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Degrees of connectivity: Systems model for upstream risk assessment and mitigation

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ABSTRACT

There is growing recognition that in order to further improve safety performance, attention needs to be given beyond the immediate working conditions and worker actions. A systems approach to construction safety enables considering: multiple project elements simultaneously; connections between different elements; and all system elements affected by safety risk. This paper describes recent and current research to conceptualize a typical building project in terms of connections between workers, activities, and design elements, and to verify and analyze impacts of the design and worker interactions on worker safety. Prior research provides the basis for a network tying the design elements, construction activities, and work crews on a typical building project together along with the extent of interaction between each of the system elements in terms of safety. In conjunction with this systems approach, the researchers propose a concept for viewing and managing construction safety through four different types of connections, or "degrees of connectivity," between the different workers, activities, and design elements in the system. The degrees of connectivity are defined as: interacting with the design element during its construction (DoC #1); interacting with the design element in its final form to attach another component to it (DoC #2) or by working in the vicinity of it (DoC #3); and indirectly interacting with the design element through another worker (DoC #4). To support and verify the presence of the concept in practice, the researchers conducted a survey of construction personnel. The survey results confirm that the four different degrees of connectivity are present and felt during construction operations, and indicate that attention should be given to all design elements, activities, and workers to which a worker is "connected". According to the survey respondents, DoC's #1 and #2 are recognized as the most widely present on construction sites. Eighty percent of the respondents believe that the design element has a moderate or greater impact on worker safety while it is being constructed. These initial research steps provide the starting point for continuing study that aims to develop and demonstrate the degrees of connectivity concept linking workers and design elements, with the goal of understanding how to design a project and work operations in order to improve safety during construction.

1. Introduction

The worldwide construction industry has experienced improvement in the recorded injury rates on jobsites over the past 50 years. However, further effort is needed to reduce the number of injuries and fatalities on a consistent basis. For example, fatalities in the United States have increased 8.7% in the construction industry between 2011 and 2012 (Dong et al., 2014). Also, according to Safe Work Australia, the fatality rate in the Australian construction industry increased between 2013 and 2014, and falls from height in the construction industry ranked first among other industries in 2003, 2004, 2010 and 2011 (Safe Work Australia, 2014). For comparison, the annual fatality rates in various countries in 2010 were as follows: 3.77 in Australia, 3.15 in Germany, 6.08 in France, 2.36 in Great Britain, 9.22 in Italy, 4.61 in Sweden, 8.1 in Singapore, 7.34 in Switzerland, and 9.5 in the US (Eurostat, 2013). Acquiring the knowledge of how safety issues arise on jobsites may be an effective way to differentiate between significant and insignificant factors that lead to accidents (Swuste, 2008). This knowledge ultimately provides the ability to build injury prevention solutions on a precise knowledge base. Creating better prevention methods can be achieved through the acquisition of accurate knowledge about the causes of safety issues (Mitropoulos et al., 2005).

The Occupational Safety and Health Administration (OSHA) in the U.S., like similar governmental health and safety organizations in many other countries, maintains a database of injury and fatality incidents on construction sites (OSHA, 2015). The database contains incident descriptions that provide information about the conditions and circumstances surrounding each incident. Review of the incident descriptions reveals connections between the injured workers and other workers, as well as connections between workers and the design elements they are constructing. For example, a carpenter

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building formwork is "connected" to the hazards associated with the formwork, to the formwork construction activities, and to fellow workers present on the site while the carpenter is performing his/her duties. In some cases the connections may be "direct", while in other cases there may be a series of links between the injured worker and the design element or other workers as suggest by the Chain of Events theory of accident causation (Heinrich, 1959; Hinze, 2006). The nature of the connections and the number of connections between workers, hazardous activities, and design elements can play an important role in the risk exposure of a worker. Safety management practices should recognize the extent to which injuries and fatalities are caused by the connections in order to effectively design safety controls.

Considering worker injuries and fatalities in this way leads to visualizing the construction site as a system of connected design elements, activities, and workers. Creating a model of such a system would enable comprehensive safety analyses and the identification and implementation of safety controls that target the predominant cause(s) of the injuries and fatalities. This paper presents envisioned degrees of connectivity, described below, between a worker and design elements, activities, and other workers on a construction site. The presence of each degree of connectivity in practice is explored to provide support for a construction site system model of the connectivity between workers, activities, and design elements. Based on a model of the construction system, it is anticipated that the degrees of connectivity can be used to effectively identify and target root causes of injury and fatality incidents.

2. Literature review

Many studies have been conducted to identify root causes of accidents and produce models and theories to understand and eliminate, or at least neutralize, their presence and impact. The theories and models can be grouped into several categories based on their focus. Worker behavior, work conditions, and mixed behavior and conditions are categories that most theories and models can be grouped in. Organizing them in this fashion is consistent with the traditional viewpoint that accidents arise from either unsafe conditions or unsafe acts (Hosseinian and Torghabeh, 2012). Heinrich's Two-Factor Model (1959) supports this viewpoint. Current models of accident causation, however, expand the thinking beyond the immediate worker and work conditions to include project, organizational, industry, and other influences as additional factors that affect safety performance (e.g., Gibb et al., 2001; Johnson, 2011; Li and Poon, 2013).

Numerous studies and models have been developed that focus specifically on the worker. One of the oldest studies of accident theories, which dates back to 1918, established the Accident Proneness theory (Vernon, 1918; Hinze, 2006). This theory introduces the premise that a worker is prone to being injured according to his/her personality, and is founded on behavioral theories. Adjustment-Stress is another behavioral theory presented by Kerr in 1950 (Kerr, 1950), which states that mental stress distracts a worker's mind from focusing on the task, resulting in an accident (Gibb, 2009; Hinze, 2006). The Adjustment-Stress theory was preceded by the Goals-Freedom-Alertness theory by the same researcher who believed that when a worker is provided clear goals and given enough freedom to accomplish the task at hand, he/she conducts it safely (Kerr, 1950, 1957; Gibb, 2009; Hinze, 2006). Rasmussen's worker behavior model combines the pressure to complete work with worker and project goals to explain how loss of control occurs (Rasmussen et al., 1994; Mitropoulos et al., 2005). Chain of events, described by Heinrich (1959), is a theory that several other researchers have built on which proposes that the events that lead to an accident are linked to each other; breaking one link in the chain can prevent the incident from occurring (Hinze, 2006; Hosseinian and Torghabeh, 2012). Abdelhamid and Everett (2000) present the Accident Root Causes Tracing Model (ARTCM) which attributes accident causes to human errors summarized as unsafe acts of workers.

System failures are another approach that researchers have introduced as the main reason for safety issues. Jiang et al. (2014) argue that workers' unsafe acts are considered an immediate basis for an accident. However, the researchers explain that the work system impacts workers and ultimately leads them to conduct unsafe work. This work system is set up and influenced by upper levels of management, project stakeholders, and the industry at large. Mitropoulos et al. (2005) explain how risky conditions outside the immediate working conditions can create a suitable environment for an accident to occur as well. Reason (1990) similarly suggests a model ("Swiss cheese model") that incorporates multiple layers of controls throughout work planning, design, and operation beyond the individual worker.

Other theories and models exist that consider mixed root causes, such as the Petersen theory which states that the combination of unsafe acts and unsafe conditions is the root cause of an accident (Gibb et al., 2014). Such theories and models are commonly limited in their scope and breadth. The predominant focus is on the root causes associated with the first line of workers, i.e., those who perform the work and experience the risks firsthand. Most literature and theories on the topic address the issue from a worker influence and behavior perspective. Less focus is placed on the series of impacts among workers themselves, such the impact of workers within a crew on each other and the impact of one crew on another crew, and between workers and their immediate physical environment. The design elements currently being constructed, plus those already in place, impact workers. How the workers interact with the design elements is not addressed in accident theories and prior literature with clarity. From this perspective, the present study intends to fill this gap by exploring the impacts of workers on each other and the impacts of design elements on workers. The present research contributes to current knowledge by investigating the connectivity between workers, activities, and design elements as an important consideration when planning safety measures on projects.

3. Research objectives and methods

The specific aim of the research is to present and confirm a concept based on degrees of connectivity that can be further developed to evaluate and improve construction site safety. Starting with a comprehensive physical model of a construction project (design elements, activities, and workers), the connections between each element in the model are envisioned as gateways to evaluate potential risk and root causes of incidents. The number and strength of connections provide an opportunity to perform this evaluation. The specific objectives established for the research were to: (1) develop and present the "degrees of connectivity" concept; (2) define the different degrees of connectivity that are present on construction sites and impact construction worker safety; and (3) assess the extent to which the degrees are present on typical building construction projects. In addition, the researchers aimed to determine the design elements, activities, and workers typically involved in a building project, and estimate the extent to which each is impacted in terms of safety. The research presented herein is part of an ongoing research study to explore and develop the degrees of connectivity model.

3.1. Degrees of connectivity (DoC)

The different elements in a system model are connected by links, also referred to as interactions. Each link signifies the impact