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A System Dynamics Model for Construction Safety Behavior

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Abstract

Construction Industry has always been reputed by its high incident rates and poor safety performance. Construction accidents are, in most cases, resulted from the unsafe behaviors of construction workers on site. The study of workers' behavior is crucial in order to understand the causation of unsafe behaviors. Therefore, the objective of this paper is to simulate construction safety behavior in order to predict the number of safety incidents and better understand their causation factors. The simulation model illustrates how construction system influences construction labors on site in terms of unsafe behavior. The standard leading indicators of safety performance are first identified from the literature. Afterwards, a system dynamics model is developed to simulate the factors that affect safety behavior of workers on site. Furthermore, cellular automaton is introduced to account for the effect of safety climate/environment on workers' behavior, and thus, to study construction safety as an emergent behavior. The model involves dependencies among managerial factors as well as environmental conditions and aims to serve as a tool for the simulation of various project and managerial decisions. A hypothetical project case study is used in order to test the model results as well as the dependencies between the dynamic variables.

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Keywords: complex system; system dynamics; cellular automaton; contracting; construction safety.

1. Introduction

Construction industry has always been reputed by its high incident rates and poor safety performance. Construction accidents are, in most cases, resulted from the unsafe behaviors of construction workers on site. The study of workers' behavior is crucial in order to understand the causation of unsafe behaviors. Safety has become a major concern for different construction projects' stakeholders due

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to the high frequency and severity of accidents in the construction industry [1]. There are different safety metrics that evolved over time and that are considered as assessment tools for safety performance; such metrics can belong to two types of indicators: lagging or leading. While lagging indicators are related to the outcome of an accident, leading indicators are considered measurements associated to preventive actions [2].

Lagging indicators are traditional measurement techniques for the safety performance; in fact, they resemble the metrics adopted by the Occupational Safety and Health Administration (OSHA) [3]. OSHA metrics include: (1) days away, transfer (DART) injury rate, or restricted work, (2) recordable injury rate (RIR), (3) or the experience modification rating (EMR) on workers' compensation [3]. On the other hand, leading safety indicators have evolved as an efficient alternative to the lagging indicators, which help improve the safety performance in the construction industry [1]. Leading indicators comprise variety of areas such as safety planning, management commitment to safety culture, rewards and recognitions for safe behavior and accident investigation, as well as safety orientations and training [3].

The Bureau of Labor Statistics ranks the construction industry well above the national average for nonfatal occupational injuries and illness. Construction related injuries are a major contributor to total project costs for both contractors and owners. These costs have only increased in recent years due to increased cost of worker's compensation insurance, healthcare and increased incidence of litigation. Therefore, it is in the interest of all parties to plan for safety during all phases of the construction processes. As such, new emphasis has been placed on improving safety knowledge in all areas of construction. Therefore, it is crucial to simulate construction safety behavior in order to better understand the causation factors and predict the number of safety incidents on construction site.

2. System Dynamics Model

The model is inspired from the work of Jiang et al. 2014 [4].The system dynamic model simulates the trade-off between production system and safety system. In fact, management efforts and time spent on production and safety are limited resources and thus any increase on one side may result in a decrease on the other. This is reflected in figure 1, which shows that the overall system consists of two subsystems: the production and safety system.

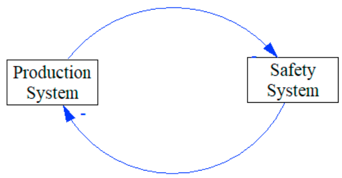

Fig. 1. Trade-off between management conditions on safety and production.

2.1. Production Subsystem

Each subsystem in the model needs an input in order to be adjusted for different situations and circumstances. The inputs for the production system are initial labor hours, maximum labor productivity, target production and remaining work. Initial labor hours represents the number of workers on site multiplied by the number of daily working hours. On the other hand, the maximum productivity rate is the highest labor productivity rate that can be attained in the project. Labors exhibit an increase in their productivity rates with time as they acquire necessary knowledge of the task to be performed and higher familiarity with the work [5]. Therefore, the productivity rate is expected to increase each time step as a learning curve. A sigmoid function was used in order to represent the learning curve and it is as follows:

$$Labor\ Productivity\ Rate = max.productivity\ rate\ \times \frac{1}{(e^{-0.05\times time}+1)} \quad (1)$$

Construction labor productivity is further affected by the weather conditions. In cold weathers, the construction production rate tends to be lower than that in warmer conditions. In order to account for construction seasonality, the production rate at each time step is then computed as follows:

$$Production\ rate = \frac{-\cos\left(time\times\frac{\pi}{6}\right)+5}{6} \times Labor\ Productivity\ Rate\ \times\ Labor\ Hours \quad (2)$$

Moreover, remaining work represents the quantity of work to be completed in the project. Target production is the production rate, set for the production, by the management or client. The production subsystem is shown in figure 2.The actual production is dependent on the production rate at a time step t and the management commitment to production. The production gap is also dependent on how much the production target is far from the actual production. Higher gaps lead to higher management commitment to production and thus higher actual production. In fact, an increase in schedule pressure may increase the number of work defects [6]. Thus, high production gap leads to higher work overload, which can cause an increase in construction rework. Construction rework decreases production rate, as the defects are considered incomplete work in the model.

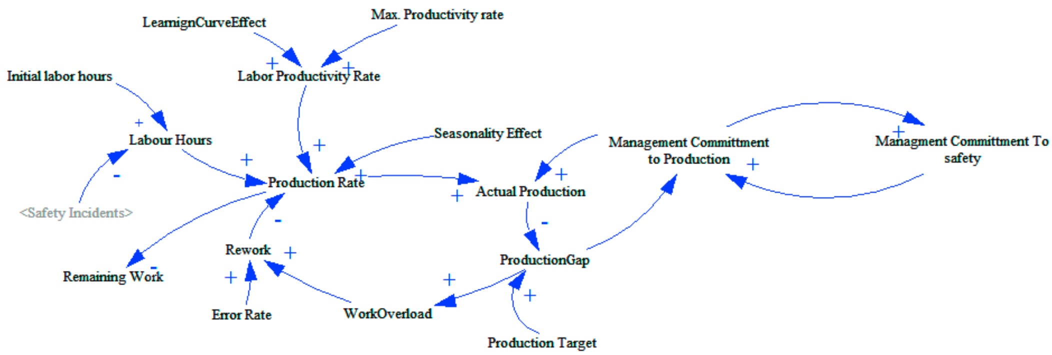

Fig. 2. The production subsystem of the system dynamics model.

The production subsystem affects the safety subsystem through the management variations in their commitment to production and safety. The next sections discuss the safety subsystem, cellular automata and details on how both subsystems affect each other.

2.2. Safety Subsystem

The production subsystem influences the safety subsystem through the variation in the management commitment on production and thus the management commitment on safety. The safety subsystem consists of the management conditions on safety and the individual conditions on safety. Jiang et al. 2014 collected in their work eight factors that make up the components of management conditions on safety [4]. Only four of these components are used in this paper's model, which are: (1) Safety Communication, (2) Safety Training, (3) Safety resources and, (4) Safety Inspection.

Safety communication represents how effectively and frequently the safety-related information are exchanged between management and workers [7]. However, safety training represents how frequently and effectively the workers are trained in safety [4]. On the other hand, Safety resources refers to the availability of qualified safety personnel as well as safety equipment and materials [8]. Finally, Safety inspection refers to how frequently and effective the management inspect workers' unsafe behavior and site hazard [9].

The management conditions on safety affect the individual conditions on safety as shown in figure 3. Individual conditions on safety represents the building blocks for the overall safe behavior of workers. The factors that can lead to unsafe behavior and that make up the components of individual conditions on safety in the model are: (1) Subjective norms, (2) Safety awareness, (3) Safety knowledge, (4) Attitude, and (5) Perceived behavioral control.

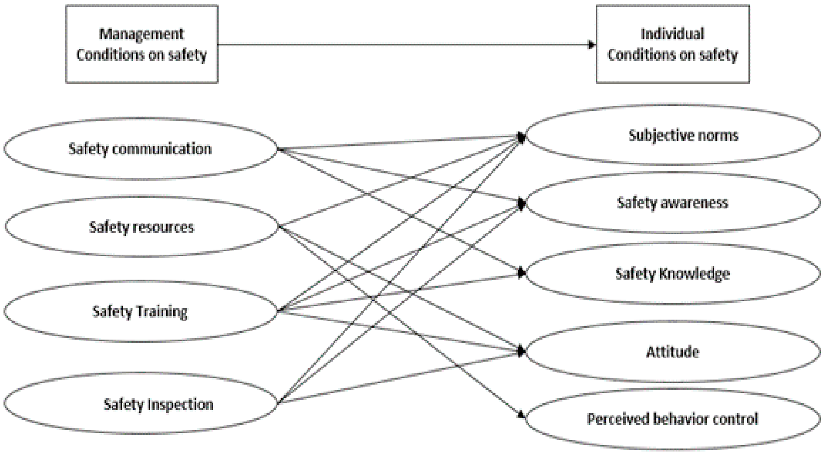

Fig. 3 Cause and effect relationships between management and individual conditions (adapted from Jiand et al. 2014) [4].

Each of the five components of individual conditions defines the behavior of workers on site. Figure (4) shows the safety subsystem in the system dynamics model. The inputs needed for the subsystem are the weights for the different available policies in the management conditions. For instance, some contractors tend to invest in their safety resources more than in safety training. Thus, the model gives the opportunity to test different policies by changing the weight allocated for each component available in the management conditions on safety. Moreover, the production and safety subsystems are inter-dependent in terms of the work pressure exerted on labors during the project. Higher work pressure lead to higher possibility of unsafe behavior [10]. Work pressure tends to affect the subjective norms, attitude and perceived control behavior of workers [4]. Moreover, co-workers' behaviors tend to affect the subjective norms of the individual workers on site. The effect of co-workers' behavior on each worker is to be considered in the cellular automata model incorporated to the system dynamics model.

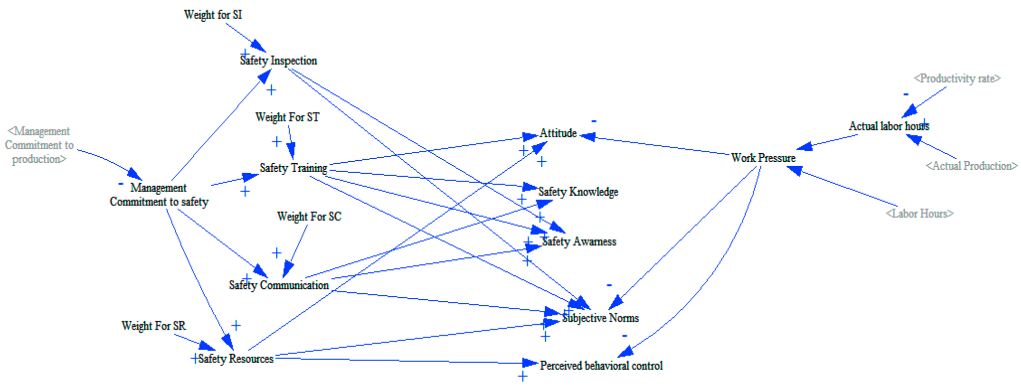

Fig. 4. The safety subsystem of the system dynamics model.

3. Cellular Automata

Cellular automata was incorporated to the model in order to account for the effect of co-workers in a more innovative way as compared to previous literature works. In safety behavior, Individual workers tend to work more in a safe manner if most of the Co-workers are working safely. Therefore, cellular automaton principle can be incorporated in the model to account for the interaction of neighboring individuals with different safety levels/indices in the environment/site and thus simulate the effect of co-workers on overall safety. The safety index is an index that ranges between 0 and 100. The safety index of a labor is the sum of the five components of individual conditions.

Since most of the construction incidents are due to labors 'unsafe behaviors, this model assumes that the incidents would occur only when the labor exhibits unsafe behavior. In order to assess the behavior of labors on site, each cell in the model represents a labor on site with a certain subjective norms, attitude, perceived behavioral control, safety awareness, and safety knowledge. The assumptions used in the incorporated CA rules are the following:

- Each cell represents a worker on site.
- Each cell has eight neighbors (Moore Neighborhood). In other words, each labor is going to be affected by the eight adjacent labors.
- The safety Index of each labor is the sum of subjective norms, attitude, perceived behavioral control, safety awareness and safety knowledge.
- Each component of individual conditions contribute equally to the safety index of the labors on site.

Moreover, each cellular automata model has rules through which the agents, labors in this case, change their states alternatively (safe or unsafe behavior). Those rules are the following:

- Any worker with a safety index higher or equal to 50 is more likely to behave safely; otherwise, the worker is more to behave unsafely.
- Any worker with four or more co-workers behaving safely (Safety Index >=50), its safety index is expected to increase by 5%; Otherwise, its safety index is to be decreased by 5%.

The cellular automata simulates the interaction of co-workers through simple rules and results in an emergent behavior. This emergent behavior represents the proportions of labors exhibiting unsafe and safe behavior on site. Next section discusses the model holistically in order to clarify the role of the system dynamics and cellular automata model in the system.

4. Integrated System Dynamics and Cellular Automata Model

The number of incidents is derived from the number of unsafe behavior on site and the latest OSHA recordable incident rate for the company. The OSHA incident rate is calculated by multiplying the number of recordable cases by 200,000, and then divided by the number of labor hours at the company [11]. Figure (5) shows the role of the system dynamics and the cellular automata model and their interaction in the simulation process.

The system dynamics model, whose detailed variables were discussed in the previous sections, consists of two subsystems (production and safety). The system dynamics model simulates the effect of production as well as the managerial safety policy preferences on the individual conditions of labours. Managerial safety policy preferences represents the weights allocated to each of the component of management conditions. The effects and changes in the individual conditions on site are exhibited in the cellular automaton model. In other words, in each time step, the managerial safety policy preferences and the production system affect the individual conditions positively or negatively. These effects are incorporated in the cellular automata along with the effect of co-workers' unsafe behaviours on site. The number of unsafe behaviours are then taken from the cellular automata and used in the system dynamics to calculate the number of incidents. The number of incidents, in turn, affects the labour hours since each incident leads to loss in production and time. Moreover, each time an incident occurs management commitment shifts from production to safety in order to mitigate or enhance the safety performance in the project. Moreover, the model was used on a hypothetical case study whose inputs are presented in table (1).

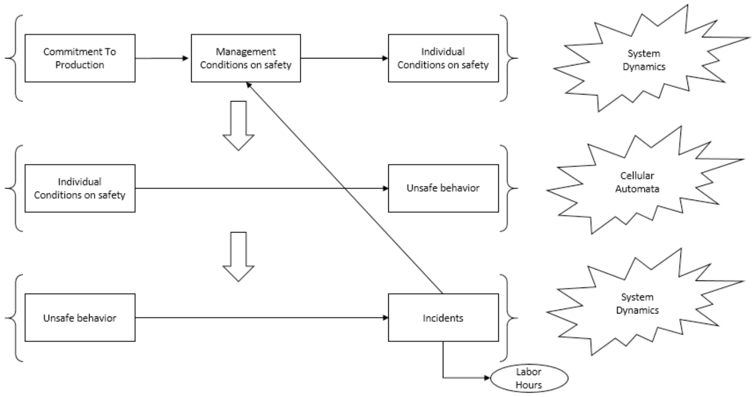

Fig. 5: Interaction and role of system dynamics and cellular automata system.

Table 1: The inputs of the project case study.

Input	Value	Unit
Remaining Work	5000	m^3 per project
Labor Hours	4000	man-hours per month
Maximum Labor Productivity	0.083	m^3/ man-hour
Production Target	250	m^3/ month
# of labors	100	Workers

The results of using different safety policies are going to be presented and discussed in this section. Table 2 shows the inputs of the safety subsystem for the different safety policies. For instance, the first policy gives higher weight for the safety inspection (0.5) which means that 50 % of the management commitment on safety would be dedicated for safety inspection. The results of three different policies are going to be highlighted in this section.

Table 2: The input for different safety policies.

Input	1	2	3
Weight for safety resources	0.167	0.25	0.15
Weight for safety training	0.167	0.25	0.15
Weight for Safety communication	0.166	0.25	0.15
Weight for safety Inspection	0.5	0.25	0.55

5. Results and Analysis

Figure (6) shows the number of potential incidents at each time step. As shown in the graph, different policies lead to different pattern of incident rates. All of the three policies exhibit high incidents at the beginning and then start to decrease with time. This is due to the fact that labors witness an increase in their productivity without any compromise in their safety behavior. The highest total number of incidents was for policy 3. However, the lowest total number of incidents was for policy1. Moreover, the peak monthly incident was witnessed in case of policy 2.

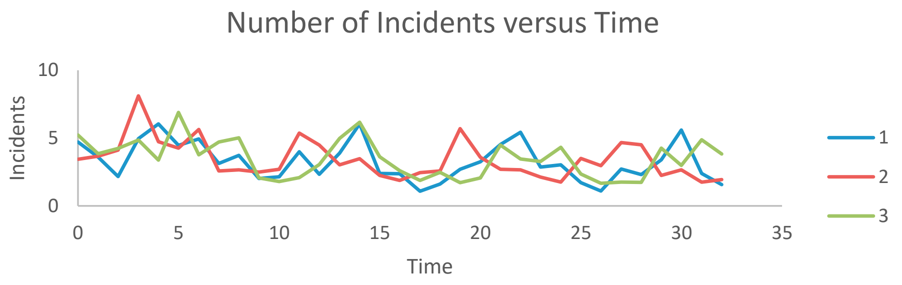

Fig. 6: Number of incidents during the project.

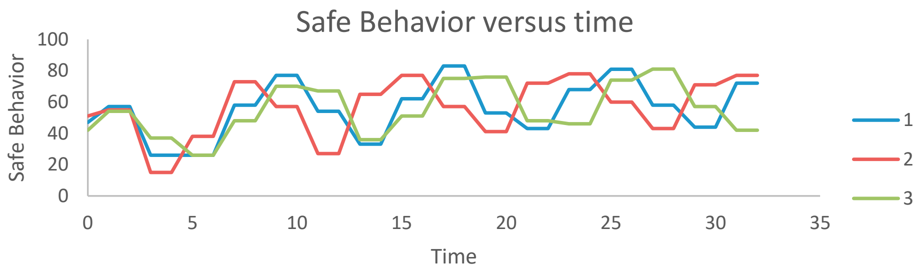

Fig. 7: Number of safe behaviours on site

Figure (7) shows that the highest safe behavior can be attained using the first policy (around 80 %). On the other hand, the second policy shows the lowest percentage of safe behavior on site (around 18%). Figure (8) shows the variation of remaining work as a function of time. The project, for all policies, finishes after around 32 steps. However, some policies led to delays more than others did. For instance, policy 2 exhibits the highest delays. The other two policies are approximately close in terms of project duration. It can be concluded that although safety and production competes together for scarce resources in terms of time and commitment, delays of project completions in the results (Policy 2) is related to high unsafe behavior and incident rates at the beginning of the project.

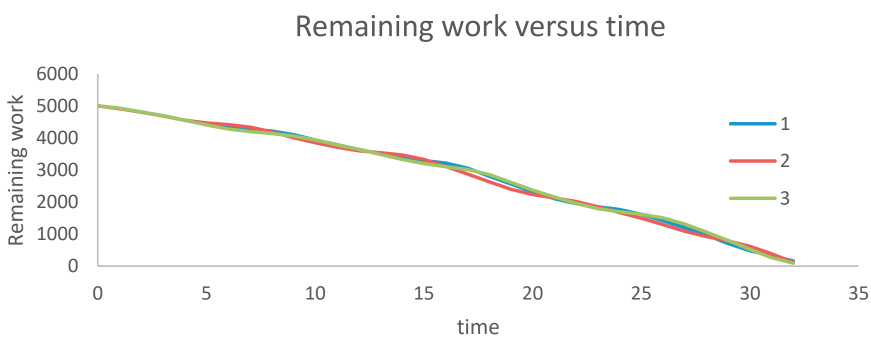

Fig. 8: Remaining work versus time.

6. Limitations and Future Works

This section presents the limitations related to the developed model, and thus the future works that needs to be conducted to the current work. In fact, no real world data were available in order to calibrate and validate the model. The weight of each individual condition on the overall labor's safe behavior is unknown, and thus the weights were distributed equally. To this end, empirical studies should be conducted to accurately assess the contribution of each individual condition to the overall safety behavior of the labor. Moreover, the cellular automaton does not represent the actual site and its dimensions, which may misrepresent the effect of co-workers on individual labor behavior.

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