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A hybrid simulation approach for integrating safety behavior into construction planning: An earthmoving case study

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ABSTRACT

One of the key challenges in improving construction safety and health is the management of safety behavior. From a system point of view, workers work unsafely due to system level issues such as poor safety culture, excessive production pressure, inadequate allocation of resources and time and lack of training. These systemic issues should be eradicated or minimized during planning. However, there is a lack of detailed planning tools to help managers assess the impact of their upstream decisions on worker safety behavior. Even though simulation had been used in construction planning, the review conducted in this study showed that construction safety management research had not been exploiting the potential of simulation techniques. Thus, a hybrid simulation framework is proposed to facilitate integration of safety management considerations into construction activity simulation. The hybrid framework consists of discrete event simulation (DES) as the core, but heterogeneous, interactive and intelligent (able to make decisions) agents replace traditional entities and resources. In addition, some of the cognitive processes and physiological aspects of agents are captured using system dynamics (SD) approach. The combination of DES, agent-based simulation (ABS) and SD allows a more “natural” representation of the complex dynamics in construction activities. The proposed hybrid framework was demonstrated using a hypothetical case study. In addition, due to the lack of application of factorial experiment approach in safety management simulation, the case study demonstrated sensitivity analysis and factorial experiment to guide future research.

1. Introduction

The Workplace Safety and Health Institute (2015) in Singapore highlighted that the construction industry contributed to 57% of all fatal injuries in the first half of 2014. This is despite a decrease in total number of fatalities in all sectors. A total of 311,623 man-days were lost during the first half of 2014 due to workplace injuries in Singapore. Similar alarming trends could be seen throughout the world, including the United States (Zhang et al., 2015), Hong Kong (Li et al., 2015), Taiwan (Cheng et al., 2010) and Kuwait (Kartam and Bouz, 1998). Hence there is heightened interest to improve construction safety for both humanitarian as well as economic reasons.

An important aspect of construction safety management is the quality and depth of safety consideration during construction planning. Computer simulation is an established method for analysis and planning of construction operations and processes (Martinez, 2010). It had been applied in a wide range of construction contexts, e.g. planning for material laydown yards (Alanjari et al., 2014), floating caisson fabrication (Pantouvakis and Panas, 2013), bored piling (Zayed and Halpin, 2001), earthmoving (Marzouk and Moselhi, 2004) and bridge construction (Said et al., 2009). The range of problems that construction simulation models were meant to resolve is very wide, and some of the typical output variables evaluated include completion time, cost, productivity, number of resources deployed, and resource utilization. However, safety behavior considerations such as number of safety violations and diffusion of safety behavior are usually not considered in construction simulation. This is despite the fact that accidents is a perennial problem in the construction industry (Zhou et al., 2014) and safety behavior of workers is an important direct cause of construction accidents (Zhang and Fang, 2013). Safety behavior is also an important indicator of safety culture, which is fundamental to safety performance of organizations (Choudhry et al., 2007). Even

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though some of the current construction simulation studies do take safety into consideration, they are typically limited to basic constraints like space limitations (Marzouk and Ali, 2013) and working hours restrictions (Alvanchi et al., 2012).

Thus, this study presents a hybrid simulation framework to integrate safety behavior considerations into construction simulation models. The proposed framework utilizes a combination of discrete event simulation (DES), agent-based simulation (ABS) and system dynamics (SD) to represent the different components of a construction activity. In general, DES is used to represent work processes, ABS is used to model individual agents (e.g. workers and machines), and SD is used to represent complex variables in agents. Such approach will facilitate a more balanced view of construction activities, where safety considerations will be considered earlier. A detailed case study is included to demonstrate the proposed framework. In view of the lack of application of simulation techniques in construction safety management research, the simulation methodology is presented in detail to guide future research in this area.

2. Simulation approaches

Even though the range of simulation techniques is very wide, there are three main approaches: SD, ABS and DES (Pidd, 2004; Carley, 2009). SD is grounded in systems of differential equations and a SD model is made up of stocks, flows, and auxiliary variables that are inter-connected (Sterman, 2000). SD is known for its emphasis on feedback between variables and the delay between cause and effect. The core of a SD model is the stocks, which vary at each time step based on the difference between the flow rates in and out of the stock. A mathematical equation or an if–then rule is embedded within each variable or flow rate in the model and the values are analyzed using numerical methods. Variables are usually continuous and aggregated, where individual entities cannot be identified. However, the SD approach can be tweaked to track individual entities within the model. The modified approach is known as agent-oriented SD (e.g. Feola et al., 2012).

In comparison to SD, ABS is focused on the design of individual agents and the adaptive decisions and actions that they perform. The ABS approach is also known as the “bottom-up” approach (Miller and Page, 2007), which contrasts with the “top-down” approach of SD (stipulating high level equations to represent different parts of a system). In ABS, agents can be heterogeneous and they have the ability to adapt and interact with each other and its environment in an autonomous fashion. Agents follow certain sets of rules and system behavior emerge from the interactions among the agents.

Unlike SD models, DES models advance time from one event to another, rather than continuously. Each event corresponds to some significant change in the model and a queue of events is maintained in the model. Even though DES can be modeled in different ways, most DES models take a process view of the world, i.e. the core of the model is a sequence of steps or a flow chart, e.g. in a production line. Entities and resources such as material, equipment and people flow in the processes of a DES. By default, entities and resources are not able to interact with each other and they do not display adaptive behaviors as in ABS. DES is the most common form of simulation in construction research (Martinez, 2010).

Hybrid simulation refers to a combination of two or more simulation approaches in a model. Even though it is possible to model most real life systems using one of the abovementioned simulation approaches, increasing level of complexity will often require significant improvisation of the selected simulation approach (Swinerd and Mcnaught, 2012). When dealing with multi-faceted systems, it may be advantageous to integrate two or more simulation approaches so as to enable simple, natural and efficient representations. For instance, many DES would be more representative of the real world if entities are agents with the ability to adapt to changes in the model. It is also advantageous to integrate ABS with established SD decision making models by having the SD models embedded into the agents.

3. Simulation and safety management

Safety management is the process of planning, implementing, checking and improving safety risk controls or interventions. Successful construction safety management hinges on detailed and early planning of construction activities. However, there is a lack of detailed planning tools to help managers assess the impact of the construction activities on safety behavior and performance. Due to its ubiquitous application in other areas of construction planning and evaluation, simulation appears to be a useful tool to facilitate safety planning of construction activities. Nevertheless, this study could not identify a comparable work that uses the full potential of simulation to identify safety interventions in construction management. As a sample of current safety management simulation studies, six papers were reviewed in detail: (1) Rudolph and Repenning (2002), (2) Cooke (2003), (3) Cooke and Rohleder (2006), (4) Salge and Milling (2006), (5) Sharpanskykh and Stroeve (2011) and (6) Feola et al. (2012). The first four papers were based on SD, the fifth is based on ABS and the last is based on agent-oriented SD. The SD models illustrated safety management theories based on major accidents. The agent-oriented SD model (Feola et al., 2012) and ABS (Sharpanskykh and Stroeve, 2011) were more practical and were focused on evaluation of safety interventions. A detailed review of the six papers can be found in (Goh and Palak, 2014). It was observed that SD was the most common approach and ABS is more suited for modeling safety behavior issues. It was noted that none of the six papers used factorial experimental design, which is an important analytical technique in simulation studies (Kelton and Barton, 2003).

4. Hybrid simulation framework

Instead of using the simulation approaches individually, this study proposes a hybrid simulation framework to integrate safety behavioral considerations into construction activity planning. There are different ways to integrate DES, ABS and SD approaches. For example, Peña-Mora et al. (2008) used a SD–DES hybrid approach to model both operational and strategic levels in earthmoving activities. In their study, SD is used to model the strategic level, while DES is used to model the operational level. On the other hand, Swinerd and Mcnaught (2012) conducted a detailed review of ABS–SD models. Alvanchi et al. (2011) used a combination of SD and DES in modeling effect of working hours on construction activity. Some possible hybrid simulation frameworks adapted from Borshchev (2013) are summarized in Table 1.

In this study, a DES–ABS–SD approach was selected. The proposed conceptual model framework is presented in Fig. 1. As highlighted earlier, even though it is always possible to stretch any of the simulation approach to cover all the desired features, the hybrid approach has the advantage of allowing complex problems to be represented more “naturally”, leading to improved efficiency and better communication with stakeholders of the simulation project.

The framework consists of four quadrants, each highlighting a critical component of the framework. Since the proposed simulation is focused on operational concerns, it is useful to use DES as the core of the model. DES is widely accepted in the construction simulation literature as the default approach for modeling construction