Planning Building Renovation Projects for Safe Evacuation Provisions - An Agent-Based Modelling Approach

Roshanak Eftekharirad, Abdelhady Hosny, Mazdak Nik-Bakht*, Amin Hammad
Concordia University, Montréal, Canada

* Corresponding Author mazdak.nikbakht@concordia.ca

Abstract

During building renovation projects, the space is shared between the construction crews and occupants. The construction works change the building layout and movement flow, which increase the occupants' vulnerability, affecting their evacuation behaviour under emergency conditions. Hence, the safety and wellbeing of the occupants should be considered during renovation planning. Accordingly, this paper presents an Agent-Based Model (ABM) co-simulation framework that utilizes workspace management to represent the occupied spaces during construction, and to evaluate their impact on evacuation under fire incidents. This framework was used to evaluate the construction plan alternatives of the 9th floor of Concordia's EV building, resulting in a maximum of 17% delay in evacuation time in one alternative.

Introduction

Renovation projects include reconstruction, rehabilitation and remodelling of existing buildings. They constituted around 30% of the construction expenditures in the commercial and institutional sectors alone (Lee, 2012). The nature of renovation projects makes them harder to plan than new projects due to the additional constraints imposed from the existence of a fully occupational / operational building. Examples of such constraints are: (1) avoiding any unnecessary demolition and maintaining the integrity of existing structure, hence limiting the construction space; (2) adding specialized tasks / equipment to minimize impacts as dust and noise during construction; (3) using limited equipment and resources that can function safely within a building; (4) increasingly complex demolition plan to avoid the interruption of existing operations within the building; and (5) operating and transporting materials at non-regular hours to minimize interruption to the building occupants.

However, the main complexity of renovation projects is planning the construction works, while considering the occupants' safety and wellbeing as the primary objective during the entire project duration. This is critical under both normal and emergency conditions; to ensure minimal disruption and maximum health and survival circumstances respectively. On one hand, the works may deal with flammable or toxic materials, which increase the risk of fire and jeopardize the air quality in a building. On the other hand, the works may block or limit the access to

certain areas, which creates an additional challenge when evacuating the building under emergency conditions. These factors increase the uncertainties, and accordingly, the vulnerability of the occupants in any hazardous incident, such as fire, which is the focus of this paper. By considering not only the physical-spatial limitations, but also psychological factors, our proposed ABM is a genuine contribution to improve the resilience of a building during renovation construction phases.

This research project approaches the problem of construction planning from a safety point of view. In this regard, safe evacuation of occupants is taken as an objective while sequencing construction activities. The framework is designed to evaluate the impact of various construction plans on the evacuation time under emergency conditions. The modelling framework brings together attributes of agents, rules governing their behaviour, and decision models for occupants of an under-renovation building, under emergency conditions. The incidence of fire hazard is introduced to the model and the simulation evaluates the behaviour of occupants during emergency evacuation, under the construction constraints. A comprehensive review of the literature was performed to summarize critical attributes influencing occupants under emergency condition. Specific scenarios for construction operations are defined, while a building is in operation. Then, the requirements of modelling evacuation behaviour in each scenario under emergency condition are set.

Review of related works

Building evacuation modelling is a requisite to emergency planning and associated decision-making. Simulation can help to examine various what-if scenarios with respect to occupant's behaviour and evaluate evacuation strategies.

Several research studies have proposed models for human behaviour and movements, which focus on agents' reactive behaviour using pre-determined static rules or domain knowledge. Recently, there has been an increasing use of intelligent agents in modelling emergency evacuations scenarios (Sharma et al., 2017).

Building Information Modelling (BIM) is used to improve building disaster management by 3D visualization of building physical components. Moreover, BIM is a rich resource of spatial and semantic information that facilitates the design of simulation and data integration. Thus, simulation to study fire propagation and human

safety has been enhanced using BIM (Sun and Turkan, 2019).

Agent-based modelling for evacuation

Previous studies have used three general approaches for simulating indoor evacuation behaviour: (1) coarse networks, (2) fine networks, and (3) continuous networks (Chooramun et al., 2011). The simplest approach to simulate an evacuation scenario is using coarse networks, which represent the space as a network of nodes and arcs. Each of the mentioned methods has its benefits and limitations. Coarse networks can facilitate the model representation and have high computational efficiency because occupants move from segment to segment (e.g. room to room). However, this class of models does not typically include any occupants' behaviours. Fine networks are able to represent a space as a grid of uniform cells, where nodes and tiles usually cover the space of enclosure (Ronchi and Nilsson, 2013). In this method, tracking occupants' locations is improved because each cell can be occupied by one occupant. Using continuous networks for the building space results in an accurate representation as well as the movement and interaction of individual agents (Chooramun et al., 2011). On the down side, however, the computational time of the latter method is more than the other two approaches. Moreover, the increased complexity in the latter method, and the higher level of correlations demanded with the agents' attributes' and behavioural patterns will be an additional drawback for applying continuous network models in practice.

Using numerical simulation is a popular method in the context of building fire and evacuation (Gao et al., 2012; Tan et al., 2015). Ronchi and Nilsson (2013) presented a list of most frequently used building evacuation models. These models include: STEPS (Mott MacDonald, 2011), Pathfinder (Thunderhead Engineering, 2011) buildingEXODUS (Galea et al., 2004), FDS+Evac (Korhonen and Hostikka, 2009) and EXIT89 (Fahy, 1991). Despite differences in the approaches, all these tools are originally designed for modelling high-rise building evacuation. While several studies have conducted simulation for the indoor fire evacuation (Kobes et al., 2010; Luo et al., 2014); they have not investigated the effects of occupants' attributes. Recently, limited studies have focused on occupants' behavioural factors and their impact on the efficiency of building evacuation (Xiong et al., 2017; Eftekharirad et al., 2018). One of the building evacuation models that has the capability of including occupant's behavioural attributes is Pathfinder. Pathfinder is a continuous network that uses two methods: hydraulic model and agent-based model, to simulate the occupants' movements. In this model, the movements of occupants along their path and their interactions with the environment as well as other occupants are defined. In addition, the interactions between vertical and horizontal egress components, such as stairs, elevators, and refuge floors are presented in Pathfinder. (Ronchi and Nilsson, 2013).

Behaviour of agents can be classified in nine general categories consisting of: seek, flee, arrive, pursuit,

wander, path following, cohesion, alignment, and separation (Ogunlana and Sharma, 2014). Each agent has a set of certain behaviours that can be classified in two main groups: (1) physical attributes, and (2) psychological attributes (Trivedi and Rao, 2018). These attributes are affected by the environment, obstacles, and behaviour of other agents.

Evacuation planning for occupants with disability

There is a growing interest in evacuation planning for occupants who have physical or mental limitations (Proulx, 2002; Hashimi and Karimi, 2015; Butler et al., 2017; Gaire et al., 2018). Based on the statistics of Canada in 2017, the number of Canadian persons with disabilities in 10 domains of functioning, such as mobility, seeing, hearing, and mental health is 6,246,640, as shown in Figure 1 (Statistics Canada, 2017).

Canadian Survey on Disability (CSD), estimated around 20% of Canadians aged 15 years and over had limitations in their daily activities, due to one or more sources of disability (Statistics Canada, 2017). Research studies have shown that occupants with physical or intellectual disabilities are at a greater risk for fire-related death and injury. The rate of death and injuries for physically disabled occupants are 8% and 2%, respectively. Moreover, the fire-related death rate of occupants over 65 is more than 18%, and the fire-related injury rate for the same group of occupants is 7% (Hall, 2000). Therefore, disabled people need extra caution during building evacuation. For this purpose, different evacuation strategies have been developed based on the occupants and building characteristics including profile, condition, role, knowledge and experience of occupant, building's architecture, activities and fire safety features in the building (Proulx, 2001; Shields et al. 1998).

Figure 1: Type of disability for persons with disabilities aged 15 years and over in Canada (Generated based on Statistics Canada, 2017).

The evacuation strategy should consider that certain emergency features, such as wayfinding signage, areas of refuge, safe elevators, communication system, and sprinkler systems should be used in the buildings to improve fire safety for all building users, especially disabled occupants. In addition, a variety of evacuation equipment and procedures should be determined based on the nature of each occupant's disability (Proulx, 2002).

For instance, occupants on a wheelchair should be carried down the stairs by using evacuation chairs or sleds when safe elevators are not available during the building fire evacuation.

Construction works in renovation projects

Any typical renovation project would undergo four main stages: (1) dismantling existing systems and relocating them to avoid interruption; (2) demolition of existing structure and removal of debris; (3) construction and transport of new materials; and (4) re-assembly and reconnection to overall building network. As explained above, it is highly possible that the construction crews would block / reduce the usage of public spaces and corridors to utilize the occupied space for any of their activities. Additionally, the occupants are reallocated to different spaces, which shifts the density of the building occupancy, redefining the paths, usage and reliance on the public areas and corridors. The crew movements, space occupation and evolution throughout the construction can be modelled in BIM environment as workspaces in the 4D model.

Workspace modelling in construction is the simulation of the spaces that labour, and equipment use to execute the works alongside the construction of the building in the 4D model in BIM. It identifies four major parameters for any construction activity: (1) the size and crew location for completing the task at hand; (2) the path taken from any pre-defined access points to the task location; (3) the nature of the materials and equipment being used; and (4) the time of execution. Additionally, workspace behaviour can be modelled statically (occupy the same space throughout activity execution) or dynamically (occupy different spaces throughout activity execution) (Hosny et al., 2018). This is performed regularly to optimize construction schedules by adjusting activities' duration and sequencing to ensure maintaining the targeted project budget and schedule under the assumption that all spaces are dedicated for construction only, which is not the case in renovation projects. Nevertheless, by modelling workspaces during construction of renovation projects, the spaces occupied by labour and equipment can be considered as extra physical obstacles that impact occupants' behaviour during evacuation. Moreover, since workspace modelling is done for the entire project duration, the most vulnerable moments with most obstruction are detected and analysed.

Methodology

Figure 2 shows the suggested methodology for developing a construction plan that considers the impact on occupants' evacuation as the objective function. The process is divided into seven steps. The first step is utilizing the BIM environment to study the floor layout considering parameters, such as main exits, main facilities, space functions, corridor widths, occupants' capacity and density, etc. The second and third steps are to identify the construction scope and methods. Identifying the construction scope would entail defining target locations, required activities for each location, budget/schedule requirements, allowed access points to

be used, etc. The construction methods would focus on workspace planning determining the crew size, choice of materials and equipment, work sequencing, suggested access routes to be taken (from the allowed access points to the target location and vice versa). This step is done for each target location separately, producing alternatives for various construction methodologies and route paths.

Afterwards, the fourth step is route analysis, where each suggested route is investigated to check compliance with fire codes and regulations. Step five generates the construction scenarios and step six evaluates them. The alternative scenarios are created based on the number of crews, alternative construction methods available per location, and alternative construction routes (workspace plan). The expected number of scenarios will be the product of: (1) the alternative construction methods for each crew; (2) the alternative sequencing arrangements; and (3) the alternative number of crews assigned to the job.

Figure 2: Construction planning methodology considering occupants evacuation time as the objective function.

Next, the evaluation of scenarios is branched into two parts: (a) route analysis (as in step 4) for activities executed simultaneously at different locations; and (b) a schedule quality check. Referring to previous research regarding formation of metrics to evaluate the quality of a developed schedule, a checklist was developed covering five aspects: (1) acceptable load distribution between crews; (2) satisfying any sequencing constraints (hard and soft) between execution locations; (3) minimal non-productive time wastage for crews resulting from shifting between locations; (4) optimized schedule duration; and (5) minimal cost possible (Moosavi and Moselhi, 2014; Department of Defence, 2012). The concluding scenarios are analysed for fire evacuation in step seven. Fire instances are created at areas of maximum vulnerability, i.e. near the corridors and exit stairs. Then, the results are recorded against the developed physical and behavioural attributes of the occupants. Finally, based on the evacuation time and any additional selection criteria determined by the user (i.e. the construction planner or emergency planner), the best construction scenario will be selected. The detailed implementation and transformation of building information from BIM (i.e. digital model) to the fire evacuation analysis system, highlighted in Figure 2 (i.e. the simulation engine) is explained in the next sections through a case study.

Case study

The 9th floor of the Engineering, Computer Science and Visual Arts Complex (EV Building) of Concordia University was chosen for this case study. The EV building, opened in 2005, is two towers (connected via common corridors) with 17 stories, housing research and graduate teaching labs, administrative offices, art studios, and a fitness and recreation centre. The daily average number of occupants in EV building is 1000, operating 24-hours a day, 7 days a week, with limited access after 23h00 and during national holidays. The 9th floor was selected specifically for its vulnerability owing to its spaces' functions. Spaces in this floor are: 6 Laboratories, 21 student offices, 1 general lab, 8 professor offices, 1 kitchenette, 5 bathrooms, 8 elevators, 2 service elevators, 4 exit-stairs, 2 regular stairs, and storage rooms. All these spaces are connected by one corridor at the lab area, which diffuses into two paths at the student offices as shown in Figure 4. The expected scope of construction work is the complete renovation for the labs (A through F in Figure 3) and routine maintenance work in the corridors of the student offices (the solid line at student office in Figure 4). The access points for the construction crew were the two service elevators (marked with arrows in Figure 4). We made the following assumptions to perform the simulation: (1) the scope of work in all labs are identical, and there was only one possible construction method for the works; (2) the lab with active construction at a time was condemned not operational for occupants until works are completed; (3) to consider the worst case scenarios, renovation in the labs would require a route between (to and from) the access point which would be completely blocked during the entire construction project, and the works had to be done within normal building

operation hours; (4) the renovation works were within the labs' walls at all times and the external / connecting walls between the labs were not demolished; (5) a "renovation crew" with a fixed rate was considered; (6) flame of fire is not propagated due to fire-resistant materials based on our assumption. However, smoke and other products of fire such as toxic gases and heat are spreading; (7) sprinklers do not work during the fire based on our assumption; (8) the elevators are closed during the fire; (9) occupants are evacuated through four main exits; and (10) occupants close all doors of offices and labs after leaving them, except for the one in fire.

In the next step, the route analysis was conducted for each lab, based upon the National Building code of Canada (NBC) and the National Fire Code of Canada (NFC), considering the following: (1) minimal interruption to the neighbouring labs; (2) minimal blockage to the shared facilities (bathrooms, kitchenette) and passenger elevators; and (3) allowing enough corridor width (more than 44 inches wide) for safe travelling (National Research Council Canada, 2016).

Figure 4 shows an example for the route analysis for lab D. As shown, one path would partially interrupt the entrance of Lab F and operation in Lab E; while the other only partially interrupts the entrance for Lab C and hence it was chosen.

Bearing in mind the assumptions detailed above, high level construction schedules were developed, considering renovation works at each lab as one activity. The scenarios were developed so that they allow working on the labs sequentially, or two labs simultaneously. Referring to the developed schedule quality checklist, considering the labs sizes as indication for work, three hard constraints were considered. (1) lab A and B had to have a sequential relation; (2) labs C to F had to have a sequential relation that starts from either lab F or C, and moves the other direction; and (3) the amount of works in labs A and B match the amount of works in labs C through F. Accordingly, the results were eight construction alternatives; four for each crew assignment (sequential / two labs simultaneously). The construction alternatives revealed forty-six route movements. Upon the analysis, it was determined that the four route options shown in Figure 4 cover all the possible route blockages and are the most critical ones (in terms of corridor blockage duration and distance).

Figure 3: Lab D Route Analysis.

As Figure 4 shows four fire instances were created, each near to one exit, and each of the workspaces was tested to

investigate their influence on occupants' behaviour in the evacuation time and probability of occupants' injuries and death.

Building fire and evacuation simulation

The interoperability function of BIM facilitates importing a detailed model of the building (e.g. created in Autodesk Revit) into other software. In the case study, the 9th floor of EV Building was modelled in Revit. Then, the following steps were performed to simulate a building fire and evacuation during different renovation' scenarios in the building as shown in Figure 5.

1. Creating the workspaces based on the different scenarios of renovation in corridors and labs.
2. Changing the format of the BIM model into a readable format for the simulation software. In this step, the Revit model was exported as an AutoCAD file (DWG or FBX format) because both PyroSim, i.e. the fire simulation software, and Pathfinder, i.e. the evacuation simulator, can read these formats.
3. Using a reliable method of changing the format to support all information about materials and textures in the model. There are several methods for importing Revit file to PyroSim and Pathfinder, such as Revit to DWG (or FBX) directly; or Revit to DWG (or FBX) using a third-party plugin. Since the type of material is one of the main factors in fire simulation, choosing a method that produces good results with materials, textures, and texture coordinates is required. Among existing methods, Revit to FBX using third-party plugin performs a perfect conversion that can reproduce the graphical representation of the original Revit file with all information related to materials.
4. Simulating fire scenarios. The BIM model with FBX format was exported in PyroSim as a fire simulator platform. To create a fire, three main steps were taken: (1) creating the mesh; (2) defining the reaction; and (3) creating the fire surface.
 - **Creating the mesh:** For the range of spread of the fire and all Fire Dynamics Simulator (FDS) calculations, the model of building needs to be transferred into rectilinear volumes called meshes. Each mesh includes rectangular cells that have a certain size. The size of cells has an impact on the resolution of the flow dynamics.
 - **Defining the reaction:** To simulate a surface made of heat-conducting solids or a fuel, its thermal properties (e.g. density, specific heat, conductivity, absorption coefficient, etc.) as well as pyrolysis behavior (which is related to the heat of combustion and burning reactions, e.g. heat of reaction, heating rate, heat of combustion, etc.) should be defined.
 - **Creating the fire surface:** Surfaces are used to define the properties of objects by defining heat conduction, specifying the ignition temperature, and giving a vent a supply velocity in the FDS model.
5. Simulating evacuation scenarios— In this step, occupants' attributes, such as the number of

occupants, the initial location of occupants, and occupants' physical / behavioral attributes are defined, as shown in Table 1. Mobility condition has been added in our study, to account for the occupants with "limited mobility", where their movement conditions have been taken into account while simulating the scenarios. Also, egress components (e.g. doors, elevators, stairs, ramps, etc.) are defined in the model for controlling the movement of occupants. Then, all obstructions including furniture (desks or tables) as well as construction workspaces are modeled.

6. Performing co-simulation (building fire and evacuation simulation).

Table 1: Type of occupant's attributes.

Attributes type	
Physical	- Age
	- Gender - Speed
Behavioural	- Size of body - Mobility condition
	- Exit Familiarity - Delay time to start
Others	Number of occupants
	Initial location of occupants
	Role of occupants (Assistant, firefighter, etc.)

Results and discussion

After running the simulation, as shown in Tables 2, 3 and 4, the results of the 24 scenarios (in terms of evacuation time) were obtained. Each fire incident (shown in Figure 3) was tested alone against each workspace route (shown in Figure 5), resulting in 16 scenarios. Then, as reference for comparison and evaluation, the evacuation times for each fire incident, without the influence of construction was measured, giving four more scenarios. Lastly, the impact of the construction workspace without the influence of immediate danger (no fire incident on that floor) on the evacuation times was measured. The scenarios were run on an average of 300 occupants, with a five percent of limited mobility persons at the time of evacuation.

Table 2: Max evacuation time for all occupants.

Fire scenario	Construction scenario				
	None	CS1	CS2	CS3	CS4
None		443.5	419.9	445.1	427.5
F1	480.0	516.1	530.8	513.0	500.5
F2	470.2	494.8	526.3	488.8	518.7
F3	449.2	463.4	529.4	464.8	457.4
F4	460.3	—*	—*	—*	—*

Table 3: Average evacuation time for all occupants.

Fire scenario	Construction scenario				
	None	CS1	CS2	CS3	CS4
None		297.9	291.5	301.5	293.1
F1	319.8	332.0	333.5	330.1	325.3
F2	300.2	323.9	325.8	319.8	326.8
F3	298.6	317.3	339.4	314.4	315.0
F4	305.3	—*	—*	—*	—*

Table 4: StdDev evacuation times for all occupants.

Fire scenario	Construction scenario				
	None	CS1	CS2	CS3	CS4
None		81.7	74.6	82.9	76.4
F1	89.8	99.1	101.2	99.9	91.9
F2	89.2	92.2	97.3	91.6	95.9
F3	79.5	83.7	100.3	85.3	85.0
F4	89.5	—*	—*	—*	—*

*Note: Simulation was not completed because several occupants were stuck.

The results show that initially CS2 provided the least impact to evacuation times when there was no fire incident in the floor. However, when combining the effects of fire and construction, CS2 presented the largest delay to the building evacuation by around 17%. Yet, the alarming results was under F4, where occupants were stuck in the building and could not escape. The simulation indicates that these stuck occupants could have been affected by smoke, heat and toxic gases, which blocked the paths to the exits, keeping them in the building. The number of stuck occupants is shown in Table 5.

It is worth mentioning that F4 presented the most extreme scenario of workspace planning, where the fire started near the only exit with a clear path to it, as the construction workspaces were limiting the access to the other exits. Hence, slower occupants probably realized late that this exit was also block and could not evacuate fast enough due to the overcrowding on the other exits. Consequently, the results of F4 revealed possible overlook that Fire Officers may fall into when approving the construction plan. All the scenarios were acceptable according to the code standards: all occupants had 2 exits, and the clear corridor width was always greater than 44 inches. However, there are not more specifications to the quality of the corridors leading to the exits. Hence, all the construction scenarios were planned on the assumption that occupants at any time would have a clear path for one exit, but limited access to any other exits. The other paths that occupants would use would be passing through the labs & offices, which have narrower corridors due to the existing furniture and narrower connecting doors. Consequently, in F4, people wasted time by rushing first to the clear exit, which was blocked due to the fire. Then, after realizing so, they started using the other restricted paths, which couldn't absorb the mass flow and hence the evacuation was delayed due to the overcrowding.

Table 5: Occupant number based on the scenario.

Scenario	Number of Occupant
F4- CS1	42
F4- CS2	60
F4- CS3	113
F4- CS4	93

Conclusion and future work

This paper proposed an ABM-based co-simulation that uses BIM to improve building fire safety management. By analysing the results of simulation in different combinations of fire and construction workspace scenarios, it was verified that the renovation works

considerably increased the evacuation time under emergency conditions and increased the probability of injuries and casualties. Additionally, the simulation results revealed the risk of developing construction plans that satisfy the minimum fire code requirements without taking into the consideration, the dynamism of interaction between occupants and physical spaces, particularly under the incident of hazards.

The present work demonstrates a proof of concept to the necessity of developing new planning methods (for emergency and construction management), capable of capturing the highly stochastic nature of occupant-space interactions. On the one hand, such methods shall capture the dynamism of physical and spatial attributes of the building, particularly when additional constraints (such as renovation operations) are imposed. On the other hand, they must accommodate dynamic parameters of the human (i.e. occupants and construction crew) behaviour during planning the construction of renovation projects. The solution provided in this paper can help to evaluate the impact of interaction between evacuees' dynamic behaviour and physical limitations imposed by construction projects (which also have a temporal nature), on the performance of safe evacuation under the incidence of fire. The workspace modelling in this study is still preliminary and can advance in future studies. It did not consider the budget as a parameter, and due to the building's layout, only one construction route was determined per location. In addition, it was assumed that the entire location was not operational during construction. Accordingly, the future work will focus on modelling more complex scenarios that would (1) consider duration and budget in the objective function; (2) test for more than one construction method / crew combination / workspace route per location; (3) allow for construction phasing / zoning at each location and not shutting down the entire location at once; and (4) create a feedback loop from the fire analysis results.

Regarding the fire analysis, the future work will include a co-simulation implementation with the following conditions: (1) a fire propagation based on materials and firewalls; (2) a larger scale model that is occupied with large number of occupants that has different attributes; and (3) a sprinkler system being triggered at a specific time. Further, the behaviour of occupants in the mentioned co-simulations will be analysed to improve fire safety management.

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