Agent-Based Simulation of Labour Emergency Evacuation in High-Rise Building Construction Sites

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ABSTRACT

Construction sites are vulnerable to natural and manmade disasters that impose direct threat to contractor employers. High-rise building projects are more critical in such emergency situations because of the need to evacuate a large number of laborers who are working on the different floors of the building. Occupational safety regulations require general contractors to establish employee emergency action plans that specify emergency evacuation procedures and escape route assignments. These emergency plans are usually evaluated and practiced using real life drills, which face some critical challenges related to egress practicality and changing construction environment, especially in high-rise building construction sites. To overcome these challenges, this paper presents a conceptual agent-based simulation framework that would support general contractors in evaluating labour emergency evacuation plans in high-rise building construction projects. The framework is designed to facilitate: 1) modelling of construction activities workspaces that represent the number and locations of activities crews; 2) representing labour egress behaviour using software autonomous agents; 3) modelling of the physical space and evacuation routes of the building; and 4) evaluating the performance of emergency action plans. The proposed framework should prove useful to general contractors and public safety officials in effectively analyzing emergency action plans.

INTRODUCTION

Construction sites can be subject to a wide array of emergencies and hazards, such as fire, earthquakes, unexpected severe weather conditions, and building collapse (OSHA 2001). Accordingly, these emergency situations would impose dangerous working conditions on the employees that require immediate evacuation. Occupational safety regulations require contractors to prepare emergency action plans to specify employees evacuation procedures and escape route (OSHA 2003). The purpose of these emergency plans is to prevent injuries and fatalities during egress time and accordingly accelerate the resumption of normal construction operations.

The evaluation of construction personnel emergency plans in high-rise buildings is a challenging task. Construction site emergency plans are usually evaluated using real life drills, where all employees are asked to evacuate the building after a false emergency alarm. Nevertheless, the implementation of real evacuation drills in construction projects faces three main challenges: 1) these drills interrupt the
construction schedule and result in remarkable time and cost overheads (Chu 2009); 2) the behavior of the evacuated personnel in the drills doesn’t represent real evacuation situation (Pan et al. 2006-b); and 3) the dynamic environment of the construction site requires multiple drills for different evacuation plans that consider the change in building physical environment and number of labors, which would be infeasible or impossible (Pan et al. 2006-a). Accordingly, this paper presents a conceptual agent-based simulation framework that would help contractors and project managers in evaluating site personnel emergency evacuation over the duration of the project. The paper is organized in three main parts. First, previous models of buildings evacuation and crowd dynamics are reviewed. Second, the proposed agent-based framework is presented with its two main component models. Finally, remaining work and future directions of the proposed framework are reported.

EVACUATION AND CROWD DYNAMICS MODELS
Computational models were developed to simulate people evacuation and crowd dynamics to assess the competence of buildings space design in emergency situations. Although detailed codes of “means of egress” exist, complying with these codes may not ensure occupants safety during emergency evacuation. These standard codes are not designed to consider the unique spatial characteristics of each building (i.e. room shapes and obstacles) and non-uniform flow of occupants through designated escape routes (Hajibabai et al. 2007). Accordingly, a group of mathematical and simulation models were developed to estimate occupants evacuation times considering human behaviors and their physical movement. These models can be classified in three main categories: social forces (particles) systems, cellular automata, and rule-based (agent-based) models.

First, social forces or Helbing’s models (Helbing et al. 2000, Helbing and Molnár 1995) utilize Newton’s theory to describe human crowd behavior that is controlled by socio-psychological and physical forces. Each person in the crowd frequently updates his/her current speed and direction to reach a destination (i.e. exit door) considering a group of social repulsive forces as well as physical interaction forces with other people and room obstacles (i.e. walls, furniture). Despite the success of social forces models in generating realistic crowd phenomena (i.e. queuing, herding, and arching behaviors), they were criticized for the fact that people cannot be represented solely by the laws of physics (Still 2000). The second category of evacuation simulation models utilize cellular automata (CA) modeling (Von Neumann and Burks 1966), which divide building floor into a grid of cells that represent free spaces, walls, and obstacles. Free space cells are only allowed to accommodate one pedestrian, who transit to neighbor free cells based on computed probabilities. Pedestrian transition probability to a cell depends on two main attributes associated to each cell (Burstedde 2001, Nishinari et al. 2003): 1) static field that is computed based on the distance between the cell and the evacuation destination; and 2) dynamic field that represents the virtual trace left behind pedestrians over their path to the destination. CA models were expanded and refined to include friction effects and clogging of evacuees (Kirchner et al. 2003), detections of other pedestrians in local neighborhoods (Narimatsu et al. 2004), and real-coded cellular automata (Yamamotoa et al. 2007). Third, rule-based or agent-based models create a virtual entity for each evacuee and
equip it with behavioral rules that govern the interactions with the other evacuees and the environment (Xiaoping et al. 2009). Agent-based models are more computationally expensive, but it facilitates heterogeneous representation of human. Geometric space and human movement in agent-based evacuation simulation are modeled using either discrete cellular representation (Was et al. 2006, Toyama et al. 2006, Bandini et al. 2006, Pan et al. 2006) or continuous representation (Zarboutsis and Marmaras 2004, Braun et al. 2005, Pelechano et al. 2007).

Despite the contributions of existing models of evacuation simulation models, they are limited to operational buildings that have fixed spatial and occupants’ configurations. High-rise buildings under construction create continuously changing environment where new spaces are constructed, construction crews are changing with project progress, and building spaces are dynamically obstructed by construction temporary facilities (i.e. equipments and material storage).

AGENT-BASED SIMULATION OF CONSTRUCTION SITE EVACUATION

This paper presents a conceptual agent-based simulation of construction emergency evacuation (AB-SCEE) framework, which considers the dynamic construction environment. The proposed framework would support project and safety managers to estimate site evacuation time profile over the construction duration. As shown in Figure 1, the proposed framework consists of two main component models: 1) Building and Construction Environment Representation (BCER) model, and 2) Construction Personnel Evacuation Simulation (CPES) model. The next subsections present these two component models in more details.

![Figure 1. AB-SCEE Framework Architecture](image)

**Building and Construction Environment Representation (BCER) Model**

Building and Construction Environment Representation (BCER) model is designed to acquire all necessary information related to the geometric configuration of the building, construction schedule, 4-dimensional linkage, and construction workspaces. First, building geometry is defined by its major components: floor slabs, columns, walls, rooms, staircases, and openings (e.g. doors). Furthermore, association relationships between these building elements are identified, including the relation between each floor and its rooms as well as the relation between each room and its surrounding walls and openings. These relationships between building elements are required for virtual laborer agents to query surrounding spatial environment. In order to support AB-SCEE users in providing such significant amount of building geometric data, BCER model employs one of the available libraries (IFCEngine, TNO 2009) to parse the IFC (Industry Foundation Classes) file that is exported from
the Building Information Model of the project. Second, project schedule data include construction activities, relationships, material quantities, and crews. These data can be retrieved from existing electronic files of construction schedule that are generated using common commercial software packages. Third, the 4-dimensional linkage data are identified between each construction activity and its related building elements, mainly walls and partitions, the existence of which greatly affects labor evacuation times. Fourth, construction workspace data are identified for each activity to define: 1) work-rooms that would be occupied by labor during the activity’s duration; and 2) the locations and sizes of activity storage areas which represent the long-term and short-term inventories of construction material.

Construction Personnel Evacuation Simulation

The objective of the Construction Personnel Evacuation Simulation (CPES) model is to estimate the evacuation times of construction labor from the building at different times during the project. As shown in Figure 2, on a specific day of the project, CPES model retrieves from BCER model the previously described building and construction environment. Accordingly, the CPES model performs the following preparatory steps for the simulation session: 1) identify all the building elements that are scheduled to be built until the analysis day by considering finished construction activities and their linked elements; 2) generate and randomly position virtual labor agents of each activity in its work-rooms; and 3) position material storage areas of each activity in their identified locations. To this end, the simulation session is ready to be performed by the two main sub-modules of the CPES model: strategic way-finding module and cellular automata maneuvering module. The following subsections describe in more details the design of these two modules.

### Strategic Way-finding Module

Strategic way-finding module controls simulation agents’ navigation through the rooms of the buildings to reach the closest evacuation exit. This module is designed
based on two main assumptions: 1) construction labor (evacuees) are familiar with the building and its rooms as they are involved in the construction activities that occur in different parts of the building; and 2) based on their space familiarity, construction laborers are able to mentally represent building space and identify the best evacuation routes. Accordingly, agents maintain, use, and update a mental map of the building, which is represented using rooms connectivity graphs (Yan et al. 2010), as shown in Figure 3. These unidirectional graphs represent building rooms as nodes, which are connected using edges that represent doors or openings between the rooms. Agents would estimate the evacuation time on a link considering the following: 1) the summation of the distances between the linking door to the centroids of the connected rooms; and 2) the average evacuation speed which would range between 1.0 and 1.5 m/s (Helbing and Molnár 1995, Pelenchano and Malkawi 2008). Accordingly, every agent identifies the shortest path to the evacuation exit considering links estimated times and using Dijkstra’s shortest path algorithm (Dijkstra 1959). For example, labor 1 in room R1 selects the shortest of the two evacuation paths to the staircase: path (R1 – H – C – S) and path (R1 – C – S). Moreover, the simulation agents would be equipped with adaptive learning capabilities to: a) exchange room connectivity graphs between the agents in the same room to share any information regarding blocked openings; and b) update link evacuation times based on experienced congestions or delays. The micro transition and movement of the agents within the rooms on their evacuation paths are simulated in the Cellular Automata Maneuvering Module, as explained in the next section.

**Cellular Automata Maneuvering Module**

The movement of labor software agents within the rooms is modelled using cellular automata approach. Room space is broken down into small cells which can be empty, occupied by only one evacuee, or permanently unavailable to represent obstacles (material or equipment) or barriers (walls). The common size of these cells is 40 × 40 cm, which corresponds to the space occupied by pedestrian in dense crowds and represents the travelled distance with average speed of 1.3 m/s in human’s average reaction time of 0.3 seconds (Burstedde et al. 2001). At these discrete
reaction time steps, each evacuee attempts to move from his/her current location to one of the free cells in the *Moore’s neighborhood* (Tissera et al. 2007), which represents the eight cells adjacent to the current occupied cell, as shown in Figure 4.

Figure 4. Cellular Automata Modeling of Building Rooms and Evacuation

The movement of Agent $v$ to neighbour cells in room $r$ in the way to opening $e$ is controlled by certain transition probabilities ($P_{ij,ek}^{v}$) that are computed based on two main floor fields associated to each cell $(i,j)$: static ($S_{ij}^{v,e}$) and dynamic ($D_{ij}$) fields. First, a static field value ($S_{ij}^{v,e}$) is computed, in the beginning of the simulation, for each pair of cell $(i,j)$ and opening $e$ of room $r$ to represent cells initial attractiveness to evacuees. Accordingly, static fields are computed as the inverse of cells distances to exit doors, which infer that cells closer to the exit would have higher static fields and appear more attractive to the evacuees. As shown in Figure 4, cell’s distance to an exit door is computed as the shortest visible Euclidian distance using a combination of Visibility Graph method and Dijkstra’s algorithm (Nishinari et al. 2003), to consider the obstruction of possible construction storage areas. It should be noted that multiple static fields could exist for a single cell in the case of rooms with multiple doors or openings. Second, dynamic fields represent a virtual trail left by preceding evacuees to be followed by succeeding evacuees, similar to chemical pheromone of insects (Ben-Jacob 1997). Dynamic fields are initialized to zero in the beginning of the simulation sessions and are changing over time to represent two main dynamics: 1) $D_{ij}$ of cell $(i,j)$ is incremented by 1 in time step $t$ if an evacuee from neighbour cells selects and move to cell $i,j$; and 2) dynamic fields are subject to diffusion and decay to mimic the dilution, broadening, and vanishing of the trail, as shown in Equation 1 (Nishinari et al. 2003). Based on static and dynamic fields, normalized transition probabilities are calculated as shown in Equations 2 and 3 (Kirchner et al. 2003).

$$D_{ij}^{D} = (1 - \alpha) (1 - \beta) D_{ij}^{D} + \frac{\alpha (1 - \beta)}{4} \left[ D_{i+1,j}^{D} + D_{i-1,j}^{D} + D_{i,j+1}^{D} + D_{i,j-1}^{D} \right]$$ (1)

$$P_{ij,ek}^{v} = N^{v} \cdot \exp \left( \frac{S_{ij}^{v,e}}{\beta^{v}} \right) \cdot \exp \left( \frac{D_{ij}^{D}}{\delta^{v}} \right) \cdot (1 - \alpha_{e}) \cdot W_{ek}$$ (2)
Where, \(D_{ij}^t\) and \(D_{ij}^{t+1}\) = dynamic field of cell \((i,j)\) at times \(t\) and \(t+1\); \(\alpha\) and \(\beta\) = diffusion and decay constants that range between 0 and 1; \(N\) = normalization parameter of all transition probabilities \(P_{ij}^{E}\) of Moore’s Neighbourhood cells; \(K_D\) and \(K_S\) = sensitivity parameters (any value bigger than 0) of agent \(v\) to static and dynamic fields, respectively. Higher \(K_D / K_S\) ratios (panic degree) result in herding behaviours where evacuees would give more priority to following others than figuring shortest distances to exits; \(n_{ij}\) = cell occupation variables, 1 if occupied by an evacuee, 0 otherwise; and \(W_{ij}\) = cell forbidding factor, 0 for cells occupied by barriers or obstacles, 1 otherwise.

The agents in each room of the building proceed to the chosen target door (based on Strategic Way-finding Module) considering the following simulation algorithm:

1) The dynamic fields (D) of all cells are updated based on diffusion and decay calculation shown in Equation 1.
2) Each agent \(v\) in room \(r\) updates its panic ratio \((K_D / K_S)\) based on evacuees density of room \(r\) (i.e. number of agents in room \(r\) / room \(r\) area). This update is performed based on a defined utility function that correlates higher panic ratios to higher density ratios. Accordingly, \(K_D\) and \(K_S\) values are changed based on the updated panic ratio.
3) Each agent \(v\) in room \(r\) calculates the transition probabilities \((P_{ij}^{E})\) for the movement to neighbour cells using Equations 2 and 3.
4) Each agent chooses a neighbour cell to be the next move target cell \((i,j)^n\), based on the calculated transition probabilities (from step 3) using a probabilistic selection technique.
5) If two or more agents select the same cell, this conflict can be solved considering their transition probabilities to select only one of the competing agents to move to the conflict cell, while the other remain in their current locations, i.e., \((i,j)^{n+1} = (i,j)^n\).
6) Dynamic fields of agents’ current locations are incremented by 1.
7) All agents are moved to their assigned target cells. Occupation variables \((n_{t+1})\) of original and target cells are updated.
8) If an agent reaches an opening cell, update its current room index \(r\) and the new target opening index \(e\) based on the route specified in the Strategic Way-finding Module.
9) Increment time counter \((t = t + 1)\). If all agents exited the building, terminate simulation session, otherwise go to step 1.

**FUTURE WORK**

The proposed simulation framework requires further development efforts which include prototype implementation and performance evaluation. First, an agent-based simulation package, named REcursive Porous Agent Simulation Repast Simphony (Repast-S) package (North and Macal 2007), will be used to implement the proposed framework. Repast-S is a widely used free and open-source agent-based modelling
and simulation toolkit that provides necessary functionalities to create, run, display, and collect data from agent-based models (Crooks 2007). Repast-S is selected for the implementation of the proposed framework because of its user-friendly graphical interface, diverse visualization capabilities (i.e., Geographical Information System, continuous spaces, and grids), rich runtime environment that provide wide array of reporting forms, and flexible development environment that supports various object-oriented programming languages (Java and Groovy). Second, the implemented prototype will be verified and validated to ensure that it performs as intended and correctly represent and reproduce the behaviours of the real world (North and Macal 2007). Verification process will be accomplished by performing logic and code checking; while the prototype will be validated through the use of extensive sensitivity analyses and applications of real-life and hypothetical case studies.

SUMMARY AND CONCLUSIONS

This paper proposes an agent-based simulation framework for the modeling and evaluation of personnel emergency evacuation on high-rise buildings construction sites. The proposed framework is composed of two main component models. First, Building and Construction Environment Representation (BCER) model is responsible for representing and acquiring all necessary data pertaining to building geometry and construction operations. Second, Construction Personnel Evacuation Simulation (CPES) model is designed to model construction personnel behaviors during emergency egress to estimate site evacuation times. Personnel evacuation behavior is modeled on two levels: strategic way-finding to identify shortest evacuation routes, and discrete-time maneuvering in the individual rooms. The end result of the proposed framework is a profile of estimated evacuation times for the dynamically changing environment over the duration of the construction project. After accomplishing future implementation and validation works, the proposed simulation framework should prove useful to contractors and project managers in securing employees safety on their jobsites.

REFERENCES


