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Understanding the relationship between safety investment and safety performance of construction projects through agent-based modeling

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ABSTRACT

The construction industry in Hong Kong increased its safety investment by 300% in the past two decades; however, its accident rate has plateaued to around 50% for one decade. Against this backdrop, researchers have found inconclusive results on the causal relationship between safety investment and safety performance. Using agent-based modeling, this study takes an unconventional bottom-up approach to study safety performance on a construction site as an outcome of a complex system defined by interactions among a worksite, individual construction workers, and different safety investments. Instead of focusing on finding the absolute relationship between safety investment and safety performance, this study contributes to providing a practical framework to investigate how different safety investments interacting with different parameters such as human and environmental factors could affect safety performance. As a result, we could identify cost-effective safety investments under different construction scenarios for delivering optimal safety performance.

1. Introduction

It is a general belief that higher safety investment may result in better safety performance (Laufer, 1987; Brody et al., 1990; Tang et al., 1997). The construction industry in Hong Kong increased its safety investment by 300% in the past two decades, from about 0.5% of the contract sum in the 1990s (Lai, 1995) to 2% in recent years (Rowlinson, 2014); however, the accident rate per 1000 workers has plateaued to around 50% in one decade, which has accounted for one third of all industrial accidents (Hong Kong Special Administrative Region, Labour Department, 2014). As a result of the poor safety records, the industry incurred an estimated direct cost of HK$107 million annually (Kwong, 2015).

Against this background, both researchers and practitioners have called for conducting more rigorous analyses and empirical examination on the relationship between safety investment and safety performance (Levitt, 1975; Laufer, 1987; Brody et al., 1990). Unfortunately, research showed inconclusive results on the causal relationship (Teo and Feng, 2011). Some studies (e.g., Riel and Imbeau, 1996; Jervis and Collins, 2001; Teo and Feng, 2010) showed the positive impacts of safety investment on the enhancement of safety performance, on the one hand; on the other hand, Crites (1995) compared the safety performance of 13 sites over an 11-year period (1980–1990) and found that safety performance was independent of – or even inversely related to – safety investments. Tang et al. (1997) also discovered a weak correction between safety investment and safety performance after investigating data from 18 building sites in Hong Kong. In fact, recent studies showed that the relationship could be affected by safety culture, which composed of elements such as management commitment and employee participation (Feng, 2013; Teo and Feng, 2011). Although all these studies provided empirical evidence for the relationship between safety investments and safety performance, they typically used a "top-down approach" to model and understand the impacts of safety investment on safety performance.

In a top-down approach, researchers start from thinking up a theory on the relationship between safety investment and safety performance, and then narrow that down into specific hypotheses that they can test with the equation-based modeling (EBM) methods. To use EBM, top-down researchers need to make the following assumptions: (1) construction agents (e.g., construction workers and superintendents) are homogenous resources that have identical quality to work safely (Watkins et al., 2009); and (2) interaction of construction agents, and their work environment (e.g., construction sites and peers) have a minimal impact on safety investment and safety performance (Sawhney et al., 2003). Yet, these assump-

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tions are not realistic in practice. First, it is hard to find construction agents with equal quality. For instance, some are more risk-taking than others, and they thus are more likely to behave unsafely. Second, situations could become more complex in the real world when construction agents interact with their working environment. For example, a risk-taking worker who works in a low-hazardous worksite with a strong safety culture could have a better safety performance than a risk-averse worker who works in a high hazardous worksite with weak safety culture. As a result, using a top-down approach to study the relationship between safety investment and safety performance, as most of the existing literature has done, may oversimplify the real-world situation in which we intend to study, and thus lead us to misleading research outcomes.

To study the relationship between safety investment and safety performance more pragmatically, this paper takes a bottom-up approach by using the agent-based modeling (ABM) method. ABM is a computer simulation technique that allows us to exam how system rules and patterns emerge from the behaviors of individual agents (Epstein and Axtell, 1997). In addition, ABM is regarded as a modeling technique that matches more closely with the real world situation than traditional EBM (Wilensky and Rand, 2015). By using ABM, we can study safety performance on a construction site as an outcome of a complex system defined by interactions among a worksite, individual construction workers, and safety investments. Specifically, in our ABM model, the worksite is modeled with different levels of danger and workload; an individual construction worker is simulated as a heterogeneous person who has different safety awareness and productivity. Also, each is allowed to develop and adapt dynamically in the mode. The safety investments are: implementation of innovative technological tools, employment of safety supervisors for conducting inspections, and encouragement on being responsible for other co-workers' safety; and safety performance is measured by safety awareness, safety records, accident cost, safety cost and construction productivity.

To sum up, we recognize that the relationship between safety investment and safety performance is a complex one because other factors (e.g., safety culture) have roles to play in the relationship. Therefore, instead of focusing on studying the absolute relationship between safety investment and safety performance, as many of the previous studies have done, this paper aims to provide a practical framework by using ABM to investigate how different safety investments interact with different parameters (e.g., human and environmental factors) could affect safety performance. As a result, the framework could enable us to identify cost-effective safety investments under different construction scenarios for delivering optimal safety performance.

2. Literature review

2.1. Safety investment

Safety investment often refers to the funds that are used in injury preventive measures or activities in a workplace, which aims to protect the health and physical integrity of workers, and the financial assets of a contractor (Tang et al., 1997; Zou et al., 2010). The components of safety investment have been discussed in many previous studies, such as drug testing, safety training, safety equipment, co-workers' cooperation, and safety inspections (Jaselskis et al., 1996; Toole, 2002; Hinze and Gambatese, 2003). Specifically, in an attempt to optimize safety cost in construction, Tang et al. (1997) collected data on safety investments from 18 building projects in Hong Kong, and found that safety investments were divided into three major components: safety equipment, safety administration personnel, and safety training and promotion. Investments in safety equipment include the spending on personal protection equipment and other equipment that help the provision of safety on construction sites. Investments in safety administration personnel include the salaries of hiring safety personnel such as safety officers, safety supervisors, or safety managers, etc. Expenditures on safety training and promotion involve activities that improve employees' responsibility and engagement in safety.

Using the three major components categorized by Tang et al. (1997) as a point of departure, we chose to study three safety investments: (1) implementation of innovative technological tools—proactive construction management system; (2) employment of safety supervisor for conducting inspections; and (3) encouragement on being responsible for other co-workers' safety, because:

- they showed positive impact on safety performance in previous studies,
- they relate to human behaviors and interactions that are essential requirements for the application of ABM method, and
- they can be defined and tracked objectively in the simulation.

2.1.1. Implementation of innovative technological tools (Proactive Construction Management System)

Proactive Construction Management System (PCMS) is an innovative technological tool of safety management developed by the construction virtual prototyping laboratory (CVPL) of the Hong Kong Polytechnic University (Li et al., 2015a). It consists of two major parts: the Real-time Location System (RTLS) and the Virtual Construction Simulation System (VCS) (Fig. 1). RTLS is used to (1) manage the location network, (2) calculate the location of workers and (3) relay danger alarm signals to specific workers through the location network. VCS is a web-based application for visualizing construction processes, tracking people and equipment, and replaying construction processes. In PCMS, the locations of the observed objects (workers, equipment, and vehicles) are translated and visualized in real-time. Once the detected distances between workers and their surrounding dangers are less than a safety distance, warning signals are triggered and sent to the real-time location engine, which then relays the signal to activate the warning devices installed on workers' helmets or a crane hook. A limitation of PCMS is the limited visibility of construction work, which can only detect the location-based behavior of workers.

The function of PCMS in this study is to assist on-site workers in detecting dangers, such as the risk of being struck by a moving vehicle, providing proactive warnings to them, and ultimately reducing the occurrence of accidents and fatalities. The PCMS experiments were conducted at two construction sites in Hong Kong, with the benefits gained from including PCMS in construction safety training (Li et al., 2015a) and from proactive behavior-based safety management (Li et al., 2015b) both being substantiated.

2.1.2. Employment of safety supervisors for conducing inspections

Hinze and Raboud (1988) found that companies that employed full-time safety supervisors to conduct jobsite inspections achieved better safety performance than companies that did not. Sawacha et al. (1999) supported this position, stating that there was a moderately strong correlation between safety performance and safety representative on site. In addition, later research also suggested that appointing a trained safety officer on site for inspections is one of the critical factors for improving safety performance (Ng et al., 2005; Aksorn and Hadikusumo, 2008; Sparer and Dennerlein, 2013). In particular, safety supervisors' inspection in this study refers to the communication of front-line safety supervisors with onsite workers about imminent dangers.