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Tower crane safety on construction sites: A complex sociotechnical system perspective

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ABSTRACT

Tower crane is the lifeline of the construction industry, but tower crane accidents are still too frequent. Despite the significant progress in tower crane safety research, system thinking-based approaches are lacking. The aim of this paper is to analyze tower crane safety from a complex sociotechnical system perspective through implementing both qualitative and quantitative analysis methods. Characteristics of five tower crane safety system components are summarized with a new framework comprised of five system-based levels based on Rasmussen's risk management theory. Fifty-six contributing factors of tower crane safety were identified. The AcciMap technique was applied to qualitatively build a generic model for tower crane safety, which comprehensively presents the systems levels and casual paths of the contributing factors. A survey was conducted to quantitatively research the tower crane safety system. Nine main dimensions and 25 critical factors were found pertaining to the tower crane safety system. These results provide a new lens for tower crane safety and contribute new systems thinking applications in tower crane safety management.

1. Introduction

As the main vertical and horizontal transportation tool in construction, the tower crane is the lifeline of the building process. However, accidents are frequent. According to MOHURD statistics, in July of 2017, 14 crane accidents occurred in China, resulting in 9 deaths and 11 injuries. For example: on July 22, 2017, a tower crane collapse accident occurred in Guangdong, Guangzhou, resulting in seven deaths and two injuries. Tower crane accidents not only threaten the safety of workers, but also cause immediate damage to machinery, equipment and buildings (Marquez et al., 2014; Swuste, 2013). Besides, tower crane construction can threaten the safety of pedestrians and facilities near the construction site due to its large size and broad coverage area even beyond the boundary of the construction site, causing a serious social impact (HSL, 2010; McDonald et al., 2011; Tam and Fung, 2011). Therefore, establishing the safety factors that can improve the tower crane safety management is essential. Much research has contributed to this area of study (Shapira and Lyachin, 2009; Shapira and Simcha, 2009a, b; Shin, 2015; Swuste, 2013). Prior research has promoted the development of targeted preventive strategies for tower crane accidents. However, these studies primarily adopted a reductionist approach to identify safety factors affecting tower crane concerning a certain phase (e.g., the operation phase, the installation and dismantling phase) (Shapira and Lyachin, 2009; Shin, 2015) or some aspects (e.g., equipment, worker and environment) (Lee et al., 2009; Li et al., 2012a,b; McDonald et al., 2011). More comprehensive factors are required to be systematically identified. Furthermore, tower crane safety issues can be regarded as a system problem. From a system lens, safety and indeed accidents are emergent properties of nonlinear interaction among different components of a complex sociotechnical system (Leveson, 2004; Mohaghegh et al., 2009). It is the interactions between the components that are of importance. Prior research identified tower crane safety factors through decomposing the system into component parts and analyzing these parts alone, the complex hierarchy and correlations among tower crane safety factors have been ignored. A sociotechnical system-based analysis is required to understand tower crane safety, so that systematic strategies can be developed to improve tower crane safety.

Tower crane safety issues can be regarded as complex sociotechnical system problems with multiple technological, environmental and societal components. The tower crane is always in high frequency usage after structural safety checks and site assembly (McDonald et al., 2011). The equipment is composed of multiple components and devices. Stakeholders involve manufacturers, the main contractor and subcontractor (Shin, 2015). From start to finish, the main staff includes designers, supervisors, crane drivers, signalers, slingers and erection/dismantling workers (Raviv et al., 2017a,b). Construction sites usually have crowd working faces, adjacent building and facilities, complex

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weather phenomena, and a dynamic operating environment for the tower crane (Aneziris et al., 2008; Shepherd et al., 2000). Tower crane on-site work phases include installation, operation, maintenance and disassembly (Li et al., 2012a,b; Shin, 2015). Moreover, a high degree of uncertainty and a complex environment add to the construction site dynamics (Li et al., 2012a,b). In summary, tower crane safety issues come from the coupling effects of various components across the system, and influencing factors of tower crane safety require system thinking and analysis.

This paper presents a process of systematic thinking and a tower crane safety analysis, which captures the complex system of factors influencing tower crane safety. From a qualitative point of view, the hierarchy and framework of the tower crane safety system are based on Rasmussen’s (1997) risk management theory, and the characteristics of tower crane safety influencing factors were analyzed by the AcciMap method. The critical factors and main dimensions of the tower crane safety system were explored through statistical data analysis from a survey.

System analysis results not only elucidate the structure and characteristics of a tower crane safety system, but also provide a system foundation for tower crane accident prevention and analysis. Furthermore, a tower crane safety evaluation and control system can be established based on these key factors and main dimensions of system safety, making the promotion of tower crane safety management a top priority.

The paper is organized as follows: A literature review of tower safety is part of an introduction to the system theory-based approach, which includes Rasmussen's (1997) risk management framework and the AcciMap method. Second, the research process design and research methods are presented. Third, the structural framework, critical factors and main dimensions of the tower crane safety system are delineated. Finally, both qualitative and quantitative analysis are used to discuss the systematic thinking and implications of tower crane safety.

2. Literature review

2.1. Tower crane safety research

Lots of research has been carried out on tower crane safety, which includes accident analysis, interviews and surveys of construction sites as well as modeling analysis (Shin, 2015).

Research on the operation phase of tower cranes safety is abundant. Beavers et al. (2006) analyzed crane accidents occurring in the USA between 1997 and 2003 and found that low safety performance of the crane drivers and slingers were the main cause of crane accidents. Sertyesilisik et al. (2010) investigated the lifting operation in Britain and found that experience and safety knowledge of the lifting team needed to be strengthened. Tam and Fung (2011) found the main factors influencing tower crane safety were negligence or misjudgment of participants, inadequate training, multi-level subcontracting systems and schedule pressure. Their questionnaire survey and structured interviews showed provision of safe systems and safety programs thorough inspection, effective communication and provision of safety training for workers. Shapira and Lyachin (2009) used structural interviews and a survey to research safety factors influencing tower crane operation and identified 21 factors grouped into four categories: project conditions (obstacles and congested site, power lines, blind lifts, overlapping cranes, sight distance and angle, cab ergonomics, length of work shift, multiple languages, operator aids and type of load); environment (winds, weather and visibility); human factor (operator proficiency, operator character, employment source, and superintendent character and signal person experience); safety management (site-level management, company-level management and maintenance management). Guidelines on safety of tower cranes (CIC, 2010), established by the Construction Industry Council of Hong Kong, recommended several measures for enhancing tower crane safety including checking site and equipment before erection of tower cranes; improving site supervision; improving qualification and experience requirements of subcontractors and workers. Accidents analysis carried out by Raviv et al. (2017a,b) presented the key causes of tower crane failures including: failure of lifting accessories, overriding of limiters, improper rigging, error of signalers, bad visibility, communication failure, inattention, strong wind, rail failure, operator fatigue, technical failure in crane, load mishap, wrong layout of crane, error of crane diver, horizontal pull of load and no signaler.

Shin (2015) conducted focus group interviews to investigate factors influencing the safety of tower crane installation and dismantling, and found several majors factors including inadequate knowledge and skills of the erection and dismantling workers, insufficient instructions on safe work procedures, deterioration of crane components; insufficient supervision on construction site, time pressures, and space constraints.

Prior research has promoted the development of targeted preventive strategies for tower crane accidents. However, these studies primarily adopted a reductionist approach to identify factors affecting tower crane safety, and system thinking was still lacking.

2.2. Rasmussen’s (1997) risk management framework and AcciMap technique

At present, system thinking is advocated to understand and enhance the safety performance of complex sociotechnical systems. From a system lens, safety and indeed accidents are regarded as emergent properties of nonlinear interaction among different components of a complex sociotechnical system (Leveson, 2004; Mohaghegh et al., 2009). Safety cannot be understood by simply breaking the system into components and examining these parts individually. From the perspective of system safety based on system theory and control theory, safety is actually a system property acquired through imposing constraints on the interaction of system components (human, technology, environment, and so on), making safety issues control problems (Leveson et al., 2003; Rasmussen, 1997; Reason, 1997). To improve tower crane safety and prevent accidents, one of the essential premises is to systematically analyze its structure and components.

2.2.1. Rasmussen’s (1997) risk management framework

Rasmussen proposed a safety risk management framework for complex sociotechnical systems, and described the sociotechnical systems as a hierarchical structure comprised of six levels, as shown in Fig. 1. From top to bottom, a system can be divided into: a government level, regulators and associations level, company level, management level, staff level and work level (Rasmussen, 1997; Svedung and Rasmussen, 2002). These levels influence each other through top-down decision flows (such as laws, regulations, and policies, etc.) and down-to-top information feedback (such as the actual state of the system, and changes in the external environment, etc.). Instead of being static, these levels are constantly affected by the external environment, such as technical, economic and policy circumstances.

Rasmussen considers accidents as the result of out-of-control of hazardous work processes. The out-of-control scenario is not just caused by certain actions or errors (such as workers' unsafe behavior), but instead a broader sociotechnical context should be used to gain more focus. Therefore, system safety is influenced by the decisions and actions of all actors across all levels of the system (Salmon and Lenné, 2015). Maintaining the safety of the system is essentially a dynamic control process involving all levels of the whole sociotechnical system, and a vertically integrated view of system behavior is required.

2.2.2. AcciMap technique

To support the use of a risk management framework for system analysis, Rasmussen developed the AcciMap approach as an appropriate methodology for modeling the sociotechnical system. The approach can be applied to describe “how the conditions, and decisions