Understanding the Causation of Construction Workers’ Unsafe Behaviors Based on System Dynamics Modeling

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Abstract: The unsafe behaviors of construction workers are often the immediate causes of construction accidents, but the underlying causation of such behaviors are not well understood. This research regards the management of construction safety as a system, and seeks to use system dynamics to demonstrate how the system influences construction workers in terms of unsafe behaviors. First, individual and environmental conditions that can lead to an unsafe behavior are identified through a holistic cognitive analysis and management conditions that affect such conditions are identified. Second, a system dynamics model for the causation of unsafe behaviors (SD-CUB) is developed to characterize the causal structure of the system. The SD-CUB model involves relationships among management, individuals, and environmental conditions that can eventually lead to workers’ unsafe behaviors. Third, a variety of model tests are conducted to build the confidence of the SD-CUB model. A five-week survey and observation on a building construction project is conducted to demonstrate that the SD-CUB model generates correct patterns of behavior. The model tests also imply that safety and production can actually support each other, management conditions on supervisory level are effective on the improvement of workers’ safety awareness, and preventive actions are more effective than reactive actions on the enhancement of safety performance. The SD-CUB model can also be used as a basis for simulation of various site scenarios to explore the best solution to prevent and correct unsafe behaviors, and by redesigning the causal structure, the leverage points and critical management strategies can be determined. DOI: 10.1061/(ASCE)ME.1943-5479.0000350, © 2014 American Society of Civil Engineers.

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Introduction

The construction industry has long been criticized for its poor safety performance. In the United States, 775 fatal injuries were reported from the construction industry in 2012, a number substantially higher than other industries (U.S. Bureau of Labor Statistics 2012). Although the construction industry in Britain accounts for 5% of the employees, it still accounts for 27% of fatal injuries to employees and 10% of reported major injuries (U.K. Health and Safety Executive 2012). In China, the reported number of fatal injuries on construction sites reached 2,437 in 2012, which exceeded that of the mining industry and became the most dangerous industry (China State Administration of Work Safety 2012). In China, the reported number of fatal injuries on construction sites reached 2,437 in 2012, which exceeded that of the mining industry and became the most dangerous industry (China State Administration of Work Safety 2012). During recent years, construction safety management has increasingly attracted the attention of various governments and organizations, but still no obvious improvement has been observed.

From the perspective of accident investigation, construction workers’ unsafe behaviors are often the immediate causes of accidents on construction sites (Reason 1990). Haslam et al.’s (2005) case study found that 70% of the accidents were caused by workers or work teams; Suraji et al. (2001) identified that 88% of the accidents in construction projects involved unsafe behaviors. From the results of behavior observation onsite, unsafe behaviors are pervasive. Sa et al. (2009) investigated workers’ behaviors toward the use of fall protection equipment, and found that one-third of workers actually did not behave safely; Lipscomb et al.’s (2008) research showed that the use of fall prevention equipment was rare on residential construction sites; and through the observation of workers’ behaviors on two construction sites in Singapore, Fang and Wu (2013) found that one-third of workers’ operation behaviors were unsafe.

Study on Unsafe Behaviors

Behavior-based safety management focuses on preventing and modifying workers’ unsafe behaviors through interventions like goal setting and feedback. A great number of research and practices have supported the effectiveness of such interventions (Choudhry 2014; Cooper 2009; Fang and Wu 2013; Laitinen and Ruohomäki 1996). However, the research on behavior-based safety management is “victim blaming,” which emphasizes the responsibility of the individual worker and always indicates that the worker should be able to act safely under all circumstances (DeJoy 2005), while ignoring the management conditions behind the scene (Pidgeon and O’Leary 2000). Virtually, all work injuries involve person-environment interactions. If only the person side is emphasized, the effectiveness of interventions will be critically affected (DeJoy 2005). Cameron and Duff (2007) and DePasquale and Geller (2000) showed that the effectiveness of interventions was significantly affected by management commitment and other management conditions. Cameron and Duff (2007) stressed that intervention methods were unlikely to be effective if the organization lacked appropriate materials and facilities, or if the worker lacked...
the basic skill to perform a task safely. Lindard and Rowlinson’s (1997) research also indicated that the lack of adequate safety infrastructure was a major reason when the behavioral safety approach did not work well. Therefore, it is crucial to shift the focus to the systematic causes of behaviors, to study how the system affects construction workers’ behaviors (Chi and Han 2013).

Meanwhile, the research on safety management and safety culture attempts to build a bridge between management conditions and individual behaviors through empirical analysis. Lu and Yang (2010) and Mearns and Reader (2008) collected survey data from workers and found that factors such as safety policy and safety concern could positively affect workers’ behaviors. By analyzing the data of union health insurance, training records, and workers’ compensation, Dong et al. (2004) provided evidence for safety training to prevent injuries among construction workers. After interviewing 19 senior equipment and safety experts, Shapira and Simcha (2009) indicated that behaviors of the crane operator and general superintendent onsite were crucial. However, the mechanism for how such management conditions affect individual behaviors still remains unclear (Fang et al. 2006). Research dependent on statistics and empirical analysis has sometimes also failed to find the significant relevance of factors (Glendon and Litherland 2001; Tomas et al. 1999). In addition, the current safety culture models merely list some broad issues that may affect workers’ behavior without thoroughly analyzing the underlying cause-effect relationships (Biggs et al. 2013; Guldenmund 2000; Han et al. 2014; Zou and Sunindijo 2013). And when the effect is not supported by statistics, researchers find it difficult to explain why the factors are not relevant (Zhou and Fang 2009). Therefore, it is crucial to depict the cause-effect relationships in a dynamic system—in other words, to characterize the paths through which major management conditions can exert influence on workers’ behaviors, so as to facilitate the development of strategies for learning, job redesign, and training that will in turn improve workers’ behaviors (Biggs et al. 2013; Choudhry et al. 2007; Hoffmeister et al. 2014; Reiman and Rollenhagen 2014).

System Dynamics

System dynamics, contrasting with other sequential models, highlights the feedback and complex interactions between variables, where causes and effects are often indiscernible. The foundation of system dynamics is reflected in three basic processes: reinforcing feedbacks, balancing feedbacks, and delays, the details of which can be found in Sterman’s (2000) work. By modeling the activity of the industrial system, Bouloiz et al. (2013) applied system dynamics to assess the safety of a storage unit for chemical products. Cooke and Rohleder (2006) built a safety and incident learning system and showed that future incidents could be prevented by learning from the past. Ng et al. (2007) developed a simulator for management conflicts in projects. Lé and Law (2009) used a system dynamics model to simulate experience-transfer scenarios in the architectural/engineering/construction (AEC) industry. Goh et al.’s (2012a) study demonstrated that risk perception could deteriorate when management had a strong production focus. And by using a group model building approach, Goh et al. (2012b) attempted to understand the reasons why even if the organization had invested a mass of resources into safety, the injury rate could not be decreased. Han et al. (2014) developed a system dynamic model to understand the impact of production pressure on safety performance. Minami and Madnick (2009) looked beyond human error in combat vehicle accidents and, instead, studied the organizational problems that were regarded as the real causes. Salge and Milling (2006) found that the Chernobyl power plant accident was caused by the combination of design failures and on-line operations. The studies in the literature have already shown the capability and fitness of system dynamics to the improvement of understanding the complex safety system.

Objective of the Paper

Traditional research methods in accident investigations follow a linear process of root-cause analysis, and ignore the effect of inter-actions between various factors of a system (Cooke 2003; Goh et al. 2010; Qureshi 2007). While describing safety issues in a sequential fashion, workers are usually at the “sharp end” of a system being incorrectly blamed (Underwood and Waterson 2014). So there is a need for a systematic and effective solution to enhance construction safety (Guo et al. 2013). Recently, Shin et al. (2014) developed a system dynamics model of construction workers’ mental processes to understand the feedback mechanisms of workers’ safety attitudes and safe behaviors. However, the model still did not get the whole picture of the underlying factors which are the cause of such safety attitudes and safe behaviors of workers.

Therefore, on the basis of the previous work, this paper regards the management of construction safety as a system, and seeks to build a system dynamics model for the causation of unsafe behaviors (SD-CUB) based on a holistic cognitive analysis of why unsafe behaviors happen. Based on the SD-CUB model, how the system influences construction workers can be understood. Through model building and testing, the implications for construction safety management can be derived. The SD-CUB model can also be used as a basis for simulation of various site scenarios to explore the best solution to prevent and correct unsafe behaviors.

Factors Identification

Cognitive Analysis

The information processing models are widely used to analyze human errors and unsafe behaviors (Furnham 1994; Kontogiannis 1997; Sharrock and Kirwan 2002; Kines 2003; Chang and Mosleh 2007). This paper regards a worker’s unsafe behavior as the result of a cognitive failure, and based on the widely recognized model proposed by Surry (1969), a holistic cognitive analysis approach is developed by the authors to identify the critical factors that could result in a worker’s cognitive failure (Zhang 2012). The analysis covers five cognitive stages:

1. Detecting hazards,
2. Recognizing hazards,
3. Perceiving responses,
4. Selecting a safe response, and
5. Executing the safe response.

Before a worker conducts a safe behavior, he or she sequentially experiences (1) detecting a surrounding hazard; (2) realizing the possibility of injury due to the hazard, or realizing that the potential behavior is hazardous; (3) retrieving a memory or looking at others to perceive safe responses; (4) selecting the safe response; and (5) correctly executing the safe response. Cognitive failure in any of the above stages could result in an unsafe behavior (Zhang and Fang 2013).

In Stage 1, the ways of searching for hazards are further distinguished into intentional searching and nonintentional searching according to Chang and Mosleh’s (2007) information decision and action in crew (IDAC) model. “Nonintentional searching” means when a worker does not intend to search for hazards, a hazard can still be detected if it could attract the worker’s attention. Therefore, there are three possible scenarios when a cognitive failure happens in Stage 1:
1. Not searching for hazards intentionally because of time saving, overconfidence, etc.; 
2. Not detecting hazards when searching intentionally because of hazards being blocked, hazards exceeding physical capabilities, not expecting hazards, underestimate the risk, etc.; or 
3. Not detecting hazards when searching nonintentionally because of hazards being blocked, hazards exceeding physical capabilities, work overtime, lack of sleep, fatigue, biological clock disruption, low vigilance, etc.

In Stage 2, a cognitive failure can happen because of deficiency of relevant knowledge, low frequency of using the knowledge, etc.

In Stage 3, a cognitive failure can happen because of deficiency of relevant knowledge, low frequency of using the knowledge, negative impacts from management, negative impacts from coworkers, etc.

In Stage 4, a cognitive failure can happen because of not recognizing the importance of the safe response, not convenient, not comfortable, negative impacts from significant others, perceived internal control, perceived external control, etc.

In Stage 5, a failure can happen because of fatigue, deficiency of relevant knowledge, no supportive external conditions, etc.

**Individual and Environmental Conditions**

The factors identified that can lead to an unsafe behavior through the cognitive analysis above can be further categorized into individual and environmental conditions.

**Individual Conditions**

- **Safety awareness:** This can be interpreted as a psychological state of mind vigilant to the potential hazards on construction sites which may hurt oneself or others. With a low level of safety awareness, a worker may not expect hazards existing nearby; thus he or she may not search for hazards intentionally, or not be able to detect hazards when searching unintentionally (Chang and Mosleh 2007), which may be associated with a failure of detecting hazards in Stage 1.

- **Safety knowledge:** This represents the personal experience on safety issues and the ability of understanding, mastering, and applying safety-related regulations, protection skills, etc. A company with a higher worker turnover is more likely to encounter accidents (Hinze 1978). With a low level of safety knowledge, an inexperienced worker may not have the ability to detect a surrounding hazard, may not recognize the risk, may not know the way to get rid of the hazard, or may lack the right skill to execute the correct response, which may be associated with failures of detecting hazards, recognizing hazards, perceiving responses, and executing the safe response in Stages 1, 2, 3, or 5.

In Stage 4, if a worker has perceived the safe response but does not select it, this kind of unsafe behavior is classified as “violation,” and the theory of planned behavior (TPB) is proper to be used to explore the causes (Reason 1990; Zhang and Fang 2013). In TPB, attitude, subjective norm, and perceived behavioral control are the three main constructs that affect behavior (Ajzen 1991).

- **Attitude:** This refers to “the degree to which a person has a favorable or unfavorable evaluation or appraisal of the behavior in question” (Ajzen 1991), and is mostly based on the degree to which this behavior meets the person’s motivations (Zhang and Fang 2013). There are basically three motivations for construction workers—motivation for safety (Edelson et al. 2009), motivation for convenience (Lipscomb et al. 2008), and motivation for comfort (Bohm and Harris 2010).

- **Subjective norm:** This refers to “Perceptions of significant others’ expectations to the behavior” (Zhang and Fang 2013). The “significant others” of workers include the management and coworkers. Subjective norm also affects the process of safety response perceiving in Stage 3.

- **Perceived behavioral control:** In other words, “Perceptions of the ease or difficulty of performing the behavior and it is assumed to reflect past experience as well as anticipated impediments and obstacles” (Ajzen 1991). A worker’s perceived behavioral control contains the perceived internal control and the perceived external control. The perceived internal control is affected by the worker’s experience, knowledge, and physical conditions, and the perceived external control is the perceived availability of resources and facilities for the execution of the behavior (Zhang and Fang 2013). “External control” in Stage 5 is the actual availability of external factors, which this paper assumes to be reflected in workers’ perceived availability.

- **Worker’s physical condition:** This represents the physical state of a worker. A worker in a weak physical condition may be not as vigilant as a worker in a good condition (Chang and Mosleh 2007), which can lead to a failure of detecting hazards in Stage 1. Meanwhile, a worker in a weak condition (e.g., fatigue) may not be able to execute a safe response, which can lead to a failure of executing the safe response in Stage 5.

**Environmental Conditions**

- **Hazardous exposure:** The conditions of site arrangement that may let workers be exposed to certain hazards. A worker in high hazardous exposure may be blocked from detecting hazards, or many hazards may exceed the worker’s physical capability to be detected (Kines 2003), which can lead to a failure of detecting hazards in Stage 1.

The comprehensiveness of the identified factors has been demonstrated by a case study on a metro project (Zhang and Fang 2012). By 3 weeks’ observation onsite, nine types of unsafe behaviors were determined, and six construction workers were interviewed to understand their psychological activities while they were performing unsafe behaviors. The result shows that the identified factors can explain all the major psychological activities of the construction workers investigated.

**Management Conditions**

Virtually, management conditions exert influence on workers’ behaviors by affecting the individual conditions and environmental conditions (Wachtler and Yorio 2014). Eight factors are summarized as the components of management conditions by learning from literature on topics of accident causation analysis, safety management, safety culture, etc. (Ashcroft and Parker 2009; Brown and Holmes 1986; Cooper and Phillips 2004; Fang et al. 2006; Glendon and Litherland 2001; Lin et al. 2008; Neal et al. 2000; Pousette et al. 2008; Varnen and Mattila 2000; Zohar 1980).

**Self-example** refers to management’s commitment to safety and management’s own behaviors, which are usually regarded as role models for workers (Hinze 2006). Idealized management behaviors are most important for workers’ safety participation (Hoffmeister et al. 2014). Through their own personal commitment, management members can convey safety as a core value, thereby facilitating workers’ belief in safety (Barling et al. 2002). If management does not abide by safety rules, workers will be negatively affected by taking management as an example and behaving in the same way. A worker is less likely to consider safety as important if there is a perception that management does not care about safety (Fogarty and Shaw 2010).

**Safety communication** refers to the extent, frequency, and effectiveness of the information exchange on safety issues between
workers and management (Probst 2004). If workers are spoken to when changes in work practices are suggested, their safety awareness would be improved (Glendon and Litherland 2001; Wachter and Yorio 2014). Kaskutas et al.’s (2013) research shows that through safety communication with foremen, unsafe behaviors of inexperienced workers are significantly reduced. Thus, safety communication is significantly associated with safety knowledge (Cigalarov et al. 2010; Neal et al. 2000; Probst 2004).

Safety inspection refers to the frequency and thoroughness of management inspection on workers’ unsafe behaviors and onsite hazards (Tam et al. 2004). The review of the safety considerations of routine and nonroutine tasks is a reminder of safety, which can enhance workers’ cognitive concentration and the situational awareness (Wachter and Yorio 2014). If the inspection is frequent enough to make workers feel pressure on unsafe behaviors, the motivation for convenience and comfort will decline, and in turn the motivation for safety will rise, so as to affect workers’ attitude (Neal et al. 2000).

Behavior feedback refers to the feedback from management toward workers’ behaviors such as economic awards or penalties, oral praise or criticism. Management who realizes the importance of learning from even the minor incidents will support and encourage workers to report incidents by means of rewarding instead of punishment, which in turn enhances workers’ safety awareness (Jones et al. 1999). If workers get awards from management because of safe behaviors and get penalties because of unsafe behaviors, the motivation for safety will be raised, and the motivation for comfort will be restrained (Cope et al. 1986). However, evidence shows that workers’ safety knowledge still cannot be improved simply by positive behavior feedback from management (Cameron and Duff 2007).

Safety training refers to the frequency, pertinence, and thoroughness of training provided to workers. The important role of safety training on the improvement of construction projects’ safety performance has been observed and emphasized by many researchers (Lingard 2002; Williams et al. 2010). Routinized safety training aims at improving workers’ safety awareness and safety knowledge (Burke et al. 2011; Hinze 2006; Wachter and Yorio 2014). Workers’ motivation for safety can also be enhanced by the emphasis on safety during training (Han et al. 2014; Lingard 2002).

Safety resources refers to the amount and qualification of personnel designated to deal with safety issues, as well as the availability and accessibility of safety equipment, materials, and facilities onsite (Cheng and Teizer 2013). The adequacy of safety equipment, materials, and facilities can directly affect workers’ perceived behavioral control (Cameron and Duff 2007), and the comfort of safety equipment, materials, and facilities can affect workers’ attitude by improving workers’ motivation for comfort (Bohm and Harris 2010). Besides, the safety competency determined by the adequacy of personnel, equipment, materials, and facilities is the basis for the thoroughness and effectiveness of other management conditions.

Incident learning refers to management’s willingness for incident investigation and learning. A strong willingness to investigate incidents can lead to a systematic learning from past wrongdoing, and through appropriate dissemination such as posting and other means among workers as regular warnings, workers’ safety awareness can be improved (Garrett and Teizer 2009; Hinze 2006; Saurin et al. 2008). Review from past experience can also generate lessons and boost workers’ motivation for safety, so workers’ safety knowledge and attitude are affected (Wachter and Yorio 2014).

Emphasis on production represents the efforts of management on production. When production pressure is perceived by workers, they perceive increasing risk and barriers, which will lead to a higher possibility that they favor unsafe behaviors (Han et al. 2014). This factor enables the discussion of the trade-off between management conditions on safety (i.e., the first seven management conditions) and management conditions on production (i.e., the last management condition) due to limited management time, which will be further unfolded in the next section.

SD-CUB Model

The SD-CUB model is shown in Fig. 1. The main factors in the model are presented in the dashed boxes such as “management conditions,” “individual conditions,” “environmental conditions,” and “effect on safety.” Here, “effect on safety” categorizes the endogenous consequences of the feedback structure (Sterman 2000).

A preliminary model is first developed through the following logic:
1. First, under the assumption that unsafe behavior is the result of a cognitive failure, a link is built from probability of cognitive failure to unsafe behaviors.
2. Second, as identified by the cognitive analysis in the above section, individual and environmental conditions are the direct causes of cognitive failure. Thus, the links from individual and environmental conditions to probability of cognitive failure are built.
3. Third, because management conditions identified in the above section are regarded as the underlying causes of cognitive failure, and they affect workers’ cognition process through affecting the relevant individual and environmental conditions, the links from management conditions to individual and environmental conditions are built.
4. Fourth, feedback from unsafe behaviors to management conditions through incidents is built. When more incidents happen, management will react with positive feedback through the emphasis on safety (Cooke 2003; Han et al. 2014). Here “incident,” which is a broader definition that includes any abnormal event which could possibly lead to an accident, is intentionally used. The data of incidents could serve as a foundation for management actions and learning (Cooke and Rohleder 2006).

After the preliminary model is built, semistructured interviews are conducted to ensure the model’s appropriateness in depicting the structure of the real system. The questionnaire for suggestion gathering is designed as a set of predefined questions, but is free to depart from the script to pursue particular interests. The primary loops are introduced at first, then each relationship is described, and additional experts’ comments on the model’s structure are encouraged. The questionnaire is available to readers upon request. With reference to Hallowell and Gambatese (2009), the experts are chosen upon certain prequalification, and three distinguished experts have responded. They are all prominent scholars with experience in the industry. The results show that the experts generally agree to the structure of the model. And the preliminary model has been properly adjusted according to the experts’ suggestions.

The basic balancing and reinforcing loops are:
1. Loop B1 (Effect of Management on Workers: “Management conditions – Individual conditions – Probability of cognitive failure – Unsafe behaviors – Incidents – Management conditions”) shows that management conditions exert influence on workers’ behaviors through individual conditions.
2. Loop B2 (Hazard Mitigation): “Management conditions → Hazard mitigation measures → Hazardous exposure → Probability of cognitive failure → Unsafe behaviors → Incidents → Management conditions”) shows hazardous exposure that can lead to unsafe behaviors is affected by management conditions through hazard mitigation measures.

3. Loops B3 (Limited Mgmt Time: “Management conditions on safety ↔ Emphasis on production”) and B4 (Production Control: “Emphasis on production ↔ Production pressure”) show how management conditions on safety trade off with management emphasis on production, which in turn affects workers’ workloads by the variation of production pressure.

4. Loop R1 (Catch Up Due to Lost Time: “Emphasis on production → → Unsafe behaviors → Incidents → Production pressure → Emphasis on production”) shows a vicious cycle that when production pressure is high, the emphasis on production will reduce the management efforts on safety, which will further increase the loss of production time because more incidents occur.

5. Loop R2 (Work Pressure: “Individual conditions → Probability of cognitive failure → Unsafe behaviors → Incidents → Production pressure → Work overload → Individual conditions”) and Loop R3 (Fatigue Accumulation: “Production pressure → Work overload → Worker’s physical condition → Probability of cognitive failure → Unsafe behaviors → Incidents → Production pressure”) show the effect of working overload on workers’ individual conditions.

6. Loop R4 (Effect of Coworkers: “Individual conditions → Probability of cognitive failure → Unsafe behaviors → Individual conditions”) indicates the effect of coworkers’ unsafe behaviors on workers’ subjective norm, which is regarded as a critical component of individual conditions.

In the following subsections, the subsystem of “effect of management on workers” (Loop B1), “hazard mitigation” (Loop B2), and “production versus safety” (Loops B3, B4, R1, R2, R3, and R4) are unfolded in details.

**Effect of Management on Workers**

This subsystem (Loop B1) describes the cause-effect relationships between management conditions on safety and workers’ individual conditions. Fig. 2 presents the model’s assumptions of such cause-effect relationships based on the identification of management, individual, and environmental conditions in the above section through literature review.

**Hazard Mitigation**

This subsystem (Loop B2) stands for management efforts to mitigate workers’ hazardous exposure. It can be further unfolded according to hazard mitigation measures. Essentially, management takes corrective actions to hazards through the process of incident learning and safety inspection (Cook 2003; Cooke and Rohlleder 2006; Garrett and Teizer 2009; Goh et al. 2012b; Hinze et al. 2013;
Leveson et al. 2005; Wang et al. 2004). According to surveys onsite, it is common practice that management also takes action when hazards are reported by workers.

**Hazard Mitigation through Incident Learning**

Management should use incidents arising from the internal system to gather information and develop strategies, so as to prevent future incidents by correcting the analogous hazards (Cooke and Rohleder 2006; Hinze et al. 2013). Fig. 3 shows how management seeks to reduce workers’ hazardous exposure on construction sites through learning from incidents.

Loop B2.1 (*Safety Pressure*) shows the main logic: with the accumulation of hazards onsite, the number of incidents ascends, hence management senses the incidents’ control pressure, and pays more attention to incident learning, which along with Loop B2.2 (*Investigation Correction*) corrects hazards and reduces incidents.

Loop R2.1 (*Incident Learning*) is a reinforcing loop, where confidence is gained through the success of incident investigation (Lee and Harrison 2000). Because the effectiveness of incident investigation is also dependent on the number of incidents that has been reported, Loop R2.2 (*Incident Reporting*) shows the process of workers’ incident reporting. Reported incidents are dependent on workers’ commitment to safety (Cooke and Rohleder 2006), which is reflected in individual conditions such as safety awareness, safety knowledge, attitude, and subjective norm (Kingston et al. 2004; Evans et al. 2006). Also by the dissemination of lessons that have been learned through incidents, workers’ commitment to safety can be further enhanced.

**Hazard Mitigation through Safety Inspection and Hazard Reporting**

Fig. 4 shows how management seeks to mitigate workers’ hazardous exposure through safety inspection and correction. Loop B2.3 (*Safety Pressure*) shows that when management senses the pressure from incidents increasing, more attention is paid to safety inspection, and through Loop B2.4 (*Hazard Mitigation by Inspection*) the inspection corrects hazards to reduce incidents. Loop R2.3 (*Hazard Inspection*) is a reinforcing loop, where confidence is gained through hazard inspection, and will further enhance management efforts to safety inspection and correction.

Loop B2.5 (*Hazard Reporting*) in Fig. 5 shows how management seeks to correct hazards reported by workers. The path from
Workers’ hazardous exposure to incidents’ control pressure has been discussed above, hence in Figs. 4 and 5, it is simplified with a dotted line.

As reflected, safety competency, which depends on the investment in safety training and safety resources, is a determinant factor on the effectiveness of corrective actions as well as the ability to identify hazards in the process of hazard inspection.

**Production versus Safety**

This subsystem (Fig. 6) characterizes the trade-off between management conditions on safety and management emphasis on production because of limited management time (Goh et al. 2012b).

As Goh indicates, management time and efforts on safety and production are scarce resources and any increase on one side may result in the focus on the other side falling, which is reflected in Loops B3.1 and B3.2 (*Limited Mgmt Time*).

Loop B4 (*Production Control*) shows that actual production is dependent on management emphasis on production, and if more effort is put into production, the production gap between actual production and the production target set by management or client will decline, so as to relieve the production pressure.

Actual production is smooth when there are few incidents distracting management and workers’ attention. Loop R1 (*Catch Up Due to Lost Time*) shows that the occurrence of incidents may be associated with a loss of production time, which will affect the actual production, and then production pressure will be raised. However, as management puts more emphasis on production and relatively less emphasis on safety in order to catch up with the production schedule while letting incidents keep increasing, it will further jeopardize the process of production. Cooke (2003) has given a real example of how this cycle turns to be lethal.

Loop R2 (*Work Pressure*) shows the effect of working overload caused by production pressure on workers’ individual conditions. Workers who perceive a higher work pressure are more likely to hold negative perceptions of the safety climate and a low level of safety awareness (Clarke 2006; Salge and Milling 2006; Rudolph and Repenning 2002). Heavy workloads may also force workers to deviate from safety rules (Cooper and Clarke 2003); thus individual conditions such as attitude, subjective norm, and perceived behavioral control are likely to be affected.

Loop R3 (*Fatigue Accumulation*) shows that working overload is the reason for work fatigue (e.g., lack of sleep, biological clock disruption), which may deteriorate a worker’s physical condition (Spencer et al. 2006).

Because heavy workloads may affect workers both psychologically and physically, it is an important message that should be communicated by top management and the site management team including site engineers and supervisors (Choudhry and Fang 2008).

Loop R4 (*Effect of Coworkers*) indicates the effect of coworkers’ unsafe behaviors on workers’ subjective norm.

**Model Tests**

Upon Forrester and Senge’s (1980) suggestion, system dynamics models should be tested as much as possible, so as to assess and testify the realism of model assumptions and behaviors, and to generate insights into the causes of observed phenomena.

Assume that the maximum value of each variable is 1, the minimum value of each variable is 0. The relationship between each pair of cause and effect is linear, and there are basically two types of parameters (constants) in the model: “delay” and “time to change.” The “delay” parameters refer to the delayed effect one factor has on another, [e.g., there is a time lag between hazard identification and the enforcement of hazard mitigation measures (Manuele 2009)]; and the “time to change” parameters refer to the normal time needed for one “stock” factor’s adjustment, [e.g., because of management emphasis on safety training, workers’ safety awareness can be increased gradually (Bahn and Barratt-Pugh 2012)].

Before the implementations of specific model tests, to make sure that the SD-CUB model is structurally verified, a variety of extreme conditions tests are conducted. By examining the correspondence between the model-generated behavior and the theoretical reality under extreme conditions (i.e., imaginary maximum and minimum values of each variable), the tests are crucial for flaw discovery (Forrester and Senge 1980; Saysel and Barlas 2006). The extreme conditions tests show that the model behaves as expected.

**Behavior Prediction Test**

Supervisors are direct monitors to worker behaviors (Ismail et al. 2012). Simard and Marchand (1994) found that participative supervisors were more effective in the improvement of safety performance. In the behavior prediction test, management conditions such as self-example, safety communication, safety inspection, and behavior feedback are regarded as management conditions on the supervisory level. In order to test the effect on workers’ behaviors, the test focuses on the “future” behavior when management conditions on the supervisory level are enhanced. Fig. 7 shows that, from week 2, as the emphasis is placed on such management conditions, unsafe behaviors are reduced. If the percentage of unsafe behaviors is standardized to 100% before test begins, the

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percentage declines to 66% after the enhancement of management conditions on the supervisory level.

To further explore the mechanism underlying why the percentage of unsafe behaviors are reduced, Fig. 8 examines the individual conditions such as workers’ safety awareness and safety knowledge. In the model test, workers’ safety awareness is significantly improved from 100 to 152%, which implies that such management conditions exert influence on safety performance through workers. Fig. 8 also shows an improvement of workers’ safety knowledge, but it is not as significant as the improvement of safety awareness.

The possible interpretation is that management conditions on the supervisory level are more effective in enhancing workers’ safety awareness. But in terms of workers’ safety knowledge, more focused safety training and incident learning should have been implemented.

In order to demonstrate that the predicted pattern by the model test is a correct reflection of the real system, a five-week survey and observation on a building construction project in Hong Kong was conducted by the authors. The major measures that were taken from week 2 to enhance the management conditions on the supervisory level.
level include lunch box meeting, dynamic risk assessment, toolbox meeting, equipment and tools inspection, best supervisor award, and best worker award. In the real project, the percentage of unsafe behaviors declined to 65% in week 5 after the measures were placed in week 2. Fig. 7 shows the comparison between the percentage changes of unsafe behaviors observed by the 18 pretrained observers on the project and the model test result, which indicates that the test’s predicted pattern is qualitatively correct.

Meanwhile, by referring to Zhou (2009) and Mohamed’s (2002) safety climate questionnaires, two questionnaires to measure “workers’ safety participation” (to reflect workers’ safety awareness) and “worker competence” (to reflect workers’ safety knowledge) were developed. And 148 workers on the construction site (63% of the total workers) answered the two questionnaires on week 1 and week 5, among which 127 questionnaires were valid. Table 1 shows that “workers’ safety participation” was significantly improved (P = 0.043). Although “worker competence” was also improved, it did not show statistical significance. This indicates that measures like lunch box meeting and best worker award are more effective in improving workers’ safety participation, which is a good reflection of workers’ safety awareness (Wachter and Yorio 2014). And in terms of workers’ competency, direct safety training may be more effective. The result is consistent with the model test result.

Policy Implication Test

The ultimate goal of the model test is the identification of policies that can improve the performance of the real system. The model is tested when the “incidents’ control target” factor is reduced in week 3, and when the “priority coefficient” factor is increased in week 9.

Before week 3, because of a high production target and a high tolerance number of incidents, management’s emphasis on production reaches a very high level, while management conditions on safety remain steady at a very low level. However, as Fig. 9 shows, actual production is much lower than the production target because of the loss of production time caused by the frequent occurrence of incidents. From week 3, the tolerance number for incidents is reduced, which indicates a policy of putting safety on a more important level. As a result, a substantial growth of actual production and a reduction of incidents are achieved at the same time. From week 9, the priority coefficient is increased, which represents a policy of further putting safety as the project’s first priority, and a steady pace of production with even fewer incidents is achieved.

The test result shows that concession on safety will in turn jeopardize productivity, and only when putting safety as the first priority will a project have both a good safety record and a steady productivity.

Policy Sensitivity Test

Zohar (2002) classified management actions into three dimensions: reactive action (RA), preventive action (PA), and prioritization (P). A policy sensitivity test is conducted while regarding each dimension of management action as a policy package, so as to analyze the effects of safety policies on safety performance.

The components of the four policy packages involved are listed in Table 2. Package 1 is to maintain a balance between management reactive and preventive actions, Package 2 is to strengthen the reactive actions, Package 3 is to strengthen the preventive actions, and Package 4 is to prioritize safety over production while maintaining a balance between reactive and preventive actions. The weight of a factor refers to the priority of management investment under the condition that management time is always limited. And if the value of priority coefficient is 1.5, it means that the priority on safety is 1.5 times over production.

The model test result (Fig. 10) shows that, beginning in an initial high-incident situation, the four policy packages are all effective in the reduction of incidents. Package 3’s effectiveness also indicates that preventive actions seem to be more effective than reactive actions. Package 4’s effectiveness again emphasizes the importance of safety prioritization. It is worth noticing that the number of incidents is on oscillation under Package 4, which shows that without the emphasis on preventive action, Package 4 is only as effective as

Table 1. Differences of “Safety Participation” and “Worker Competency” between Week 1 and Week 5

<table>
<thead>
<tr>
<th>Item</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>95% confidence intervals</th>
<th>t</th>
<th>DOF</th>
<th>Significant (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workers’ safety participation</td>
<td>−0.13189</td>
<td>0.72841</td>
<td>−0.25980 to −0.00398</td>
<td>−2.041</td>
<td>126</td>
<td>0.043</td>
</tr>
<tr>
<td>Worker competence</td>
<td>−0.06929</td>
<td>0.77557</td>
<td>−0.20549 to 0.06690</td>
<td>−1.007</td>
<td>126</td>
<td>0.316</td>
</tr>
</tbody>
</table>

Note: DOF = degrees of freedom; t = Student’s t test.

Table 2. Parameters of Four Packages of Safety Policies

<table>
<thead>
<tr>
<th>Factor</th>
<th>Package 1 (RA + PA)</th>
<th>Package 2 (RA)</th>
<th>Package 3 (PA)</th>
<th>Package 4 (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-example weight</td>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Safety communication weight</td>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Safety inspection weight</td>
<td>1</td>
<td>1.5</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Behavior feedback weight</td>
<td>1</td>
<td>1.5</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Safety training weight</td>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Safety resources weight</td>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Incident learning weight</td>
<td>1</td>
<td>1.5</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Production target</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Incidents’ control target</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Priority coefficient</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

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Package 3 when there is conflict between safety and production. But when there is little conflict, the number of incidents will rise to the same level as under Package 1. Such analysis indicates that a combination of Packages 3 and 4 should be the most effective for enhancing the safety performance.

Overall, the policy sensitivity test shows that safety performance is sensitive to policies, and because the four plausible sets of parameters lead to the same direction of policy recommendation, the model is further proven to be reliable.

Discussion

Implications

Workers are working in a social environment, so their behavior patterns are highly affected by management, from whom they get praise or criticism, benefits or penalties. Management’s actions to make sure that workers can get proper safety training and adequate personal protective equipment, as well as management’s own behaviors, are all perceived by workers and will exert significant influence on workers’ behavioral choices. Therefore, the underlying causes of construction workers’ unsafe behaviors should be well understood before correction is taken. In terms of this paper’s particular interests, the SD-CUB model promotes discussion on the underlying causation of construction workers’ unsafe behaviors, and indicates ways in which unsafe behaviors can be fundamentally prevented.

The following implications for construction safety management can be learned through model building and testing.

1. Safety and production can actually support each other. When it comes to the relationship between production and safety, the general assumption is always that a high productivity is at the expense of safety. However, through the policy implication test, the result shows that safety and production can actually support each other, which is also emphasized by researchers (Reid et al. 2008; Salminen and Saari 1995). Because of limited management time, sometimes safety and production work are in conflict, especially when production pressure is high. While it may be natural for an organization to respond to the pressure as its first priority, it should be the role of management, especially senior management, to make safety the first priority (Cooke 2003). Though the production target can be caught up temporarily through management efforts, a signal that unsafe behaviors can be tolerated in the presence of production pressure is gradually released to workers, which is bound to result in more unsafe behaviors for the sake of convenience and efficiency. With incidents rising onsite, production pressure is raised because of the loss of production time, which will trigger a vicious cycle to further threaten workers’ safety and health. Cooke (2003) has given a real example of how this cycle turns lethal. With safety as the first priority, incidents will be reduced, no production time will be lost, and production performance will be improved eventually.

2. Management conditions on the supervisory level are effective on the improvement of workers’ safety awareness. During model data collection on the real project, the lunch box meeting invited subcontractors and supervisors along with workers to discuss safety issues together during lunch time; the dynamic risk assessment invited supervisors and workers together to evaluate the onsite risks; the toolbox meetings were held to share supervisors’ experience; equipment and tools inspection required supervisors to inspect the safety facilities along with workers; and best supervisor and best worker are selected weekly for awards. All these measures are aimed at facilitating the daily interactions between supervisors and workers. When workers are immersed in an environment where their supervisors are concerned with safety, are willing to discuss safety issues with them, often remind them of the surrounding hazards, and give positive feedback to their safe behaviors, their safety awareness can be significantly improved. Barling et al.’s (2002) research also found that safety leadership, which is composed of idealized influence, inspirational motivation, intellectual stimulation, and individualized consideration, predicted safety outcome through the influence on safety awareness.

3. Preventive actions are more effective than reactive actions on the enhancement of safety performance. Management commitment to safety is a good example for workers. If workers believe that management is concerned with safety, then they are also likely to act safely. And management’s communication with workers on safety issues is essential for the improvement of workers’ safety awareness and knowledge. Management should create a safety climate that encourages workers to actively report any incident onsite, to encourage workers’ involvement in hazard identification, and meanwhile enhance workers’ skill and capability. Management should also launch a series of initiatives to enhance the safety competency of the organization. Safety training is essential for the improvement of workers’ safety awareness and knowledge; the adequacy in safety resources is essential for the supply of adequate and appropriate equipment and facilities onsite; and a robust safety management system is essential for the smooth operation of activities and the normal running of resources.

Approach of Systems Thinking

As has been emphasized, the traditional research attempts to build a bridge between management conditions and outcomes through empirical analysis, while the mechanism for how such factors interact with each other remains unclear. By taking into account feedback loops and nonlinear relationships, which is not possible with conventional root-cause analysis, the developed SD-CUB model highlights the approach of systems thinking, from which new insights can be derived, and a more comprehensive understanding of the real world is likely to be achieved.

The usefulness of the approach of systems thinking can be highlighted by a discussion of a recent debate. Burke et al. (2006)
showed that safety training had a significant effect on safety performance based on meta-analyses, while Robson et al. (2010) pointed out that there was no clear evidence to support Burke et al.’s (2006) conclusion. Though Burke et al. (2011) responded to the criticism by enlarging the sample size, Brahm and Singer (2013) agreed with Robson et al. (2010) that the self-selection bias should have been appropriately addressed before Burke et al.’s (2011) research was conducted. And after correcting for self-selection bias, Brahm and Singer’s (2013) model showed that safety training failed to be statistically related to the reduction of accidents.

As this debate is clearly from the perspective of details, a more comprehensive understanding of the debated phenomenon can be derived upon the approach of systems thinking proposed by this paper: for the firms with greater safety concerns and higher management commitment to safety, relatively more engaging safety training along with other emphasis on preventive management actions such as more frequent safety communication are expected to be achieved, which in turn enhances individual conditions and reduces the number of incidents; and for the firms with less experience or lacking in safety culture, relatively less effective safety training along with other negligence on safety management such as little safety communication or inappropriate feedback to workers’ unsafe behaviors is expected, which in turn harms individual conditions and maintains the number of incidents at a high level.

Therefore, the evidence that safety training was positively associated with safety performance found by Burke et al. (2006) and Burke et al. (2011) makes sense. And after addressing the self-selection bias, Robson et al. (2010) and Brahm and Singer’s (2013) findings also make sense. Safety training is only one factor among various management conditions, and only by putting all the factors into joint forces, can significant improvement of safety performance be observed. From this perspective, the analysis upon the approach of systems thinking is in accordance with Hofmeister et al.’s (2014) suggestion: even if one of the factors did not contribute significant variance to the safety outcome, for management to be successful, they must balance all of the factors. Therefore, apart from pure statistics analysis, the approach of systems thinking can be helpful to achieve a comprehensive understanding of the underlying mechanisms.

**Basis for Simulation of Various Site Scenarios**

One should be aware that the SD-CUB model is a theoretical model without consideration of the diversity on different real construction sites. For instance, though the assumed feedback from unsafe behaviors to management conditions through incidents monitoring theoretically exists, it might be only suitable for the situation when safety practitioners regard incidents as a leading indicator of safety performance and are inclined to measure and act in a proactive way through the interpretation of such incidents. For the practitioners who only collect incidents as recordable events instead of proactive indicators, and will not take any corrective actions until injury and fatal incidents happen, this feedback may not exist (Hinze et al. 2013).

If the process of model tests could offer sufficient confidence in the model’s soundness, the SD-CUB model can be used as a basis for simulation of various site scenarios to explore the best solution to prevent and correct unsafe behaviors, so as to maximize the model’s value in use. Aiming at different practical scenarios, a variety of analyses on different safety management strategies as well as the sensitivity analyses of different parameters can be conducted, and a more thorough discussion on the characteristics and patterns of behaviors can be realized. Because the feedback structure is crucial for the dynamics of a system, by redesigning the causal structure (e.g., adding a loop indicating the function of a potential management approach such as the approach of behavior-based safety through goal setting, or eliminating the prior effect that management emphasis on production has on management conditions on safety), changing the extent and quality of information exchanges on safety issues, eliminating the time delays of incident reporting, or reinventing the decision process of the management’s focus in the system, the leverage points and critical management strategies to prevent and correct unsafe behaviors can be determined.

**Limitations and Suggested Future Research**

As Cooke (2003) and Sterman (2000) have stated, all models are limited, simplified representations of the real world. The SD-CUB model still needs to be tested on real construction projects. The model’s strengths and weaknesses are open for critics. The cause-effect relationships in the model tests are simply assumed to be linear, and the “delay” and “time to change” parameters are also assumptions. In the semistructured interview, one expert pointed out the difficulty of building credible equations to define the relationships.

Some efforts have already been done. A previous study (Zhang and Fang 2013) has developed direct measures for individual conditions such as attitude, subjective norm, and perceived behavioral control. The study has shown the feasibility of coefficients specification by analyzing the behavior of not using safety harnesses through empirical tests. It focused on workers’ cognitive Stage 4 “selecting a safe response,” and through a standardized questionnaire, the coefficients of attitude, subjective norm, and perceived behavioral control on the probability of cognitive failure in Stage 4 were derived. In order to ensure that the parameters correspond numerically to the real system, more targeted empirical studies such as site surveys should be conducted in future research.

Another limitation of a system dynamics model is that it can only realize the analysis on the macro level of a system, while ignoring the individual differences and the interactions in between. However, the roles of management from different levels are obviously disparate, and the behaviors of workers with different backgrounds, and their willingness to obey the orders from management, are also distinct (Feola et al. 2012). Through the imitations of individual behaviors and the internal interactions by artificial agents, the approach of multiagent modeling offers a bottom-up perspective to analyze the macro system by the aggregation of individuals, and is supplementary to the weakness of system dynamics (Sharpanskykh and Stroeven 2011; Watkins et al. 2009). Therefore, in the future, a series of research studies can be conducted, and by integrating the SD-CUB model with a multiagent model, a construction safety behaviors simulation model can be developed. The simulation model to be built is able to depict the cause-effect relationships among factors in a dynamic system from a macro level, as well as the behaviors and interactions of management and workers from a micro level. It will provide a new approach for further in-depth study of construction safety behaviors, so as to understand their characteristics and patterns. It also can be a helpful foundation for further development of practical safety management tools, so as to enhance safety management and eliminate accidents on construction sites.

**Conclusion**

This research promotes an approach of system dynamics modeling for the systematic understanding of the causation of construction workers’ unsafe behaviors. The SD-CUB model is developed to facilitate the understanding of how the system influences...
construction workers in terms of unsafe behaviors, to promote discussion on the system’s various cause-effect relationships and causal loop diagrams, and to indicate ways in which unsafe behaviors can be fundamentally prevented.

Through the process of model building and testing, the model’s confidence has been built, and several conclusions are reached. The five-week onsite survey and observation demonstrates that the SD-CUB model generates correct patterns of behavior. The system dynamics equations are available online in the ASCE Supplemental Data.

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Supplemental Data

The system dynamics equations are available online in the ASCE Library (www.ascelibrary.org).

References


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