Confidence Building of a System Dynamics Model on the Causation of Construction Workers’ Unsafe Behaviors

Zhongming JIANG¹ and Dongping FANG²

¹PhD candidate. (Tsinghua-Gammon) Construction Safety Research Center, Department of Construction Management, School of Civil Engineering, Tsinghua University, Beijing, 100084, China. Tel.: +86 10 62770380; fax: +86 10 62773661. E-mail address: jzm10@mails.tsinghua.edu.cn

²Professor. Corresponding author. (Tsinghua-Gammon) Construction Safety Research Center, Department of Construction Management, School of Civil Engineering, Tsinghua University, Beijing, 100084, China. Tel.: +86 10 62795113. E-mail address: fangdp@tsinghua.edu.cn

ABSTRACT

In order to gain deep insight into the underlying causation and identify correspondent management strategies in the prevention of construction workers’ unsafe behaviors, a conceptual system dynamics model was proposed. The paper mainly focuses on the confidence building of the model through model testing, which basically contains tests of model structure, model behavior and model’s policy implication. The conceptual model is quantified first before the formal process of model tests. Second, the paper applies semi-structured interviews for the structure-verification test to ensure the model’s appropriateness in depicting the structure of the real system. Third, tests of model behavior such as extreme-condition tests and behavior-reproduction tests are conducted, so as to demonstrate the plausibility of the patterns and behaviors the model generates. Fourth, model’s policy implication tests are presented to examine whether the model’s responses to predesigned policies are consistent with the real system. As a result, the model shows confidence in revealing the underlying causation of unsafe behaviors, which can be used as reference to the routine safety management in practice. Further suggestions for the application of the model as a tool of simulation in real construction projects are also given.

INTRODUCTION

Since the approach of system dynamics has a variety of advantages, it has been used to study the causation of construction workers’ unsafe behaviors, and a preliminary system dynamics model was proposed (Jiang et al., 2013), see Figure 1. The main factors in the model are presented in the grey boxes such as “management factors”, “individual factors”, “environmental factors”, and “effect on safety”. Here, “effect on safety” categorizes the endogenous consequences of the feedback structure. The logic for model development is as follows: first, unsafe behavior is the result of a cognitive failure. Thus, a first link is built from probability of cognitive failure to unsafe behaviors. Second, as identified by cognitive analysis, individual and environmental factors are the direct causes of cognitive failure. Thus, the links from individual and environmental factors to probability of cognitive failure are built. Third, since management factors are regarded as the underlying causes of cognitive failure, and they
affect workers’ cognition process through affecting the relevant individual and environmental factors, the links from management factors to individual and environmental factors are built on a theoretically driven approach. Fourth, feedback from unsafe behaviors to management factors through incidents is built. When more incidents happen, management will react with positive feedback through the emphasis on safety.

The model fundamentally consists of eight basic balancing loops and reinforcing loops. Loop B1 (“Management factors → Individual factors → Probability of cognitive failure → Unsafe behaviors → Incidents → Management factors”) shows that management factors exert influence on workers’ behaviors through individual factors. Loop B2 (“Management factors → Hazard mitigation measures → Unsafe conditions → Probability of cognitive failure → Unsafe behaviors → Incidents → Management factors”) shows unsafe conditions that can lead to unsafe behaviors are affected by management factors through hazard mitigation measures. Loops B3 (“Management factors on safety → ← Emphasis on production”) and B4 (“Emphasis on production → ← Production pressure”) show how management factors on safety trade off with management emphasis on production which in turn affects work load by the variation of production pressure. Loop R1 (“Management factors → ⋯ → Unsafe behaviors → Incidents → Production pressure → Management factors”) shows the vicious cycle when production pressure is high, the emphasis on production will in turn reduce the management efforts on safety, which will further increase the loss of time due to more incidents occurred. Loop R2 (“Individual factors → Probability of cognitive failure → Unsafe behaviors → Incidents → Production pressure → Work load → Individual factors”) shows the effect of work load on workers’ psychological factors. Loop R3 (“Production pressure → Work load → Physical condition → Probability of cognitive failure → Unsafe behaviors → Incidents → Production pressure”) shows the effect of work load on workers’ physical factors. Loop R4 (“Individual factors → Probability of cognitive failure → Unsafe behaviors → Individual factors”) indicates the effect of coworkers’ unsafe behaviors on workers’ subjective norm which consists a critical part of individual factors.

The eight loops are discussed in detail in (Jiang et al., 2013). Though some implications were learned during the model’s building process, the model is still a conceptual model, the confidence of which still needs to be enhanced by a variety of model tests, so as to further explore the value of the model.

Validity is the primary measure of the quality of a system dynamics model (Schwaninger and Groesser, 2009). Therefore, Balci (1994) emphasized the importance of validation, verification, and testing techniques, which “must be employed throughout the life cycle of a simulation study starting with problem formulation and culminating with presentation of simulation results”. Since the process of verification is in pursuit of the correctness of the simulation model technically (Balci, 1994; Lucko and Rojas, 2009), i.e. “building the model right”, and has been performed internally by the authors through the comprehensive components check in the previous paper, this paper devotes to the model’s validation through model tests, i.e. “building the right model”.

Figure 1. The preliminary system dynamics model (Jiang et al., 2013)

THE ROLE OF VALIDATION

Given that the current quality of simulation models in use is unsatisfactory in most cases, there exists a pressing need for model improvement (Grösser and Schwaninger, 2012). Validation is the process of a model’s confidence building, as well as the establishment of the soundness and usefulness of a model (Forrester and Senge, 1980). The confidence of a system dynamics model can be increased by a wide variety of tests. By testing, in other words, by the comparison of a model to the real system, the existence of errors or inaccuracies in the model can be revealed (Balci, 1994; Forrester and Senge, 1980; Schwaninger and Groesser, 2009). But there is no single test that can validate a model. Rather, confidence in a system dynamics model accumulates gradually as more tests are passed and as more corresponding points between the model and the real system are identified (Forrester and Senge, 1980).

In terms of validation, Grösser and Schwaninger (2012) pointed out that there is no
absolute validity or confidence. Validation of a model is a matter of degree, not a dichotomized property (Schwaninger and Groesser, 2009). It is also worth mentioning that, in contrast to “black box” models, system dynamics models are causal-descriptive “white box” models, the validity of which is not only dependent on the validity of results, but also the validity of the internal structure (Barlas, 1996). Therefore, system dynamics models should be tested as much as possible, so as to assess the rationality of model assumptions and behaviors, and to generate insights into the causes of observed phenomena (Forrester and Senge, 1980).

Since system dynamics models are causal loop diagrams, accuracy is required for each relationship and every loop. As long as one component is tested to be incorrect, the whole model should be rejected even if the overall results are in accordance with the real data (Schwaninger and Groesser, 2009). Grösser and Schwaninger (2012) also stated that “the existing categorization of the validation tests as well as the validation processes proposed in the literature are often perceived as too abstract and unspecific to be readily applied.”

**THE PROCESS OF VALIDATION**

The process of validation begins as the confidence is gained through the plausibility a model behaves. Validation then extends into the phases of model use and implementation. The ultimate objective is to transfer confidence in a model’s soundness and usefulness as a policy tool (Forrester and Senge, 1980; Schwaninger and Groesser, 2009). Validation tests have been categorized in several different ways (Barlas, 1996; Forrester and Senge, 1980; Grösser and Schwaninger, 2012; Schwaninger and Groesser, 2009).

**Methodology**

According to Forrester and Senge (1980)’s classification, model validation contains tests of model structure, model behavior and model’s policy implication. And before the formal process of model tests, the conceptual model must be quantified first. Second, semi-structured interviews as the structure-verification test are conducted to ensure the model’s appropriateness in depicting the structure of the real system. Third, tests of model behavior such as extreme-condition tests and behavior-reproduction tests are conducted, so as to demonstrate the plausibility of the patterns and behaviors the model generates. Fourth, model’s policy implication tests are presented to examine whether the model’s responses to predesigned policies are consistent with the real system.

**Model quantification**

The model quantification is based on the following principles: The maximum value of each variable is 1, the minimum value of each variable is 0. For example, if the variable “safety knowledge” reaches 1, it means that workers have mastered all the knowledge of safety issues; if the variable “unsafe conditions” reaches 1, it means that unsafe conditions are all over the place. But if the variable “unsafe conditions” reaches 0, it means that unsafe conditions are all cleared up from the site.
As discussed in the previous paper (Jiang et al., 2013), any failure in the five cognitive stages, could result in unsafe behaviors. The associated reasons can be categorized as individual and environmental factors such as safety awareness (SA), safety knowledge (SK), attitude (AT), subjective norm (SN), perceived behavioral control (PBC), physical condition (PC), and unsafe conditions (UC). Each stage \(i\) and its associated influencing factors \(X_{i1}, \ldots, X_{in_i}\) are shown in Table 1.

### Table 1. Cognitive stages and associated influencing factors

<table>
<thead>
<tr>
<th>Cognitive stage</th>
<th>Associated influencing factors</th>
<th>Number of factors (n_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) detecting hazards</td>
<td>(X_{11}: \text{SA}; X_{12}: \text{SK}; X_{13}: (1-\text{UC}); X_{14}: \text{PC})</td>
<td>4</td>
</tr>
<tr>
<td>2) recognizing hazards</td>
<td>(X_{21}: \text{SK})</td>
<td>1</td>
</tr>
<tr>
<td>3) perceiving responses</td>
<td>(X_{31}: \text{SK}; X_{32}: \text{SN})</td>
<td>2</td>
</tr>
<tr>
<td>4) selecting a safe response</td>
<td>(X_{41}: \text{AT}; X_{42}: \text{SN}; X_{43}: \text{PBC})</td>
<td>3</td>
</tr>
<tr>
<td>5) executing safe response</td>
<td>(X_{51}: \text{PC}; X_{52}: \text{SK}; X_{53}: \text{PBC})</td>
<td>3</td>
</tr>
</tbody>
</table>

According to Zhang and Fang (2013), linear regression is suitable for the statistics analysis on the probability of cognitive failure. This paper assumes that the probability of cognitive failure in stage \(i\) (PCF\(_i\)) is a linear function of the relevant influencing factors \(X_{i1}, \ldots, X_{in_i}\).

\[
\text{PCF}_i = 1 - \frac{1}{n_i} \sum_{j=1}^{n_i} w_{ij} X_{ij}
\]

Therefore, the eventual probability of cognitive failure follows the sequential probability model,

\[
\text{PCF} = \text{PCF}_1 + \sum_{j=2}^{n} \prod_{i=1}^{j-1} (1 - \text{PCF}_i) \ast \text{PCF}_j
\]

where \(n\) is set to 5, the number of cognitive stages.

Zhang and Fang (2013)’s study has also shown the feasibility of coefficients specification by analyzing the behavior of not using safety harnesses through empirical tests. The study 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 were derived, as shown in Table 2.
Table 2. Standardized path coefficients $\frac{W_{ij}}{n_i}$ of stage $i=4$ (Zhang and Fang, 2013)

<table>
<thead>
<tr>
<th>PCF$_i$ ($i=4$)</th>
<th>$X_{41}$ AT</th>
<th>$X_{42}$ SN</th>
<th>$X_{43}$ PBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not using safety harnesses</td>
<td>$\frac{W_{41}}{n_4} = 0.060$</td>
<td>$\frac{W_{42}}{n_4} = 0.675$</td>
<td>$\frac{W_{43}}{n_4} = 0.191$</td>
</tr>
</tbody>
</table>

Since it is a very heavy workload to specify every associated coefficient and the empirical study of Zhang and Fang (2013) has already shown the feasibility of specification, in order to facilitate the model test, this paper assumes that

$$PCF = \frac{1}{n} \sum_{i=1}^{n} \left( 1 - \frac{1}{n_i} \sum_{j=1}^{n_i} X_{ij} \right)$$

**Tests of model structure**

Verifying structure means comparing the structure of a model directly with the structure of the real system that the model represents (Forrester and Senge, 1980). The structure test of the system dynamics model can include review of model assumptions and dynamic hypotheses by experts knowledgeable about construction safety management. There are many techniques available to gather data from experts, and as semi-structured interviews have proven to be particularly effective, this paper uses this form of interview to test the model’s structure.

The questionnaire for suggestions 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, such as minimum years of professional experience and primary writer of publications in relevant journals, and three distinguished experts have responded. They are both prominent academic in construction safety management with numerous peer-reviewed journal articles. The results show that the experts agree to the structure of the model. Meanwhile, some suggestions are also valuable for the further improvement of the model.

Parameter verification test aims at comparing model parameters to knowledge of the real system to determine if parameters correspond conceptually and numerically to real life (Forrester and Senge, 1980). There are basically two types of parameters (constants) in the model, “delay” and “time to change”. The discussion of leading and lagging indicators of construction safety management has shown the time gap between safety measurements and the overall management results. The parameters correspond conceptually to the real system because, the “delay” parameters correspond 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); and the “time to change” parameters correspond the normal time needed by one “stock” factor’s adjustment,
(e.g. due to management emphasis on safety training, workers’ safety awareness can be increased gradually). However, both “delay” and “time to change” parameters are under a fixed value assumption numerically. Therefore, it is only the trends, not the exact value of the tests that count.

**Tests of model behavior**

As a particular important tool, a variety of extreme conditions tests are conducted to examine the correspondence between the model generated behavior and the theoretical reality under extreme conditions (imaginary maximum and minimum values of each variable) (Saysel and Barlas, 2006). The tests are crucial for flaws discovery (Forrester and Senge, 1980). The extreme conditions tests show that the model behaves as expected.

A behavior reproduction test is conducted. Under the extreme conditions that production target is at its maximum and incidents’ control target is at its minimum, an equilibrium is reached. From time A, the intervention aiming at enhancing management’s supervisory factors such as self-example, safety communication, safety inspection and behavior feedback is placed. As the emphasis on such factors, the corresponding individual factors are increased, and unsafe behaviors are reduced by a certain percentage. Similar symptoms has been observed in a real construction project, when supervisors’ behaviors are intervened by the design of researchers, the ratio of safe behaviors are increased (Wu, 2013), which is shown in Figure 2.

![Figure 2. The test’s result and the symptoms observed in a real project](image)

**Tests of model’s policy implication**

The ultimate goal of the model test is the identification of policies that can improve the performance of the real system. The policy implication test asks if a model correctly predicts how behavior of the system will change if a governing policy is changed (Forrester and Senge, 1980). The model is tested when the “incidents’ control target” factor is reduced at time A, as well as when the “priority coefficient” factor is increased at time B. Figure 3 shows the test’s result. Before time A, due to a high production target and a high tolerance number of incidents, management’s emphasis on production reaches a very high level, while management factors on safety maintains at a very low level. However, actual production is much lower than the production target because of the loss of production time caused by the frequent occurrence of incidents. From time A, the tolerance number of incidents is reduced, which indicates a policy of
putting safety on a more important place. As a result, a substantial growth of actual production along with a reduction of incidents are achieved at the same time. From time B, 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 are achieved. It is worth noticing that there is some oscillation after time B, which is the result of management’s trade-off between production and safety due to limited management time. The tested policy implication is found to be important in literature and are also observed in practice (Hinze, 2006). It is among the policy implications in the section of discussion.

![Figure 3. Policy implication test’s result](image)

DISCUSSION

As Hallowell (2008) pointed out, although construction safety management is operated under the ideal assumption that “more is better”, the overwhelming majority of construction companies operate with a very limited budget for safety and health management, and they are forced to select a small subset of the applicable safety program elements. However, current literature provides little guidance to help such companies in their decision-making process (Hallowell, 2008). This paper attempts to declare that, the system dynamics model, which has been through model tests in this paper, can offer a new way to capture and predict the effect of such potential programs through simulation.

It is worth noticing that, the model tested in this paper is basically a general model, which ignores the individual characteristics of different construction projects. For example, the feedback from unsafe behaviors to management factors through incidents control is fundamentally existed in the model, but it could be unrealistic on such construction sites where top management or safety personnel do not record incidents or do not regard incidents as leading indicators of their project’s safety performance. Therefore, when being used in practice as a tool for simulation, the model can encourage a thorough discussion on the characteristics of behavior-based safety management through a variety of scenario analyses. Since the feedback structure is crucial for the dynamics of a system, by redesigning the causal structure, 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.

Due to reluctant rationality, when workers are facing routine tasks or familiar work, they may subconsciously skip some of the cognitive stages and behave according to their formed habit. However, since the approach of system dynamics emphasizes on the macro level of a system, and is hard to depict the differences among individuals, thus in this paper, workers’ reluctant rationality is taken out of consideration, i.e. each behavior is produced after a worker has been through an entire five-stage cognition process. This limitation can be eliminated in the future research, by the combination with the approach of agent-based modeling, which on the contrary focuses on the micro level of a system. Another limitation is that, the cause-effect relationships in the model tests are simply assumed to be linear, and the “delay”, “time to change” parameters are also under assumption. Therefore, it is only the trends, not the exact numerical value of the tests that count. In order to ensure that the parameters correspond numerically to the real system, targeted empirical studies such as site surveys should be conducted in the future research.

CONCLUSION

Through tests of model structure, model behavior and policy implications, this paper shows the system dynamics model’s confidence in revealing the underlying causation of unsafe behaviors. Just as a safety culture can be engineered by ways of management practices such as the encouragement of incidents reporting system (Reason, 1998), the system dynamics model can be regarded as a policy implication tool. And with multivariate simulation, the model can be used as reference to the routine safety management in practice.

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REFERENCES


