MODELING CONSTRUCTION SAFETY AS AN AGENT-BASED EMERGENT PHENOMENON

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ABSTRACT

Traditional research in construction safety focused on accident data analysis, identification of root cause factors and safety climate modeling. These research efforts did not study the dynamic repetitive interaction among multiple root cause factors. Recently safety research focuses on developing accident causation models. These models attempt to explain how the interaction among multiple project factors gets translated into safety incidents. Agent based modeling and simulation (ABMS) is an appropriate technique to develop computational models of accidents causation because of its ability to model human factors and repetitive decentralized interactions. This paper presents a conceptual framework for developing agent based models of construction safety. The key components of the model such as construction crew, management, work environment, material and equipment related quality issues, project/process level complexities, interaction rules and adaptation have been discussed. Further the adaptation of agents in response to the safety culture has been demonstrated using a simple ABMS experiment.

KEYWORDS

Construction safety, agent based modeling and simulation, construction accidents causation

1. CONSTRUCTION SAFETY

Data published by the Bureau of Labor Statistics shows that there were more than 1000 fatal and 400,000 non fatal incidents in construction industry in the year 2005 [1]. Although the total number of construction related non fatal injuries and illness cases reduced from 529,300 (in year 1994) to 401,100 (in year 2004), it is a concern to note that the construction related fatal incidents increased from 1028 (in year 1994) to 1234 (in year 2004) (Figure 1). Construction related safety incident numbers are significant even in the year 2005 (1243 fatalities and 414,900 non fatal incidents). Assuming that 220 working days in a year, on average, there were 5.65 fatal and 1885 non fatal incidents every day in the year 2005. Most of the construction fatalities and injuries occur due to falls from height or struck by a moving or falling object [2]. Safety incidents occur due to production pressure [3] or inefficiencies in project planning such as lack of training, protective wearing, absence of appropriate mechanical hazard elimination, poor site house keeping practices and lack of quality in construction material/equipment [2, 4]. Previous research in construction safety focused on analysis of safety accidents data [4], identification of root cause factors [4], and safety climate analysis [5, 6].

However, the knowledge on how the multiple root cause factors such as management, crew, site, equipment, material and project/process level complexities dynamically interact and gets translated into safety incidents has generally not been captured. Recent research works focused on understanding the hierarchy of causal influences [2], map system structure with causation of accidents [7], and to develop accidents causation models [3, 8]. The basic motivation behind these works is to understand the interaction among multiple root cause factors and explain how the interaction among these factors gets translated into safety incidents.

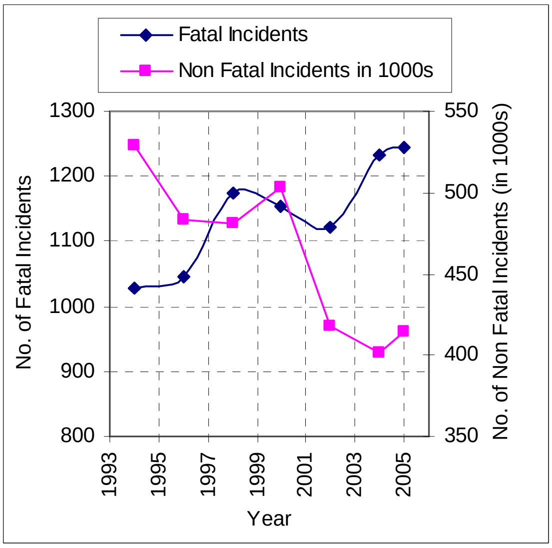

Figure 1: Construction related fatal/non fatal incidents (Source: U.S. Bureau of Labor Statistics)

2. AGENT BASED SIMULATION

Agent based models are primarily used to simulate decentralized complex adaptive emergent systems in social, economic and environmental sciences [9]. Agent based model provides a realistic natural representation of the system using object oriented concepts. Some of the key features of agent based simulation models are [10]: i) Agents have diverse set of properties and rules that mimic the real world behavior; ii) Simple rules at the micro level create complex behavior at the macro level; iii) Agent based systems are mostly bottom-up systems, i.e. no top down control; iv) Agents interact and learn from other agents; v) Agents interact with the operating environment; vi) Agents adapt over a period of time; and vii) The characteristics of the operating environment change during interaction with agents.

2.1 Review of Literature: ABMS in construction

Several attempts have been made to apply agent based modeling and simulation concepts in construction. An agent based approach was presented to dynamically re-schedule the project by all concerned coordinating subcontractors [11]. A multi-agent systems based approach was proposed to improve the efficiencies of construction claim negotiation process among distributed construction team members [12]. The use of agent based models to simulate the construction processes in production home building has been demonstrated [13, 14]. Further the adaptation of construction crew in response to the company safety culture has been demonstrated using an agent based simulation experiment [15]. The state-of-the-art on the applications of multi-agent systems for collaborative construction engineering activities has been reviewed [16]. An agent based proto-type system was developed using ZEUS toolkit to model and simulate the dynamic interactions and the inter-dependencies in collaborative project supply network [17]. A multi-agent based simulation model has been proposed to study the influence of inter-firm relations in construction organizational networks [18]. Further, a computational model has been developed to analyze the human and social behavior in emergency evacuation situations [19].

3. MOTIVATION AND OBJECTIVES

A large body of literature is available in construction safety domain about the root cause factors of accidents. Similarly, statistics on construction accidents such as fatalities, major injuries, minor injuries, near misses, number of lost working days, incident rate are available in literature. However, there is limited research conducted on how the root cause factors interact with each other in a repetitive manner and gets translated into safety incidents. The interaction among these factors happens at multiple levels namely immediate level, shaping level and originating level [2: Fig.2]. A series of safety rule violations that propagate from the originating level to the immediate level may finally result in the occurrence of a safety incident if they are not identified and treated appropriately [7: Fig.2]. Developing computational models for construction accidents causation can help us understand the interactions among root cause factors and provide possible explanation on how the interaction among these factors gets translated into safety incidents.

This work attempts to investigate how ABMS can be utilized to explain some of the key issues in the construction accidents causation process. The two objectives of this work are: i) develop a conceptual framework that illustrates the key components of an agent based simulation model for a construction safety system; and ii) implement a conceptual ABMS model that demonstrates the some of the key construction safety concepts.

4. CONCEPTUAL FRAMEWORK OF AGENT BASED MODEL FOR CONSTRUCTION SAFETY

The key components of an agent based simulation model for construction safety system consist of the following: (i) agents with diversity in agent types, properties and rules; (ii) work environment characteristics – safety risks as a function of location and space availability; (iii) project planning practices and safety policies of the management; (iv) material, equipment characteristics and associated quality issues; (v) project/process level complexities and its impact on interaction among root cause factors; (vi) rules for interaction - agent to agent (coordination), agent to site (hazardous situations), agent to management (production pressure) and agent to material/equipment (quality issues); (vii) adaptation in agent properties and rules; and (viii) changes in the company policies and (ix) changes in the work environment. The dynamic repetitive interaction among multiple root cause factors is shown in Figure 2.

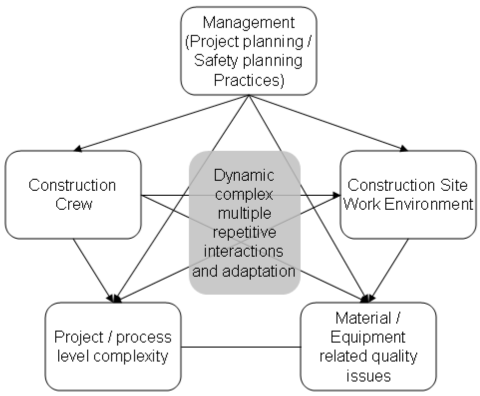

Figure 2: Interaction among root-cause factors

4.1 Agents with diversity in agent types, properties and rules

Examples for agents in construction projects include project manager, construction manager, project superintendent, site superintendent, general foreman, equipment operator, skilled labor and unskilled supporting labor. Effective coordination of multiple agents is critical for completion of the task in a timely and safe manner. Each agent has a set of properties based on personal factors and professional job responsibilities. Some of the personal variables that characterize agents include age, personal traits (safety conscious or productivity conscious), attitude, motivation, job satisfaction, fatigue, alcohol use, lack of sleep, disease, and worry or anxiety [4]. Variables related to work environment include knowledge, skill level or competency, duration on site (in months), duration in the industry (in years), duration with employer (in years) and average designated hours per week [2, 4].

4.2 Site: work environment characteristics

Construction project sites have diverse set of characteristics. Examples include hazardous conditions inherent in the work (work in high elevation or in deep trenches, work near high voltage power cables or heavy traffic), weather conditions (windy, rain, drizzling, heat stroke, snow), time of work (day or night), site layout and space availability (congested site with limited space or ample space without any restriction), operating conditions (noise, dust or slippery walking surfaces), local or protruding hazards (such as nails, scaffolding components). These factors are influenced by site constraints, work scheduling and site house-keeping practices and they change continuously during the construction process [2]; hence dynamism i.e. constantly changing work place and work activities is an inherent nature of construction sites. The location of the work place and the availability of workspace influence the safety risks of construction crews.

4.3 Management factors

Management factors directly control on how the project planning practices and safety policies are implemented in a construction project. The safety climate on a construction site is strongly influenced by management factors. Examples for management factors include safety culture (priority for production or safety), training, provision of PPE, appropriate mechanical hazard elimination, site housekeeping practices, and availability of quality construction materials, equipments, and machine tools. Further, the management factors are responsible for enforcing safe work practices in various project life cycle activities such as design, scheduling, coordination and communication (safety tool box meetings) and task execution.

4.4 Material, equipment factors and associated quality issues

At the immediate level [2], the suitability, usability and the condition of the materials and equipment influence the likelihood of construction accidents. Based on the analysis of 100 accidents [2], it was found that accidents happen 27% of the times due to material related factors and 56% of the times due to equipment factors. Material and equipment related factors are influenced by design, specification, supply, availability, and maintenance at the shaping level, and by management (construction education, economic climate and client requirements), supply vendor factors at the originating level [2].

4.5 Project / process level complexities

Certain inherent characteristics of construction projects and construction processes influence the likelihood of accidents. The safety at the project and process level is influenced by shared resources, constraints related to the location of workspace and the limited workspace availability. For example, shared or congested workspace across multiple crews increases the likelihood of one crew being affected by the action of another crew. Similarly shared resources such as cranes between two different activities increase the work pressure on the equipment as well as on the equipment operator. Examples for process level complexity can include working on high elevations, underground infrastructures such as tunnels or deep trenches, and proximity to high voltage power cables, etc. Some of the project related factors include project duration, project delivery methods, schedule status (ahead of schedule, on schedule, or behind the schedule), crew size, etc. The task or process level complexity is also a function of the type of the task. Different types of tasks include setting-up, actual task, clear-up, maintenance and movement or transit.

4.6 Interaction rules

A number of interactions happen during construction processes depend on the rules of participating agents. These include agent to agent interaction (coordination), agent to site interaction (hazardous situations), agent to equipment/material (quality issues) and management to agent (safety climate and production pressure). Some of the rules for agents include coordination, learning from other agents, ability to influence the performance of other agents, act in response to the company policies and act in response to the characteristics of the work environment. When there exists more production pressure, construction crew increases the pace or speed of their work and tend to be less cautious toward safety rules. On the other hand, when there is a rewarding atmosphere for safe performance, crew pays more attention to safe work practices. Management rules include designing project planning practices and safety policies in response to the project progress at specific time intervals. When the project is behind the schedule, management may exert work pressure on crews. Increased stress and production pressure may lead to non-compliance of safety rules by the crews and eventually this might result in the occurrence of safety incidents. Provision of safety training, regular safety tool box meetings, appropriate mechanical hazard elimination and selection of quality material, equipment and hand tools positively influences safety climate of the construction projects. Often the safety requirements are considered as conflicting goals with the productivity [3]. But when a safety accident occurs at the construction site, management will tend to pay more attention to safe work practices after that incident.

4.7 Adaptation

Adaptation refers to the change in the properties and the rules of the agents in response to the changes in the company policies, changes in work environment characteristics. For example, a front line manager plays an important role in implementing safe work practices at construction sites. If the front line manager is safety conscious and has good interaction with onsite crews, then the onsite crews adapt toward a highly safe working atmosphere. On the other hand, if the front line manager lacks safety training and have poor interaction with crews, then this may lead the onsite crews to be non compliant toward safe work practices. The characteristics of the work environment change continuously during the construction; for example change in site layout, change in geometric conditions of the site structures etc. Further the management planning and policies adapt over a period of time in response to the project status and the safety based performance of the crew.

4.8 Discussion on the conceptual framework

While most of the agent based applications in social science domain are described by only bottom-up processes, its application in construction requires certain changes to existing concepts. This is because the representation of construction processes requires a combination of top-down control (management factors, federal regulations, state/local regulations) and bottom-up control methods (localized interactions, real-time behavioral decisions). Development of agent based models for construction safety domain involves modeling complex multiple repetitive interactions and adaptation among construction crews, management policies, work environment, material/equipment related quality issues and the project & process level complexities. This can be a challenging task given the large number of variables, complexities involved in the interaction as well as in the adaptation. The scope and the level of details of the agent based simulation model can be decided based on the type of safety related questions that needs to be answered.

5.0 SIMULATION EXPERIMENT

This section presents the results of a simple conceptual agent based simulation experiment that demonstrates the adaptation of construction agents in response to the safety culture of the construction firm. This experiment is a confirmation and conceptual extension of the work reported by Walsh and Sawhney [15]. The agent based simulation tool “NetLogo” was used for this experiment. NetLogo was developed by the Center for Connected Learning and Computer based Modeling at Northwestern University (http://ccl.northwestern.edu/netlogo/).

5.1 Simulation model description

Agents: There are 50 agents in the model. Agents keep moving from pick location to place location to transport materials in a simulated construction site environment. Agents have the following properties: care-taken and speed. Care-taken refers to the safety consciousness of the agents. This means how cautious the agents are while they make each step in the site. Care-taken value is a function of many variables such as training, familiarity of the agent with the crew member and with the supervisors, number of supervisors in the site, etc. In this model, care-taken varies uniformly from 0 to 200. Speed refers to the number of steps that an agent can move forward in each time step of the simulation clock. It is assumed that speed is inversely proportional to care-taken (for example, speed is 1 if care-taken is 200; speed is 5 if care taken is less than or equal to 100).

Site: The site is represented as a two dimensional grid of size 50 by 30 cells. Each cell or patch is associated with a danger value. The danger value is function of site house keeping, site complexity and site conditions based on environmental factors. In this model, it is assumed that danger value varies uniformly from 0 to 200 for each cell.

Agent rules: (1) The number steps that an agent moves toward pick or place location is equal to the speed of the agent. Per simulation clock time step, an agent with speed 1 makes one step whereas an agent with speed 5 makes 5 steps. (2) After completing each step, the possibility of safety incident is checked. If the care taken value of the agent is greater than the danger value of the current patch or cell, then there will be no incident. On the other hand, if the care taken is less than the danger value, there is p% chance for the occurrence of safety incidents. The value of the variable 'p' can be controlled by the user (in this model p is assumed as 2%). (3) Each agent's performance is measured using two variables: 'safety-inc' refers to the number of safety incidents and 'prod-cycles' refers to the number of production cycles completed by the agent. (4) The score for each agent is computed using the following equation: Score = production cycles X production weight – number of safety incidents X safety weight (production weight refers to the priority given by the management toward production; similarly safety weight refers to the priority given by the management toward safety; these weights vary from 0 to 100). (5) After completing 1000 simulation clock steps, it is assumed that one generation is completed. After this the generation index is incremented by one and the simulation is continued for a specific number of generations. (6) After the completion of each generation, agents in the simulation model adapt. The agents are ranked based on score value. The values of speed and care-taken variables of bottom six agents (in terms of low score) are replaced by the average care-taken and average speed of top 12 agents.

5.2 Simulation results

The simulation model was initially developed in NetLogo. NetLogo provides a combination of visual animation, dynamic plots, trace and Excel based analysis report using Behavior Space. However, to minimize the run time and to produce customized output that is very specific to the modeler in each iteration (when visual animation is not needed), agent based model can be implemented using programming languages like C++. Developing agent based models using C++ supports modeling complex logic using powerful data structures. To accomplish this, the same model was re-implemented in C++. In this work, a combination of NetLogo and C++ based models were used for analyzing different scenarios.

Two types of experiments were conducted using the developed model. The first experiment studies the changes in the agent population characteristics in response to the safety culture in the firm. The safety culture influenced by the management is represented using two variables namely safety weight and production weight. The following test cases were tested: (i) safety weight: 100, production weight 0; (ii) safety weight: 100, production weight 50; (iii) safety weight: 50, production weight 100; (iv) safety weight: 10, production weight 100; and (v) safety weight: 0, production weight 100. The average care-taken of the agent population was plotted with respect to generations in each case. Figure 3 shows the summary of results of 5 test cases for the first experiment.

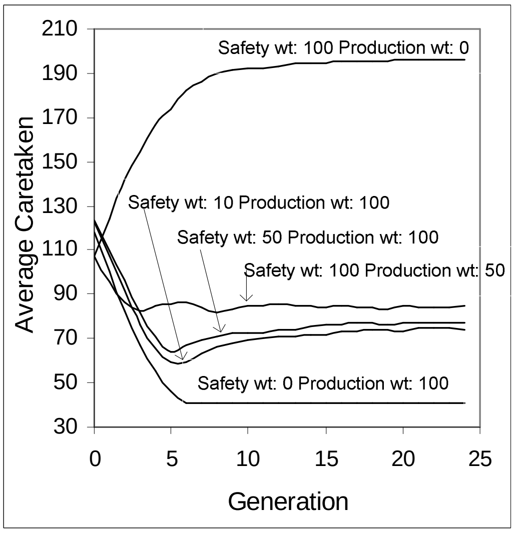

Figure 3: Plot of average care-taken

It can be noted from Figure 3 that the variation in the average care-taken of the agent population across generations is directly proportional to the safety weight and it is inversely proportional to the production weight. When the safety weight is 100 (priority is given for safety), agents adapt toward higher safety consciousness or care-taken. On the other hand, when the safety weight is zero (priority is given for production), agent population adapt toward least safety consciousness or care-taken.

The second experiment is an extension of the work reported by Walsh and Sawhney [15]. This focuses on modeling the variability in the adaptation of agent population for a given safety culture (safety and production weights). In real scenarios, variability in agent's adaptation assumes significance. Even for a given safety culture, construction crew adapts in different ways depends on the factors related to personal (training, learning and motivation), site, management, material/equipment and project/process complexity. Three types of adaptation namely 'low', 'medium' and 'high' were defined and tested in this experiment. Adaptation rate defines the rate of learning and increase in the agent's safety consciousness i.e. care-taken in each generation in response to the safety weight. In every generation, the care-taken value of bottom six agents were incremented by 20%, 40% and 60% for the three types of adaptation rates 'low', 'medium', and 'high' respectively. Figure 4 shows the plot of average care-taken of agent's population for three types of adaptation (safety weight: 100 and production weight: 0 for all 3 cases). When the adaptation rate is high, the average care-taken value of the agent population reaches maximum in 17 generations. On the other hand, when the adaptation rate is medium or low, the agent population needs more number of generations to reach high level of safety consciousness.

7.0 CONCLUSIONS

ABMS can be used to develop computational models of construction accidents causation since it supports modeling human behavioral factors and local repetitive interactions among multiple agents and entities at construction site. The resultant model may help us to understand the dynamic interaction among multiple root cause factors and provide possible explanation on how the interaction among root cause factors gets translated into safety incidents. This paper presented a conceptual framework for developing agent based models of construction safety. The key components of agent based model such as construction crew, management, work environment, material and equipment related quality issues, project/process level complexities, interaction rules and adaptation have been discussed. The adaptations of agents in response to the safety culture and the variability in the adaptation have been demonstrated using a simple NetLogo simulation experiment. Development of a realistic agent based model requires thorough understanding of construction operations and collection of safety data from construction sites for the various factors discussed in the conceptual framework. Given the fact that the development of construction accident causation models is being actively pursued by safety researchers recently, agent based modeling and simulation technique is one of the suitable alternatives to develop computational models of construction accidents causation.

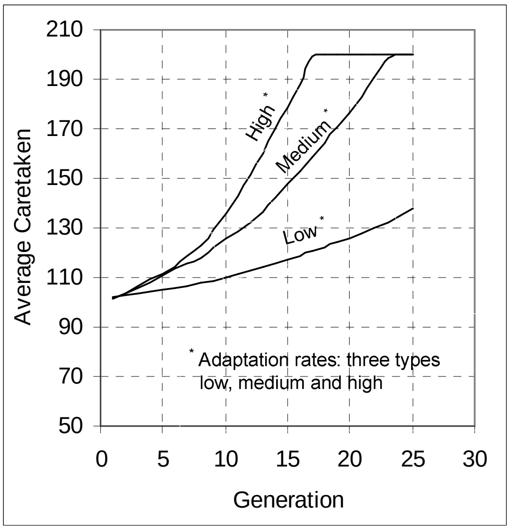

Figure 4: Plot of average care-taken for three adaptation types (Safety Wt: 100, Prod. Wt: 0)

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