State of the Art Review of Technological Advancements for Safe Tower Crane Operation

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Abstract –

This paper focuses on construction accidents, particularly those involving tower cranes. An initial analysis of the modern literature highlights tower cranes as a significant safety concern, with human error identified as a major factor. The paper in the further explores modern technological innovations addressing these human-related risks. Recognizing the potential of technology to improve safety, the review establishes a crucial link between understanding accident root causes, particularly human error, and ongoing efforts to enhance safety through technological interventions. Utilizing a systematic Web of Science keyword searches approach, including a quantitative and qualitative analysis of the respective publications, the review divides tower crane safety into two predominant fields, namely the pre-construction phase that plans, among other objectives, safe worksite layouts, and the construction phase that executes safe operations. The findings provide a comprehensive overview of the most recent technological innovations that involve tower cranes in both project phases. A synthesis informs about future research and industry initiatives for advancing tower crane safety.

Keywords –

Accidents, Construction safety, Tower cranes.

1 Introduction

The construction industry, crucial for global progress, struggles with an enduring challenge that is workplace accidents, particularly involving tower cranes. Between 2011 and 2017, there were 297 reported deaths due to crane accidents in the US alone, averaging 42 fatalities per year [1]. A more detailed analysis of the data from Spain from 1990 to 2000 shows that of the 1.630.452 accidents reviewed, 22.349 or 1,4% of the accidents are related to cranes and lifting equipment of which 165 were fatal while 1.201 are severe and fatal [2].

The construction industry relies on a diverse array of cranes, including tower cranes, mobile cranes, overhead cranes, and crawler cranes, each playing a unique role in shaping industry dynamics. Tower cranes, particularly, have emerged as a predominant type, garnering widespread use in Europe and gaining popularity in the US [3]. These statistics clearly demonstrate the safety related issues for tower crane operations. This forms the motivation to study what is being done in this field to improve the safety conditions. Therefore, this review paper tries to investigate the following major research questions:

- What is the current state of construction site safety with respect to tower cranes?
- What are the significant factors that cause accidents?
- How can technological solutions improve the safety of tower crane operations?
- What technological solutions are being explored for improving safety of tower crane operations?

This review studies the proportion of accidents related to tower crane operations. It investigates the problem of safety issues. Following that is the methodology of how the publications are found, selected and reviewed are discussed. Then, a quantitative analysis and a qualitative is performed to give the reader an objective idea about the trends being explored in this field, this allows for a better understanding of the trends and their advantages or shortcomings. At last, a conclusion section summarizes the key insights from the review.

2 Background

The construction sites where fixed site lifting mechanisms and lifting structures are used, are hazardous production facilities. The year 2020 saw 35 recorded accidents in Russia [4]. These resulted in 28 fatalities, attributed to the operation of lifting structures at monitored facilities. The majority of accidents related to lifting machinery between 2015 and 2020 were associated with the operation of tower cranes. For instance, out of 25 crane-related incidents, 12 (47%) occurred during the operation of tower cranes, 4 (20%) during the operation of crawler and mobile cranes, 2 (10%) during the use of manipulator cranes, and 2 (7%)

during the use of overhead gantry, and 1while using the portal cranes as shown in Figure 1. Despite the varied crane types, the focus on tower cranes intensifies when considering occupational accidents.

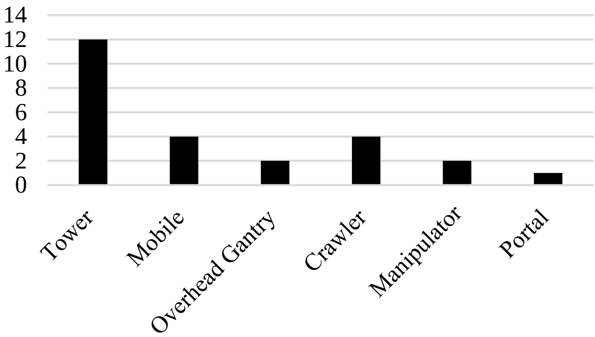

Figure 1: Involved equipment type in fatal crane accident, as an example, Russia in 2020 [4].

In addition to the human cost, crane accidents also lead to fiduciary losses as well. A study among 313 Malaysian registered contractors revealed three key areas that increase the cost of a project when an accident occurs. These being project delays, medical expenses, and damage repairs to completed work and collateral damage. Although the study does not point out an exact number value for the increase in the costs, it demonstrates that out of the contractors who undertook the survey, 97.4% agree that project delays due to accidents increase the project cost, 94.8% agree that the additional cost of repairing completed construction or adjacent structures is significant. 89.4% of the surveys agree that the medical costs for compensating injured workers also increase the cost of the overall project [5]. Moreover, human error accounts for approximately 70% of crane accidents [6].

A preliminary statistical analysis of accidents involving tower cranes, identified contributing factors. Furthermore, a Degree of Influence (DOI) was computed for each factor, providing a more nuanced understanding of their individual levels of significance [7]. According to the findings of this study “Operator Proficiency” has the highest DOI. Whereas the seven factors that can be categorized into human-factor and safety management categories also have high DOIs associated to them.

An further examination of human factor classification revealed key aspects that further refine the understanding of these incidents [8]. These aspects include:

- inattention,
- failure in communication,
- operator error, and
- error of signal person.

Another study arrives at similar conclusions however they do point out that although human error-based accidents have a very high frequency, they rank low in severity of the accidents [9]. They point out that the most prevalent failures in the dataset are:

- Inattention, a typical human factor that appeared in about 19% of incidents.
- The second most prevalent type (between 10 and 15%) contains three human factors, namely– improper rigging, – signalperson error, and– operator error.
- Environmental factors such as limited visibility and strong wind appear to reside within the least prevalent.

A point-cloud and display based safety feature was tested with five crane operators with work experiences ranging from 8 to 16 years [10]. Although they point out that their solution was still in the preliminary stage and some of the issues would be sorted out in later iterations, the key insights obtained from their tests were:

- The operators generally agreed that the new safety solution was easy to use.
- The operators agreed that a real-time vision-based safety feature would help improve safety. However, the operators were also quick to point out that this does not eliminate the need for a signal person. The main reason was a general insecurity about solely relying on technology as it also put all the responsibility on the operators too.
- The operators could not form a consensus on whether such system necessarily improves efficiency. They pointed out that being able to view the scene in 3D helped them choose an optimum path faster. However, in situations where direct line of sight application was still feasible the system acted as a hindrance.

These cases demonstrate that technological assistance plays a significant role in enhancing the overall safety of workers on a construction site, particularly in the context of crane-related accidents.

3 Methodology

This review utilizes systematic Web of Science keyword searches, similar to [11]. The review is divided in two primary phases (Figures 2 and 3, respectively):

- Pre-construction planning phase, and
- Construction operation phase.

Advanced search options were used that allow for Boolean keyword search operations. Boolean operators like “And” and “OR” were used to identify records that talk about construction safety and technology. For this purpose, following keyword searches were used:

- "ALL=(('crane') AND ('safety') AND ('pre-construction' OR 'planning'))"
- “ALL=((" tower crane") AND ("safety") and ("improving" or "monitoring"))”

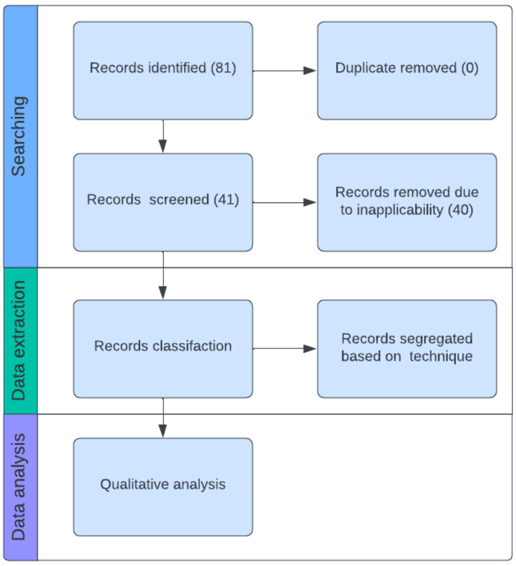

Figure 2: Flowchart for the literature review part of the pre-construction phase.

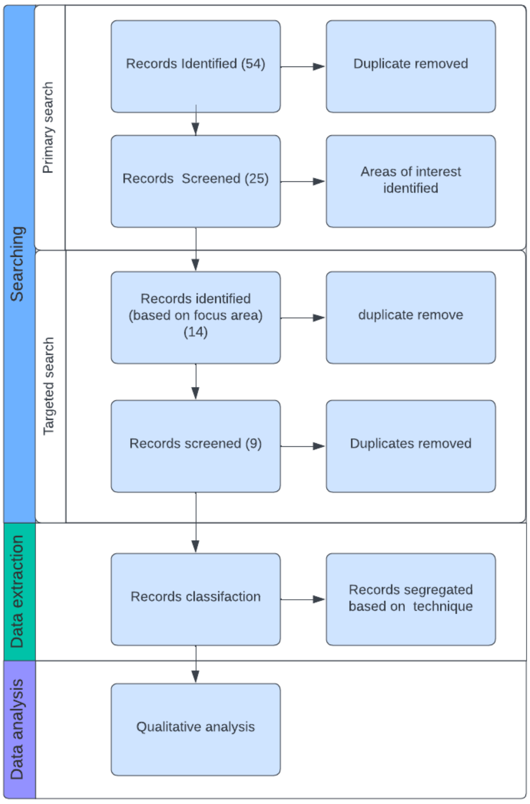

Figure 3: Flowchart for the literature review part of the construction operation phase.

A lot of technological developments exist to make construction sites safer. However, for this review, a strict criterion was chosen to only consider literature that strictly deals with tower cranes and technology that pertains to improving safety on a construction site.

Since the majority of the publications were from or before 2011, 2011 was chosen to be the cut-off date for all records to be included in the review.

The first set of keywords were chosen to target tower crane safety in pre-construction or planning, while the second set focused on tower crane safety during construction. The systematic use of these keywords allowed for a structured exploration of relevant literature, providing insights into technological innovations in both project planning and construction phases. The first planning stage part of the review required only a straightforward approach as shown in Figure 2.

The construction operations part of the review required a more nuanced approach. To address potential human bias and facilitate an unbiased search, technology-specific terms were deliberately omitted for the primary keyword selection. The goal was to prevent assumptions that particular technologies, such as RFID or cameras, exclusively dominated the field. The objective for using this approach was to identify literature that might not be widely known, or avoiding potential gaps in the knowledge base. Subsequently, targeted keyword searches were conducted to comprehensively examine the identified technology fields as shown in Figure 3. Some of the targeted search keywords are mentioned below:

- ALL=(("crane") AND ("safety") and ("IoT" or "Internet of Things" or "internet of things "))
- ALL=(("crane") AND ("safety") and ("sensor" or "sensing"))
- ALL=(("crane") AND ("safety") and ("camera" or "image" or "vision "))

4 Findings of quantitative analysis

The number of publications reviewed are shown in Table 1. Many of them that contained one relevant keyword were clubbed into a single category of ‘others’.

Table 1. Distribution based on journal publications.

Journal and *conference* name	Publications [No.]
Automation in Construction	18
Computing in Civil Engineering	5
Advanced Engineering Informatics	4
Construction Engineering and Management	4
Advances in Civil Engineering	2
Buildings	2
Sensors	2
ICMSE	2
Construction Research Congress	2
Others	34
Total	75

As seen in Figure 4, between the years 2013 until 2019 fewer publications were found. Of the 75 publications reviewed, 41 focused on the pre-construction phase while 34 focused on building solutions for real-time applications. Among those 41 papers, 21 looked at crane layout planning, while about one third (14) looked at crane trajectory planning. The remaining 6 papers focused on unique aspects of the planning phase as shown in Table 2. As for the remaining 34 papers, their focus was divided amongst several domains (Table 3).

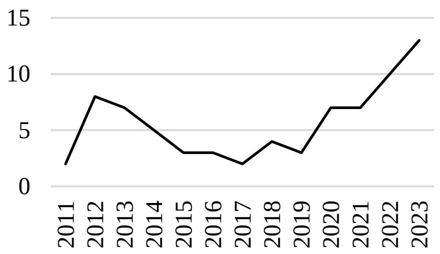

Figure 4: Total publications per year

Table 2. Distribution of publications focusing on the pre-construction planning phase

Focus Area	Number
Single crane layout	6
Multi crane layout	15
Trajectory planning	14
Unique focus areas	6

Table 3. Distribution of publications focusing on the construction operation phase

Technology used	Number
Sensor based	18
Camera based	6
Virtual reality based	4
Digital twin based	1
Model based	2
Simulation based	1
Combined areas	2

5 Discussion

Tables 4 and 5 preview techniques used to implement solutions for each focus area. Traditionally, the task of planning the stages and arrangement of equipment and heavy machinery was solely dependent on the experience and expertise of trained professionals. However, these tasks are also being relegated to automated solutions.

This can help save time, money and most importantly, human lives. The task of planning a construction site w.r.t a tower crane is mainly about identifying two key issues, the optimal position of tower crane and the optimal trajectory for the lift path. Interestingly, trajectory planning is a vital and matured aspect of the robotics field. Several of those algorithms that have been tried and tested. For example, search-based algorithms like L* algorithm [12] and A* algorithms [13] which are were tested in simulations and they show fast execution times and can successfully generate collision free lift paths. While interpolation-based algorithms like spline curve [14] or waypoint [15] calculations have also shown success, especially in time efficiency as interpolation-based algorithms lead to smoother curves that do not lead to sudden acceleration or jerk.

Moving away from the technologies being laterally transferred from robotics. Some solutions based on fundamental mathematics have also been explored.

Techniques like time-based polynomial functions [16] for accommodating complexities that arise from the double-pendulum created between the jib, hook and the weight attached via cables has shown state of the art performance. Similarly, Lagrange's kinematic equations [17] have been used for swing suppression of the payload when the trolley moves it along the jib. Alternatively, control-theory based state variable models for both double pendulum [21] and anti-swing [22] have also been experimented with. The anti-swing model is tested on an experimental setup while state variable model for double pendulum dynamics only simulated. Both show good results and are successful in meeting their objectives.

Some research has been done into creating process management systems. Prevention through Design (PtD) [18] integrated with a BIM and dependency structure matrix [19] are examples of two techniques used by these type of management system. These typically include a scheduling system, a visualization system, and some form of anti-collision safety. However, they still remain error prone and require further development. A 4D BIM [20] also acting as an overall process management, tries to look at global optimum based on resource optimization over multiple factors, it looks at not only crane movement optimization but also the cost, number of cranes etc.

Simulations and virtual environments have also been used in lift path planning recently. Reinforcement learning based models [23] are being trained in virtual environments, the models can be used to generate a collision free motion for the tower crane and also estimate the lifting time. Simulation models are also being used for near real time planning [24], the model can perform optimization tasks via simulations and provide a day-to-day planning support effectively.

One important factor to understand about most of these type of research related to tower cranes is that, due to the nature of the project real-life experimental validations is often times expensive, infeasible and risky for the construction workers. Hence a lot of research is validated on experimental setups or simulations.

The other main concern of research in the pre-construction phase is the location of the tower crane within the construction site. Mixed integer linear programming [25-28] is shown to be a very effective and popular strategy for the development of tower crane layout algorithms. This approach has shown great results in terms of collision avoidance, time and resource efficiency and safety. By also paying extra attention to planning the location of source points and destination point along with the tower crane, the amount to be carried per trip can be reduced which means the site requires a smaller crane and saves costs [30].

Table 4. Data analysis techniques for crane safety (pre-construction)

Application	Technical Details	Examples
Crane trajectory planning	Machine Learning-based	[23]
	Mathematical modelling-based	[16], [17]
	Simulation-based	[24]
	Algorithm-based	[12],[13], [14],[15]
	Management system based	[18], [19], [20]
	State variable modelling based	[21], [22]
Crane layout planning for a single crane	AI based	N/A
	Mixed-integer linear programming based	[29]
	Optimization based	[37], [38]
Crane layout planning for multiple cranes	Mixed-integer linear programming based	[25], [26], [27], [28]
Crane lifecycle estimation	Backpropagated neural network	[39]

Table 5. Data analysis for crane safety (construction operation phase)

Technology	Technical details	Examples
Sensor based	Internet of things platform	[41], [42], [53], [54], [56], [69]
	Embedded systems platform	[43], [48], [49], [50], [44], [45], [46]
	CDMA communication platform	[40]
Camera		[57], [58], [66], [59], [60], [61]
Virtual reality		[62], [63], [64]
Digital twin		[47]
Modelling	Mathematical model	[51]
	Artificial neural network	[55], [52]
Combined		[68], [67]

Artificial Intelligence also provides several alternative solutions to tackle the problem. Firefly algorithm [31] is an optimization algorithm based on the field of AI called swarm intelligence, it is a highly effective method for trying out several alternatives and then ranking them. In this approach a BIM model is integrated with firefly algorithm, and it predicts the best layout. Generative adversarial network [36] based solutions use image-based solutions where conditions based on all the details of construction site are fed in. The model tries to create an optimized solution in terms of time optimization and the safety of the site by considering the building boundary and load bearing capacity among others.

Genetic Algorithms [35] and agent-based systems [33-34] are also deployed in several solutions. A decision support system utilizing a combination of analytical hierarchy process, a 4D BIM and genetic algorithm [32] was to be capable of dynamic assistance and its capable.

Depending on the scale of the construction project the site may require a single or multiple tower cranes. Mixed integer linear programming can be applied for optimizing the location of a single crane on a small to medium size construction project [29]. Non-linear optimization techniques on models of a tower crane with realistic kinematic dynamics are also used for single crane operations, a solution like this improves safety at the site as it optimizes the location of the crane and supply points such that the trajectory of the lift is smooth with a finite jerk [37]. The firefly algorithm discussed above is also used to create the optimal layout for single cranes with considerations to safety, time and cost efficiency [38]. It uses GIS for accurate localization of the crane and a CAD model of the crane to apply the firefly algorithm to.

While looking at the publications that focus on unique areas, some interesting ideas are seen. The condition of the structure of a tower crane is dependent on not just the load being hoisted but, for instance, the repeated use, corrosion, designed lifecycle. A back-propagated neural network demonstrates that it can predict the lifetime of a tower crane with an error rate as small as 0,001% albeit it has a large training time for every crane [39]. The model can potentially enable better site safety and security as it allows planners to know how dangerous any particular tower crane's chances of collapsing are.

Sensor-based solutions [40] offer users contextual data of the TC, including swing, amplitude, weight, etc.it uses CDMA for communication. Contextual data such as these greatly assist the crane operator to perform their task safely for both the construction worker and crane itself, which indirectly impacts the construction worker, crane operator and everyone around the crane. They can also raise alarms if any safety parameter is being violated during a lifting operation.

Similarly designed systems exist that use IoT (Zigbee) [41, 42]. However, CDMA can be more suited for this type of application as it has extended range, higher data transfer rates, enhanced interference resistance and reliability, as well as capacity and scalability. It can support a large number of users simultaneously, suitable for applications with high device density or scalability requirements.

IoT has also been used for creating anti-collision systems. When operating multiple tower cranes in close proximity with each other, it is potentially a hazardous situation. To mitigate the risks RFID sensors with wireless sensor networks are used to detect incoming collisions and avoid them [53, 54], [56].

Some solutions on the other hand prefer to go for wired embedded system design architectures [43], [48] these allow for extremely high data transfer rates, security and reliability. This can also be easily scaled up with minimal losses to data rates. However, these systems can be more costly as they require more hardware equipment for the setup. Adding a fuzzy logic based PID controller into the system with a human-computer interface allows the operators to adjust the crane movements based on the data being provided to them. Using a PID controller rather than a manual control further assists them to perform safer executions [49]. Similarly, linear interpolation method is used to compute complex torque related calculations for a tower crane which get their input values via sensors and use a PLC based controller to protect the crane from overloading, excessive stress or potential damage to other crane components that can create hazardous situations for workers below or the crane operator [50].

Sensors, when placed in outdoor environments with varying temperature, humidity and other elements, cause the readings to drift. Prolonged load and continued use also cause sensor creep. Both these can introduce significant inaccuracies into the system which can endanger workers' safety. Research to create embedded systems can make such systems' operation safer [44, 45].

Another interesting approach to assist crane operators with situational awareness and contextual data of the crane is to integrate virtual models, kinematic models, and real time data from the site and the crane data. This allows for the visualization and monitoring of the crane and raises an alarm when any safety parameters are violated [46]. This system was shown to have wide acceptance within the workers and operators.

To ensure safe crane operations it is crucial to realize the impact of the environment on the crane as well as the state of the crane. Therefore, mathematical [51] and neural network models [55] can predict the effect of wind loads on tower crane operations. Artificial neural network based models with sensor data are used to monitor the state of the crane and fault diagnosis [52].

Taking that idea a step further, and allowing simulations into the visualization system too allows crane operators to test their hoisting operation plans beforehand. A digital-twin based solution [47] has been designed to perform these testing operations. This idea provides much better insights than a pre-construction trajectory planning as it utilizes a digital twin which is integrated with sensor derived real time data describing the state of the crane as well as the weather conditions around the site.

Several solutions have been investigated using cameras as well. Some of them focus on the position and displacement of the crane. This information, as mentioned before, provides the operators with crucial information on the real-time situation of the crane and helps him react accordingly. In [57] the crane focuses on detecting the displacement of the jib and the cart, experimental results show good results. While [58], [66] and [59] focus on the hook and provide the operator assistance for precision hoisting.

Apart from using cameras for tracking the crane, it has also been used for other applications. A camera situated in the operator's room is used to analyse their facial images and uses a neural network model to assess the fatigue of the crane operator [60]. This information is very crucial from a safety perspective as a fatigued operator is more likely to make mistakes.

A camera mounted on the tower crane's boom has been used to detect and track construction workers. It assesses the potential danger to the workers around the crane and warns them of it [61]. Ultra-wideband (UWB) sensor-based IoT solutions [67, 69] have also been used to detect and track workers and prevent collision. However, a UWB based solution is a costlier alternative when compared to a camera-vision based detection and tracking system. Both technologies carry high chance of missing a worker because of signal loss or unavailability.

The role of virtual reality has primarily been for training new operators. This is important because it allows the operators to train in a safe environment for longer hours, which otherwise is financially infeasible. Virtual reality based simulations have been used to train operators on how to use the tower crane [62, 63].

Context aware training for a specific construction site is also done by integrating the virtual reality model with the BIM [64]. It has also been used to train operators and workers on how to dismantle a tower crane, which is one of the more challenging aspects of operating a tower crane on a construction site [65].

There are some solutions that have tried to tackle the safety issue by using a combination of multiple technologies, a neural network combined with a simulation model with inputs from the sensor is used to predict the foundation's stability on which a tower crane sits [65]. This creates a reliable solution to predict the safe operations of a tower crane and can warn workers when a crane is too risky to operate. Another such mixed technology solution uses sensors, camera and laser to create accurate navigation paths for a tower crane and assists in blind lifts [68].

Conclusion

This state of the art review, covering mostly academic publications over the past decade, showed a growing interest in the construction domain to develop specific technologies that can assist in planning and operating tower cranes more safely. While eventually the construction site, its staff and workers, will benefit the most from such availability and use of emerging safety technologies, this review found that it is often leadership in organizations that lacks knowledge on the basic working principles, the benefits, and the shortcomings of applying advanced technology in the field. Furthermore, this study found that scientific work yet has to find effective measures that solve the proclaimed disconnect between technology in the pre-construction tower crane planning and operations phases. This state of the art review found multiple examples that explain some of the reasons for slower than needed technology adaption in the field of safe tower crane planning and operation.

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References

[1] U.S. Bureau of Labor Statistics. Injuries, Illness, and Fatalities. Accessed: 10/12/2023. On-Line: https://www.bls.gov/iif/factsheets/fatal-occupational-injuries-cranes-2011-17.htm,

[2] López M., Ritzel D., Fontaneda I., and Alcantara, O Construction industry accidents in Spain. *Journal of Safety Research*, 39(5), 497-507, 2008. https://doi.org/10.1016/j.jsr.2008.07.006

[3] Spirina A., Mironov A., Datkhuzheva R., Maksimov A., and Belova N. Analysis of occupational injuries in construction and offer of a technical solution increasing tower crane stability. *Transportation Research Procedia*, 68, 559-565, 2023. https://doi.org/10.1016/j.trpro.2023.02.076

[4] Shapira A., and Lyachin B. Identification and analysis of factors affecting safety on construction sites with tower cranes. *Construction Engineering and Management*, 135(1), 24-33, 2009. https://doi.org/10.1061/(ASCE)0733-9364(2009)135:1(24)

[5] Dahalan M., and Azmi W. Crane Accidents: Identifying the Impact on Construction Cost among Contractors. In *Intl. J. Academic Research in Progressive Education and Development, 11(3)*, 1553–1562, 2022. http://dx.doi.org/10.6007/IJARPED/v11-i3/15286

[6] Haslam R. A., Hide S. A., Gibb A. G., Gyi D. E., Pavitt T., Atkinson S., and Duff A. R. Contributing factors in construction accidents. *Applied Ergonomics*, 36(4), 401-415, 2005. https://doi.org/10.1016/j.apergo.2004.12.002

[7] Shapira A., and Lyachin B. Identification and analysis of factors affecting safety on construction sites with tower cranes. *Construction Engineering and Management*, 135(1), 24-33, 2009. https://doi.org/10.1061/(ASCE)0733-9364(2009)135:1(24)

[8] Raviv G., Shapira A., and Fishbain B. AHP-based analysis of the risk potential of safety incidents: Case study of cranes in the construction industry. *Safety Science*, 91, 298-309, 2017. https://doi.org/10.1016/j.ssci.2016.08.027

[9] Raviv G., Fishbain B., and Shapira A. Analyzing risk factors in crane-related near-miss and accident reports. *Safety Science*, 91, 192-205, 2017. https://doi.org/10.1016/j.ssci.2016.08.022

[10] Fang Y., Cho Y. K., Durso F., and Seo J. Assessment of operator's situation awareness for smart operation of mobile cranes. *Automation in Construction*, 85, 65-75, 2018. https://doi.org/10.1016/j.autcon.2017.10.007

[11] Fang Y., Cho Y. K., and Chen J. A framework for real-time pro-active safety assistance for mobile crane lifting operations. *Automation in Construction*, 72, 367-379, 2016. https://doi.org/10.1016/j.autcon.2016.08.025

[12] Lin X., Han Y., Guo H., Luo Z., and Guo Z. Lift path planning for tower cranes based on environmental point clouds. *Automation in Construction*, 155, 105046, 2023. https://doi.org/10.1016/j.autcon.2023.105046

[13] Burkhardt M. and Sawodny O. A graph-based path planning algorithm for the control of tower cranes. In *American Control Conference*, 1736-1741, 2021. doi: 10.23919/ACC50511.2021.9482797.

[14] Thomas M., Qiu J. and Sawodny O.Trajectory sequence generation and static obstacle avoidance for automatic positioning tasks with a tower crane. In *Annual Conf. Industrial Electronics Society*, 1-6, 2021. doi: 10.1109/IECON48115.2021.9589398.

[15] Burkhardt M., Gienger A., and Sawodny O. Optimization-Based Multipoint Trajectory Planning Along Straight Lines for Tower Cranes. *IEEE Transactions on Control Systems Technology*, 2023. doi: 10.1109/TCST.2023.3308762.

[16] Li G., Ma X., Li Z. and Li Y. Time-Polynomial-Based Optimal Trajectory Planning for Double-Pendulum Tower Crane With Full-State Constraints and Obstacle Avoidance. *IEEE/ASME Transactions on Mechatronics*, 28(2), 919-932, 2022. doi: 10.1109/TMECH.2022.3210536

[17] Tian Z., Yu L., Ouyang H. and Zhang G. Swing suppression control in tower cranes with time-varying rope length using real-time modified

trajectory planning. *Automation in Construction*, 132, 103954, 2021. https://doi.org/10.1016/j.autcon.2021.103954

[18] Hu S., Fang Y. and Moehler R. Estimating and visualizing the exposure to tower crane operation hazards on construction sites. *Safety Science*, 160, 106044, 2023. https://doi.org/10.1016/j.ssci.2022.106044

[19] Kim S., Kim S. and Lee D. Sequential dependency structure matrix-based framework for leveling of a tower crane lifting plan. *Canadian Journal of Civil Engineering*, 45(6), 516-525, 2018. https://doi.org/10.1139/cjce-2017-0177

[20] Lin Z., Petzold F. and Hsieh S. H. Automatic Tower Crane Lifting Path Planning Based on 4D Building Information Modeling. In *Construction Research Congress*, 837-845, 2020. https://doi.org/10.1061/9780784482865.089

[21] Ouyang H., Tian Z., Yu L. and Zhang G. Motion planning approach for payload swing reduction in tower cranes with double-pendulum effect. *Journal of the Franklin Institute*, 357(13), 8299-8320, 2020. https://doi.org/10.1016/j.jfranklin.2020.02.001

[22] Liu Z., Yang T., Sun N., and Fang Y. An antiswing trajectory planning method with state constraints for 4-DOF tower cranes: design and experiments. *IEEE Access*, 7, 62142-62151, 2019. doi: 10.1109/ACCESS.2019.2915999

[23] Cho S. and Han S. Reinforcement learning-based simulation and automation for tower crane 3D lift planning. *Automation in Construction*, 144, 104620, 2022. https://doi.org/10.1016/j.autcon.2022.104620

[24] Al Hattab M., Zankoul E., and Hamzeh F. R. Near-real-time optimization of overlapping tower crane operations: a model and case study. *Computing in Civil Engineering*, 31(4), 05017001, 2017. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000666

[25] Riga K., Jahr K., Thielen C. and Borrmann A. Mixed integer programming for dynamic tower crane and storage area optimization on construction sites. *Automation in Construction*, 120, 103259, 2020. https://doi.org/10.1016/j.autcon.2020.103259

[26] Ji Y. and Leite F. Optimized planning approach for multiple tower cranes and material supply points using mixed-integer programming. *Construction Engineering and Management*, 146(3), 04020007, 2020. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001781

[27] Zhou C., Dai F., Xiao Z. and Liu W. Location Optimization of Tower Cranes on High-Rise Modular Housing Projects. *Buildings*, 13(1), 115, 2023. https://doi.org/10.3390/buildings13010115

[28] Huang C. Wang Z. K., Li B., Wang C., Xu L. S., Jiang, K., ... and Yang H. Discretized Cell Modeling for Optimal Layout of Multiple Tower Cranes. *Construction Engineering and Management*, 149(8), 04023068, 2023. https://doi.org/10.1061/JCEMD4.COENG-13146

[29] Huang C., Wong C. K., and Tam C. M. Optimization of tower crane and material supply locations in a high-rise building site by mixed-integer linear programming. *Automation in Construction*, 20(5), 571-580, 2011. https://doi.org/10.1016/j.autcon.2010.11.023

[30] Moussavi Nadoushani Z. S., Hammad A. W. and Akbarnezhad A. Location optimization of tower crane and allocation of material supply points in a construction site considering operating and rental costs. *Construction Engineering and Management*, 143(1), 04016089, 2017. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001215

[31] Wang J., Zhang X., Shou W., Wang X., Xu B., Kim M. J. and Wu P. A BIM-based approach for automated tower crane layout planning. *Automation in Construction*, 59, 168-178, 2015. https://doi.org/10.1016/j.autcon.2015.05.006

[32] Marzouk M. and Abubakr A. Decision support for tower crane selection with building information models and genetic algorithms. *Automation in Construction*, 61, 1-15, 2016. https://doi.org/10.1016/j.autcon.2015.09.008

[33] Younes A. and Marzouk M. Tower cranes layout planning using agent-based simulation considering activity conflicts. *Automation in construction*, 93, 348-360, 2018. https://doi.org/10.1016/j.autcon.2018.05.030

[34] Khodabandelu A. and Park J. Integrating BIM and ABS for multi-crane operation planning through enabling safe concurrent operations. *Computing in Civil Engineering*, 1128-1135, 2022. https://doi.org/10.1061/9780784483893.138

[35] Yang, Fang, Luo, Liu and Dong. A BIM-based approach to automated prefabricated building construction site layout planning. *KSCE Journal of Civil Engineering*, 26(4), 1535-1552, 2022. https://doi.org/10.1007/s12205-021-0746-x

[36] Yang B., Fang T., Luo X., Liu B., and Dong M. A bim-based approach to automated prefabricated building construction site layout planning. *KSCE Journal of Civil Engineering*, 26(4), 1535-1552, 2022.

[37] Li R., Chi H. L., Peng Z., Li X. and Chan A. P. Automatic tower crane layout planning system for high-rise building construction using generative adversarial network. *Advanced Engineering Informatics*, 58, 102202, 2023.

https://doi.org/10.1016/j.aei.2023.102202
[38] Liu C., Zhang F., Han X., Ye, H., Shi Z., Zhang, J., ... and Zhang T. Intelligent Optimization of Tower Crane Location and Layout Based on Firefly Algorithm. *Computational Intelligence and Neuroscience*, 2022. https://doi.org/10.1155/2022/6810649
[39] Tubaileh A. Working time optimal planning of construction site served by a single tower crane. *Mechanical Science and Technology*, 30(6), 2793-2804, 2016. https://doi.org/10.1007/s12206-016-0346-8
[40] Liu C., Zhang F., Han X., Ye H., Shi Z., Zhang J., ... and Zhang T. Intelligent Optimization of Tower Crane Location and Layout Based on Firefly Algorithm. *Computational Intelligence and Neuroscience*, 2022. https://doi.org/10.1155/2022/6810649
[41] Yu Y., Tian Y., Feng N., and Lei M. Research on lifetime prediction method of tower crane based on back propagation neural network. *Advances in Electronic Commerce, Web Application and Communication*, 2, 111-116, 2012. https://doi.org/10.1007/978-3-642-28658-2_17
[42] Zhang N. Q., Yu M., Zhang X., Fu J., and Wu H. S. Enhancing tower crane safety using condition monitoring system. *Applied Mechanics and Materials*, 418, 80-83, 2013. https://doi.org/10.4028/www.scientific.net/amm.418.80
[43] Zhang Q. C., and Zhang Z. H. Research on wireless sensor network node for tower crane safety monitoring system. *Applied Mechanics and Materials*, 494, 781-784, 2014. https://doi.org/10.4028/www.scientific.net/amm.494-495.781
[44] Han Z. G., Hao R. Q., and Zheng X. J. The Online Assessment Method of Tower Crane Effective Life Based on Tower Crane Group Monitoring System. *Advanced Materials Research*, 189, 1066-1070, 2011. https://doi.org/10.4028/www.scientific.net/amr.189-193.1066
[45] Chen G. Z., Zhang B., and Yang Y. Safety monitoring and protection system of tower crane based on ARM. *Applied Mechanics and Materials*, 263, 610-614, 2013. https://doi.org/10.4028/www.scientific.net/amm.263-266.610
[46] Deng H. L., and Xiao Y. G. Development of General Embedded Intelligent Monitoring System for Tower Crane. *Applied Mechanics and Materials*, 103, 394-398, 2012. https://doi.org/10.4028/www.scientific.net/amm.103.394
[47] Luo X., O'Brien W. J., Leite F., and Goulet J. A. Exploring approaches to improve the performance of autonomous monitoring with imperfect data in location-aware wireless sensor networks. *Advanced Engineering Informatics*, 28(4), 287-296, 2014. https://doi.org/10.1016/j.aei.2014.08.004
[48] Li Y. and Liu C. Integrating field data and 3D simulation for tower crane activity monitoring and alarming. *Automation in Construction*, 27, 111-119, 2012. https://doi.org/10.1016/j.autcon.2012.05.003
[49] Jiang W., Ding L., and Zhou C. Digital twin: Stability analysis for tower crane hoisting safety with a scale model. *Automation in Construction*, 138, 104257, 2022. https://doi.org/10.1016/j.autcon.2022.104257
[50] Zheng M. G. and Zhu X. H. Design of Tower Crane Intelligent Monitoring Management System Based on PLC and WinCC. *Applied Mechanics and Materials*, 184, 1554-1557, 2012. https://doi.org/10.4028/www.scientific.net/amm.184-185.1554
[51] Zhou Q. H., Li Q. B, and Chen B. J. Study On Intelligent Control System For Tower Cranes Based On ARM. *Advanced Materials Research*, 518, 4449-4454, 2012. https://doi.org/10.4028/www.scientific.net/amr.518-523.4449
[52] Wang H. PLC-Based Tower Crane Torque Protection System. *Advanced Materials Research*, 694, 2685-2688, 2013. https://doi.org/10.4028/www.scientific.net/amr.694-697.2685
[53] Jin L., Liu H., Zheng X., and Chen, S. Exploring the impact of wind loads on tower crane operation. *Mathematical Problems in Engineering*, 1-11, 2020. https://doi.org/10.1155/2020/2807438
[54] Yu J. L., Zhou R. F., Miao M. X., and Huang H. Q. An application of artificial neural networks in crane operation status monitoring. In *Proc. Chinese Intelligent Automation Conference: Intelligent Automation*, 223-231, 2015. https://doi.org/10.1007/978-3-662-46463-2_24
[55] Zhang D., Li S., and Zhao H. Design of Mobile Monitoring System for Tower Crane in Assembly Construction Based on Internet of Things Technology. In *Intl. Conference on Advanced Hybrid Information Processing*, 588-603, 2022. https://doi.org/10.1007/978-3-031-28867-8_43
[56] Zhong D., Lv H., Han J., and Wei Q. A practical application combining wireless sensor networks and internet of things: Safety management system for tower crane groups. *Sensors*, 14(8), 13794-13814, 2014. https://doi.org/10.3390/s140813794
[57] Li Q., Fan W., Huang M., Jin H., Zhang J., and Ma

J. Machine Learning-Based Prediction of Dynamic Responses of a Tower Crane under Strong Coastal Winds. *Marine Science and Engineering*, 11(4), 803, 2023. https://doi.org/10.3390/jmse11040803

[58] Sleiman J. P., Zankoul E., Khoury H., and Hamzeh F. Sensor-based planning tool for tower crane anti-collision monitoring on construction sites. In *Construction Research Congress*, 2624-2632, 2016. https://doi.org/10.1061/9780784479827.261

[59] Gutierrez R., Magallon M., and Hernández D. C. Vision-based system for 3D tower crane monitoring. *IEEE Sensors Journal*, 21(10), 11935-11945, 2020. https://doi.org/10.1109/jsen.2020.3042532

[60] Li Y., Wang S., and Li B. Improved visual hook capturing and tracking for precision hoisting of tower crane. *Advances in Mechanical Engineering*, 5, 426810, 2013. https://doi.org/10.1155/2013/426810

[61] Wang J., Zhang Q., Yang B., and Zhang B. Vision-Based Automated Recognition and 3D Localization Framework for Tower Cranes Using Far-Field Cameras. *Sensors*, 23(10), 4851, 2023. https://doi.org/10.3390/s23104851

[62] Liu P., Chi H. L., Li X., and Guo J. Effects of dataset characteristics on the performance of fatigue detection for crane operators using hybrid deep neural networks. *Automation in Construction*, 132, 103901, 2021. https://doi.org/10.1016/j.autcon.2021.103901

[63] Zhang M. and Ge S. Vision and trajectory–Based dynamic collision prewarning mechanism for tower cranes. *Construction Engineering and Management*, 148(7), 04022057, 2022. https://doi.org/10.1061/(asce)co.1943-7862.0002309

[64] Shringi A., Arashpour M., Golafshani E. M., Rajabifard A., Dwyer T., and Li H. Efficiency of VR-Based Safety Training for Construction Equipment: Hazard Recognition in Heavy Machinery Operations. *Buildings*, 12(12), 2084, 2022. https://doi.org/10.3390/buildings12122084

[65] Juang J. R., Hung W. H., and Kang S. C. SimCrane 3D+: A crane simulator with kinesthetic and stereoscopic vision. *Advanced Engineering Informatics*, 27(4), 506-518, 2013. https://doi.org/10.1016/j.aei.2013.05.002

[66] Shringi A., Arashpour M., Dwyer T., Prouzeau A., Li H. Safety in Off-Site Construction: Simulation of Crane-Lifting Operations Using VR and BIM. *Architectural Engineering*, 29(1), 04022035, 2023. https://doi.org/10.1061/(asce)ae.1943-5568.0000570

[67] Cheng T., and Teizer J. Modeling tower crane operator visibility to minimize the risk of limited situational awareness. *Journal of Computing in Civil Engineering*, 28(3), 04014004, 2014. https://doi.org/10.1061/(asce)cp.1943-5487.0000282

[68] Lee G., Cho J., Ham S., Lee T., Lee G., Yun S. H., and Yang H. J. A BIM-and sensor-based tower crane navigation system for blind lifts. *Automation in construction*, 26, 1-10, 2012. https://doi.org/10.1016/j.autcon.2012.05.002

[69] Wang Y., Li T., Dong K., Guo Z., and Fu J. The influence of the inclination of lattice columns on the safety of combined tower crane. *Advances in Civil Engineering*, 1-10, 2022. https://doi.org/10.1155/2022/5072593