Estimating Hazard Exposure in Tower Crane Lift Operations Using BIM and Path Planning Algorithm

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Abstract -

Tower cranes play an essential role in the execution of most construction projects. Unfortunately, they are also a major source of fatalities and injuries in the industry, owing to their great mass and large footprint on the site. Aiming to proactively identify and mitigate safety hazards in the design and planning stage, Prevention through Design (PtD) has been proven effective in various construction scenarios. The advent of Building Information Modeling (BIM) further strengthens the power of PtD by providing early access to comprehensive and accurate project data. This study proposes a conceptual framework aiming to automatically identify and quantitatively estimate the exposure of hazards associated with the operation of tower cranes. A literature review on crane lift safety is first carried out to identify major hazards related to tower cranes. Based on the results from path planning algorithms, a quantitative approach is presented to estimate hazard exposure during the operation of tower cranes in any given period during the construction. Thirdly, BIM entities and attributes necessary to describe tower-crane-related hazards are defined. Lastly, an application scenario is discussed to demonstrate the potentials of the proposed method. Findings in this study are expected to expand the application of PtD in more dynamic and complex construction scenarios and facilitate its integration with emerging automation and information technologies.

Keywords -

Tower crane; lift safety; hazard exposure; path planning

1 Introduction

Tower cranes are one of the most valuable and indispensable material handling equipment on construction sites [1]. Yet, it is also among the major contributors to construction accidents, very likely leading to disastrous consequences [2]. As estimated by Neitzel et al., up to one-third of the fatalities in the construction industry are associated with cranes (including both mobile cranes and tower cranes) [3]. Particularly, accidents related to tower cranes are inherently more difficult to recognize and mitigate due to busy and congested construction activities taking place within the extensive workspace of tower cranes [4].

An accident could be postulated as an abnormal exchange of energy exceeding the human body's resistance [5]. Based on the "epidemiological triangle", stopping any of the connections between energy, victim and the environment would prevent accidents [6]. In the context of crane safety, abundant research works have attempted to separate the energy output to the victims in time or space. For example, various safety management systems have been developed using cutting-edge localization and sensing technologies to monitor the movements of cranes and prevent consequential spatial conflicts with other onsite workers and objects in real-time. However, not all hazards can be detected in time and it's often very costly and sometimes impossible to mitigate such hazards on the spot. In fact, a large amount of safety hazards could be addressed through appropriate design, planning and organization of construction sites and activities in the pre-construction phase (Albert et al. 2014). This safety management philosophy is also known as the Prevention through Design (PtD) [7].

This study proposes a method to quantitatively estimate the hazard exposure in tower crane operations in the construction planning phase using path planning algorithms and BIM. Towards this goal, a conceptual framework is formulated by (1) classifying and characterizing hazards related to tower cranes via literature review; (2) integrating a novel path planning algorithm; (3) proposing a quantitative approach to estimate the hazard exposure based on algorithm-planned paths; and (4) describing necessary BIM entities and attributes to facilitate the automatic generation, storage and visualization of the hazard exposure.

2 Related work

Analyzing energy sources is a crucial method to recognize hazards on the construction site. Recent studies systematically summarized ten energy sources to identify hazards before construction works begin, including gravity, motion, mechanical, pressure, temperature, chemical, radiation, and sound [8]. Thus, this section further delineates the tower crane hazards in previous literature and categorizes them according to their energy sources. This categorization then provides a unified framework to discuss the efforts that parameterize, assess and control different categories of hazards so that the method for estimating hazard exposure can be developed.

2.1 Hazards related to tower cranes

Recognizing hazards related to cranes is a valuable yet challenging research task that has been intensively investigated for decades. Many researchers adopted an empirical method that studies accident reports statistically and establishes taxonomy to provide insights into the extent, nature, and patterns of these crane accidents. As one of the earliest empirical studies, Shepherd et al. explored the forms of damaging energy and organized 525 crane fatalities between 1985-1995 into three categories: electrical energy, gravitational energy, and machine energy (i.e., motion and mechanical energy) [9]. This energy-based taxonomy proved to be effective and invaluable to describe large quantities of fatality data; however, this study was conducted before the widespread use of modern safety-assistant technologies and fatality data only were analyzed.

More recently, Beaver et al. analyzed 125 fatalities between 1997-2003 and proposed seven proximate causes (i.e., struck by load, electrocution, crushed during assembly/disassembly, failure of boom/cable, crane tip over, struck by cab/counterweight, and falls) and specified the physical contributing factors for each proximate cause (e.g., rigging failure and unbalanced load) [10]. Meanwhile, researchers have investigated not only the fatalities but damages and near-misses, so that a wider spectrum of accident types is recognized. For example, Milazzo et al. investigated 937 mobile crane and tower crane incidents between 2011 to 2015 and categorized them into twelve types [11]. It is worth mentioning that Milazzo et al.'s work has two unique incident types, namely "man struck by boom/load and fall" and "fire explosion". The former indicates that, in the context of cranes, the "fall-from-height" hazard is related to crane motion energy, while the latter suggested the existence of chemical energy as a hazard for both mobile cranes and tower cranes. Focusing on tower cranes, Tam and Fung summarized four major types of accidents based on accident statistics between 1998 to 2005 in Hong Kong, including fall-from-height, struck with/by moving objects, struck by falling objects, and trapped by collapsed objects [12]. Raviv et al. [2] thoroughly discussed the differences between mobile cranes and tower cranes and constructed a more detailed taxonomy of tower crane accidents, which further added load drops, part of load fell, electrocution, collision between cranes, collapse of cranes, fall of crane parts, crane tip over, loss of load control, load caught in static point, falls of element affected by load on top of Tam and Fung's taxonomy.

Since every empirical study applies to a group of accident reports only, it is necessary to combine different perspectives to understand the pattern of tower crane accidents. As a result, the authors organized the tower-crane-related hazards into an energy-based classification framework (see Table 1). It is worth noting that the proposed classification is subjected to the proximate causes or physical causes at the construction site level. Thus, managerial and behavioral factors are not included, neither are numerous research efforts that establish their causation models upon ergonomics, organizational, and regulatory analysis.

2.2 Efforts to quantify hazards

Targeting at tower-crane-related hazards, researchers have made unremitting efforts to reduce their likelihood of occurrence during lifting operations. Two strategies have been widely adopted: (1) eliminating collisions of the crane and loads with static obstacles (corresponding to H1.2, H1.3, H2.3) and (2) estimating hazard exposure for dynamic victims to the dropping crane parts and loads (corresponding to H3.1, H3.2, H3.3, H3.4). The first strategy is enabled by path planning algorithms that automatically generate a collision-free path from the supply point to the demand point [13], while the other strategy quantifies hazard exposure via spatial-temporal analysis of the crane location or lifting movements. For example, multiple quantitative hazard assessment models have been proposed for site layout planning, which focused on the estimation of gravitational hazard exposure of tower cranes. El-Rayes and Khalafallah proposed a piecewise-defined function to derive the risk of falling objects hazard (i.e., H3.1 and H3.2) and crane collapse hazard (i.e., H3.3 and H3.4) based on tower crane location, operating angles, and crane dimensions [14]. This function also takes the sensitivity of other facilities into account to minimize the safety impact aroused by tower crane operations. Similarly, Abunemeh et al. analyzed the safety impact among site facilities and assumed that the likelihood of falling object hazards linearly decays with the distance to the tower crane [15]. The same linear model was adopted by Ning et al. [16] but the model neglected the hazard types and crane specifications compared with El-Rayes & Khalafallah's model. These studies evaluate the hazards for the entire construction phase, which has a low granularity in terms of temporal analysis.

A more thorough model combines spatial analysis with schedule information to predict the likelihood of hazards [17]. The time granularity is single lifting activities, based on which the method assesses load dropping hazards at the supply area, demand area and intermediate area, respectively, to reflect the characteristic of the lifting activities. By integrating hazard exposure assessment with monitoring technologies, Luo et al. created a real-time approach for hazard exposure quantification [18]. This approach considers the geometry of the hazard source (i.e., point hazard, line hazard and area hazard) and assumes that the likelihood of occurrence is proportional to the reciprocal square of the distance. More importantly, it breaks down a lifting activity as multiple coordinates along the lift path to increase the time granularity of the path information. However, both methods have limitations: Sacks et al. presented an unrealistic assumption that the loads are lifted along a straight line [17], while Luo et al. did not support proactive assessment of hazard exposure in the planning stage. Furthermore, although these methods provide insights into hazard assessment of tower crane operations, none of them comprehensively assesses all tower-crane-related hazards. More specifically, these models merely identified and quantified gravitational hazards without discussing the motion and electrical hazards. Thirdly, although hazards exist in a 3D space [19], the level of hazard exposure was mainly reflected on a 2D map in previous studies.

Table 1. An energy-based taxonomy for hazards related to tower crane

Energy sources	Hazards	References
(1) Electricity	H1.1: Direct human contact with powerlines*	[9]
	H1.2: Human contacts with powerlines through load handling	[9] [11]
	H1.3: Human contacts with powerlines through crane parts	[9][10] [11]
	H1.4: Human attempting rescue electrocuted*	[9]
(2) Motion	H2.1: Struck by moving objects	[11][12][2]
	H2.2: Caught in between	[9] [2]
	H2.3: Falls of elements hit by moving load	[12][2]
	H2.4: Collision between cranes	[2]
(3) Gravity	H3.1: Falls of suspended load without boom failure	[9][10][11][2]
	H 3.2: Crane boom buckling/failure or cable failure during operation	[10][11][2]
	H 3.3: Other parts of crane fell	[9] [12][2]
	H 3.4: Crane tip-over	[9][10][11][2]
	H 3.5: Crane collapse during assembly/disassembly *	[10]
	H 3.6: Human fall from height during maintenance *	[11]
(4) Chemical	H 4.1: Explosion or fire *	[12]

** hazards not occurring during crane operations are not addressed by the proposed method in this study.*

3 Research Method

To estimate hazard exposure in tower crane operations, the proposed method first utilizes a novel path planning algorithm (PSRRT*) that is able to find a short and collision-free path from the supply point to the demand point [20]. Paths planned by this algorithm are guaranteed to avoid collision between the crane-load system and static obstacles (i.e., H1.2, H2.3). Based on the algorithm-planned paths, a generic hazard-exposure estimation algorithm is introduced to identify and quantify five major types of operational hazards, including electrical hazards (i.e., H1.3), motion hazards (i.e., H2.1, H2.2), gravitational hazards associated with loads (i.e., H3.1), failure of boom and other crane parts (i.e., H3.2, H3.3), and crane tip-over (i.e., H3.4). Other hazards that are not directly related to crane operations (i.e., H1.1, H1.4, H3.5, H3.6 and H4.1) or involve coordination of multiple cranes (i.e., H2.4) are out of the scope in this study, since the primary objective of which is analyzing the safety impact of tower crane operations to the workers and plants on construction sites. Later, the hazard exposure estimated by the generic estimation algorithm is stored and visualized on a BIM platform.

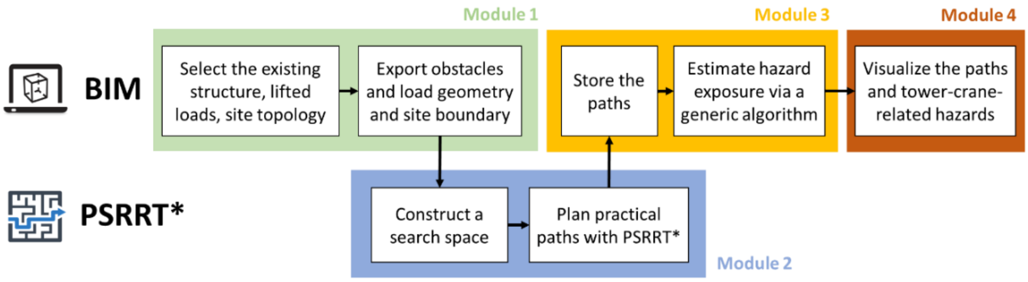

Figure 1. Research framework of the proposed method

Table 2. Equation to calculate the HE for different types of hazards

For a specific location (x_0, y_0, z_0), the hazard exposure (HE) is HE(x_0, y_0, z_0) = $\sum_{i=1}^{5}(W_i \times P_i \times E_i)$				
No.	**Hazard type**	**W_i**	**P_i**	**E_i**
1	Electrical hazards	P_m	$P_{e\text{-high}} = 1$ ($d < D_{e1}$) $P_{e\text{-medium}} = \frac{D_{e2}-d}{D_{e2}-D_{e1}}$ ($D_{e1} < d < D_{e2}$)	$E_e = E_{e0}$ where, E_{e0} is a constant energy defined by the user
2	Motion hazards	1	$P_{m\text{-high}} = 1$ ($d < D_{m1}$) $P_{m\text{-medium}} = \frac{D_{m2}-d}{D_{m2}-D_{m1}}$ ($D_{m1} < d < D_{m2}$)	$E_m = \frac{1}{2} m_l \lvert v \rvert^2$ where, m_l is the mass of the load, $\lvert v \rvert$ is the lifting speed
3	Gravitational hazards (falling load)	W_3	$P_{g\text{-high}} = 1$ ($d < D_{g1}$) $P_{g\text{-medium}} = \frac{D_{g2}-d}{D_{g2}-D_{g1}}$ ($D_{g1} < d < D_{g2}$)	$E_g = m_l \times g \times (h_l - z_0)$ where, g is gravitational field; h_l is the height of the geometry center of load to the ground;
4	Failure of boom	0.1 W_3	$P_{g\text{-boom failure}} = 1$ ($d < L_c$) Where H_c is the height of the crane;	$E_{fb} = m_b \times g \times H_c$ where, m_b is the mass of the boom or other falling parts; H_c is the height of the crane;
5	Crane tip-over	0.1 W_3	$P_{g\text{-tipover}} = 1$ ($d < H_c$)	$E_{ct} = \frac{1}{2}(m_t \times g \times H_c)$ where, m_t is the mass of the tower crane;

BIM is known as a shared resource of information about a site facility, which enables the automatic identification of hazards such as fall-from-height [19] and crane collisions [21]. In the proposed method, BIM serves as a 4D spatial-temporal analysis platform that provides up-to-date information to the path planning algorithm and stores and visualizes essential hazard information (e.g., type, location, and exposure strength). The conceptual framework of the proposed method is illustrated in Figure 1. As the first two modules has been introduced by the authors in [20], the rest of this section introduces the hazard-exposure estimation algorithm (module 3) and discusses how to store and visualize the hazard information on BIM (module 4).

3.1 Estimate hazard exposure based on algorithm-planned path (module 3)

The extend of hazard exposure (HE) describes the extent of risk at a certain location on construction sites, which is the accumulation of all hazards present at that location. The risk for each hazard equals the product of the likelihood of occurrence and the severity. The likelihood of occurrence is described by two variables: Wi describes the occurrence likelihood of different hazard types using a 0 to 1 scale, and Pi describes the function of the distance to the energy source (d) for each hazard type. Wi could be empirically derived from past accident reports and statistics. Pi has been modeled in various ways and this study adopts the linear model in [16] to describe the decay of hazards. Moreover, this paper measures the electrical, kinematic and potential energy (Ei) to describe the severity to be consistent with the energy-based hazard classification. The equations to calculate Wi, Pi, and Ei are summarized in Table 2, which are established upon several assumptions: 1) the effect of strong wind are ignored so that the potential and kinematic energy could be directly derived from the elevation, mass and the lifting speed; 2) the load is lifted at a constant speed |v|; 3) for load dropping, crane parts falling, and crane tip-over processes, the energy consumed by fractures or structure deformation is conservatively neglected; and 4) the center of mass for lifted loads coincides with the geometry center and the center of mass for the tower crane locates at the middle of the crane mast.

In the equations, Wi has been assigned as different values to represent the likelihood of occurrence within the hazardous zone. For example, 1 means the hazard

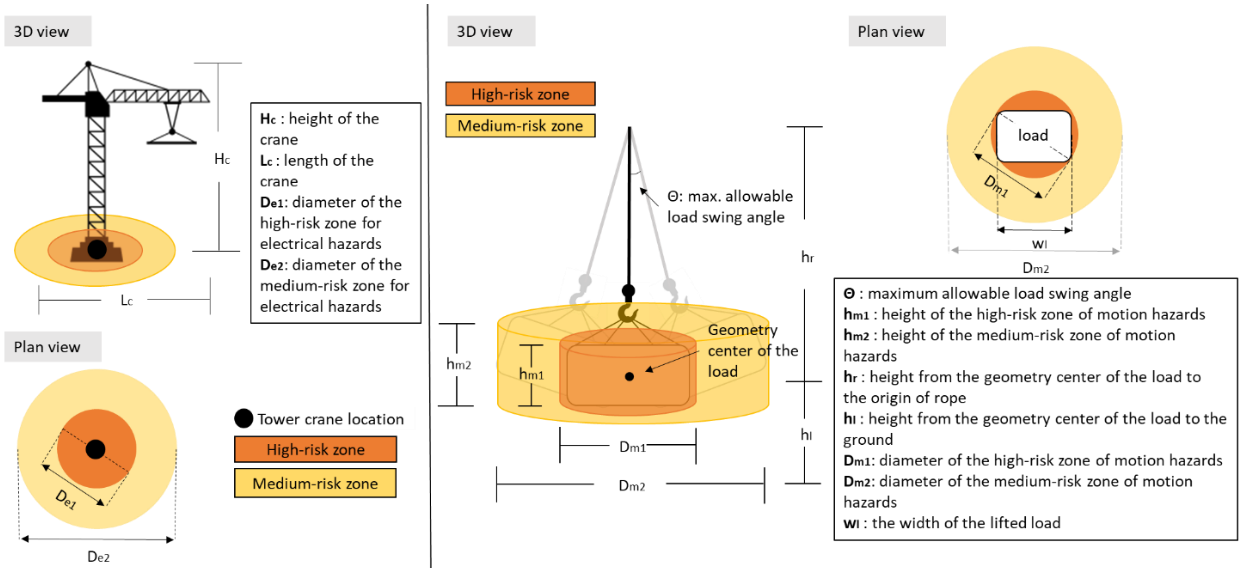

Figure 2. Hazardous zones for electrical hazards (left) and motion hazards (right)

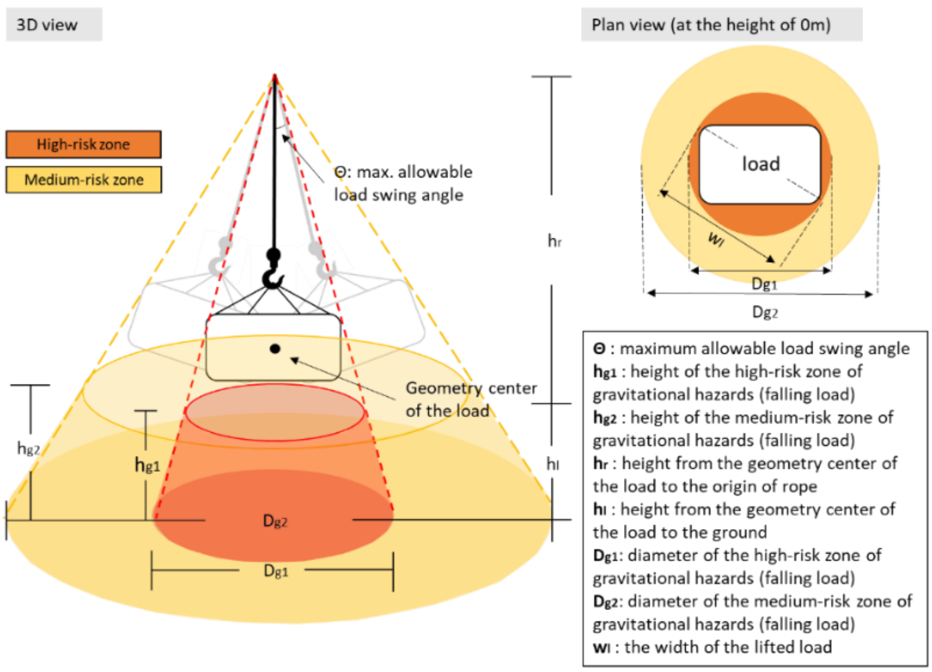

Figure 3. Hazardous zones for gravitational hazards associated to the lifted load (falling load)

certainly happens when the worker enters a hazardous zone (e.g., motion hazards), and other values indicate that corresponding hazards will not always happen (e.g., failure of the boom). Electrical hazards, in particular, happen when: (1) the load or cable contacts the powerlines and (2) workers enter close proximity to the crane mast. Thus, W1 denotes the likelihood of powerline contact, which equals Pm. Furthermore, W3 is a constant representing the likelihood of falling load, which is 10 times the likelihood of boom failure and crane tip-over [14]. Pi describes a hazardous zone as a high-risk zone, where the hazard is certainly happening, and the medium risk zone, where the hazard is likely to happen and the likelihood linearly decays due to uncontrolled load sway. The upper limits for high/medium risk hazardous zones are denoted as De1, De2, Dm1, Dm2, Dg1, Dg1 and illustrated in Figures 2 and 3, respectively. The hazardous zones for crane boom failure and crane tip-over are modeled by two columns with the radius of crane length and crane height, respectively, within which the hazard exists in a uniform pattern. The height of two columns is 3 meters, considering the height clearance of worker and plant workspaces. Although these equations are designed for a T-structure tower crane, they can be easily extended to other types (e.g., luffing cranes) by re-configuring some parameters. For example, the length of the crane boom (L) can be replaced by the lifting radius to incorporate luffing cranes.

3.2 Store and visualize hazard exposure on BIM platform (module 4)

BIM-enabled visualization has a great potential of facilitating the communication of crane-related risks [22]. Thus, the next step in the proposed method is to transform the results of the hazard exposure algorithm to a data format that can be stored and visualized in BIM. Through this transformation, the spatial relationship among of building, site layout, and hazards are specified and the distribution of hazards for one or multiple crane lifts can be graphically presented (e.g., heatmaps). Several rules are set for integrating building/site information and hazard information. Firstly, the hazard exposure for a certain location is stored in a voxel entity on the BIM platform. Such entity has 5 attributes to describe the location, size, hazard types, quantified hazard exposure (HS), and ID of the lift operation(s) that causes these hazards. Secondly, voxelization employs a midpoint algorithm to determine whether a voxel entity is within a certain hazardous zone. Thirdly, the lift path is segmented into 1-meter intervals for estimating the hazards exposure. Fourthly, the tower-crane-related hazards only influence workers on the ground, on the top surfaces of the building, and within 2-meter proximity of sidewalls of the building in progress, while electrical hazards and gravitational hazards are visualized up to 3 meters above working surfaces (i.e., the top surface of buildings or the ground). Implementation of this module presents in future works with a real-world case study.

4 Discussion

The proposed method embraces the PtD concept by leveraging the crane path planning algorithm and BIM for 4D spatial-temporal estimation of hazard exposure. The most obvious application scenario is to generate a hazard heatmap for a particular lift path to highlight areas subject to substantial lift safety risks so that they can be mitigated ahead of time. By superimposing hazard exposures for multiple lifting operations, a hazard heatmap for an extended period (e.g., one day or one week) can be generated to indicate potential needs of improving resource allocation (e.g., installing safety barriers), changing lift sequence, rescheduling works with excessive hazard exposure, or relocating site facilities. Apart from the visualization that supports communications and decision-making, the proposed method is expected to collaborate with planning and optimization algorithms (e.g., location planning algorithm and scheduling optimization algorithms) to allow a fully automated lift planning workflow.

5 Conclusion

Complex construction scenarios present enormous challenges to traditional methods for assessing tower-crane-related hazard exposure. They are typically based on 2D layout plans and make over-simplified assumptions on the lift paths. To precisely and comprehensively identify and quantify the tower-crane-related hazards, this study proposes a novel method to estimate the exposure of electrical, motion and gravitational hazards in 3D construction spaces, through the integration of path planning algorithm and BIM. This study contributes to the knowledge body by (1) comprehensively analyzing the tower-crane-related hazards through an energy-based taxonomy, (2) proposing an exposure estimation algorithm for major hazards by analyzing the algorithm-planned lift paths, and (3) specifying the BIM data format to store and visualize the hazard to enable effective and efficient hazard management. Future work will be directed to: (1) specifying the BIM data schema required to facilitate automatic path planning and hazard estimation processes, (2) implementing the hazard exposure estimation method on BIM models of complex building projects, and (3) proposing an automated workflow to manage hazards by optimizing lift sequence, scheduling, and site layout based on the quantified hazard exposure.

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