance. While their study was effective in assessing load application during initial installation, it primarily focused on startup performance and feedback. This leaves an opportunity for further research into the routine operational stress and continuous usage of load cells, particularly when installed in mobile cranes under real-world lifting conditions using the FFTA method.

In another study, Kargar et al. (2022) [41] applied FFTA to assess risks in asymmetric tandem lifting using mobile cranes. However, their focus was limited to general overturning risks without exploring the specific role of load cells. This opens a research gap for investigating the direct impact of load cell failure on overturning incidents in tandem lifting scenarios.

The primary advantage of the FFTA method lies in its ability to explore subcomponent-level risk factors in greater depth and to address uncertainty and vagueness that cannot be effectively modeled through conventional FTA. FFTA also facilitates the integration of expert perceptions through structured interviews and discussions, supporting the fuzzification of input data and broadening the analytical perspective.

TABLE 6.
RESULTS OF PROBABILITY (FPr) CALCULATIONS

No	Code	FPs	K	FPr
1	A11	0.875	1.21069	0.06156
2	A12	0.63	1.93037	0.01174
3	A13	0.7775	1.52267	0.03001
4	A21	0.83167	1.35822	0.04383
5	A221	0.87	1.22879	0.05905
6	A2221	0.795	1.47121	0.03379
7	A2222	0.725	1.67103	0.02133
8	B11	0.79	1.48605	0.03266
9	B12	0.5875	2.04755	0.00896
10	B21	0.6425	1.89627	0.0127
11	B22	0.5325	2.20424	0.00625
12	B311	0.85667	1.27551	0.05303
13	B312	0.84333	1.32032	0.04783
14	B32	0.76333	1.56346	0.02732
15	C1	0.75833	1.5777	0.02644
16	C2	0.735	1.64329	0.02274
17	C3	0.83167	1.35822	0.04383

In conclusion, the proposed FFTA model not only substantiates prior research findings but also provides an adaptive, flexible risk assessment framework suited for diverse field conditions. It serves as an effective tool for preventive evaluation and strategic planning—particularly for inspection and maintenance programs targeting load cell components in tandem lifting operations using mobile cranes.

ConclusionThis study confirms that the load cell is a critical component in ensuring the safety of tandem lifting operations using mobile cranes. Despite the limited data, the application of the Fuzzy Fault Tree Analysis (FFTA) method successfully identified internal damage as the primary contributor to potential failure, with a weight value of 0.1840 (47%). Among the identified causes, material fatigue due to cable damage was found to have the highest probability of failure, with a weighting value of 0.128178 (70%). Cable damage presents a significant risk of rendering the load cell inoperative, thereby increasing the likelihood of occupational accidents.

To minimize the risk of load cell failure during tandem lifting operations, it is highly recommended to implement a preventive maintenance program on a regular basis, particularly focusing on cable connections and components that are susceptible to material fatigue. Comprehensive inspections should be conducted prior to each lifting activity, emphasizing the physical condition of the equipment, sensor calibration accuracy, and the identification of any latent defects. Additionally, training programs for crane operators and maintenance technicians should include in-depth knowledge of load cell functionality, early indicators of failure, and appropriate risk mitigation strategies. To enhance the effectiveness of these preventive efforts, the development and integration of real-time sensor-based monitoring systems should also be considered, enabling early detection of performance anomalies and reducing the likelihood of sudden failures.

Meanwhile, a study conducted by Xu N et al. (2023) [39] applying FFTA on the Lift-Jack system using a single crane that focuses on operational activities towards potential operational errors and causing work accidents. However, the research is general and does not specifically highlight load cells as the main object of analysis and has not reached a tandem lifting scenario. This research can provide a solution to similar work with the FFTA analysis model in tandem lifting cases and focuses on load cell component failure.

Meanwhile, Kargar V et al. (2022) conducted a risk assessment study on the tandem lifting process using a mobile crane for asymmetric tandem lifting work using the FFTA method. However, this study only focuses on the probability of overtuning on a mobile crane in a general operating field perspective. This is also a gap for this study to dig deeper and specifically apply it to load cell components that can also result in overtuning in the tandem lifting process using a mobile crane.

The benefits of the FFTA approach include the ability to examine smaller parts that can influence a specific scale and its capability to deal with situations that are hard to measure accurately using traditional FTA. The FFTA approach facilitates the integration of perceptions into decision-making by using interview and discussion methods as part of input data fuzzification, allowing for a broader perspective to be explored. Thus, the results of this study not only strengthen the results of previous studies, but this study can provide another approach that is more adaptive to variations in conditions at work. This model is very effective as an evaluation tool for preventive risks, especially in compiling preventive inspection and maintenance programmes on load cell components on mobile cranes, especially in tandem lifting work using mobile cranes.

IV. Conclusion

This study confirms that the load cell is a critical component in ensuring the safety of tandem lifting operations using mobile cranes. Despite the limited data, the application of the Fuzzy Fault Tree Analysis (FFTA) method successfully identified internal damage as the primary contributor to potential failure, with a weight value of 0.1840 (47%). Among the identified causes, material fatigue due to cable damage was found to have the highest probability of failure, with a weighting value of 0.128178 (70%). Cable damage presents a significant risk of rendering the load cell inoperative, thereby increasing the likelihood of occupational accidents.

To minimize the risk of load cell failure during tandem lifting operations, it is highly recommended to implement a preventive maintenance program on a regular basis, particularly focusing on cable connections and components that are susceptible to material fatigue. Comprehensive inspections should be conducted prior to each lifting activity, emphasizing the physical condition of the equipment, sensor calibration accuracy, and the identification of any latent defects. Additionally, training programs for crane operators and maintenance technicians should include in-depth knowledge of load cell functionality, early indicators of failure, and appropriate risk mitigation strategies. To enhance the effectiveness of these preventive efforts, the development and integration of real-time sensor-based monitoring systems should also be considered, enabling early detection of performance anomalies and reducing the likelihood of sudden failures.

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