# Improving Fire Emergency Management Using Occupant Information and BIM-Based Simulation

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## ABSTRACT


## Improving Fire Emergency Management Using Occupant Information and BIM-Based Simulation

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The increasing complexity of buildings has brought some difficulties for emergency response. When fires occur in a building, limited perception regarding the disaster area and occupants can increase the probability of injuries and damages. Thus, the availability of comprehensive and timely information may help understand the existing conditions and plan an efficient evacuation. For this purpose, Building Information Modeling (BIM) should be integrated with three sets of information: (1) occupancy that defines the type of space usage; (2) occupants' information; and (3) sensory data. The Industry Foundation Classes (IFC), as a standard of BIM, has the definitions for all areas, volumes, and elements of a building. IFC also has the basic definitions of sensor and occupant entities. However, these entities do not provide enough dynamic and accurate information for supporting emergency management systems.

In addition to, building renovation projects have effect on evacuation time. During the 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 behavior under emergency conditions. Hence, the safety and wellbeing of the occupants as well as their evacuation time should be considered under emergency incidents.

This thesis aims to improve fire emergency management using occupant information and BIM-based simulation. For this purpose, a "dynamic BIM" for fire emergency real-time

management is developed that captures enough dynamism regarding the building condition as well as environmental conditions and occupants' behavior. Also, an Agent-Based Model (ABM) is used to assist in the analysis of the static and dynamic behavior of the environment and occupants in BIM.

The specific objectives of the research are: (1) extending IfcSensor entity for occupant's sensors; (2) adding new attributes to IfcOccupant to support emergency response operations and defining a new entity for occupancy; (3) defining the relationships between sensors, occupants, occupancy, time series, and building components in the context of building evacuation; (4) creating dynamic BIM for tracking occupants and environmental states; and (5) evaluating the evacuation time for specific scenarios where additional spatio-temporal constraints exist during a fire incidence. Renovation construction operations are considered as such constraint and an ABM co-simulation framework is developed under emergency conditions. The feasibility of the proposed methods is discussed using different case studies.

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# DEDICATION

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## List of Abbreviations

| Abbreviation | Description |
|---|---|
| 2D | Two dimensional |
| 3D | Three dimensional |
| AEC/FM | Architecture, Engineering, Construction, and Facilities Management |
| API | Application Programming Interface |
| BIM | Building Information Modelling |
| BLE | Bluetooth Low Energy |
| BSA | Building SMART Alliance |
| CAD | Computer-Aided Design |
| CSD | Canadian Survey on Disability |
| DEVS | Discreet Event System Specification |
| EV | Engineering and Visual Arts |
| FDS | Fire Dynamics Simulator |
| FED | Fractional Effective Dose |
| ID | Identification |
| IFC | Industry Foundation Classes |
| IoT | Internet of Things |
| NBC | National Building code of Canada |
| NFC | National Fire Code of Canada |
| RFID | Radio-Frequency Identification |

# CHAPTER 1 Introduction

## 1.1 General Information

Building Information Modeling (BIM) is becoming a rich source of building related data. Current models in BIM are developed based on static information. However, to represent the building's real-time information, a dynamic BIM will be required, capable of recording and storing the "state" of building's components, spaces and occupants. Such a dynamic/statful BIM will contain timely and accurate sensory data, which can be extremely helpful for supporting rapid responses to improve emergency conditions. In these conditions, detecting the real-time information of occupants, and the state of building elements and spaces can improve the building emergency management and enhance effective survival services. Integrating these two aspects can support evacuation decisions. In addition, visualizing the real-time information of occupants and mapping them to the building condition can assist first responders to make effective decisions for evacuation planning.

In order to pursue such goals, BIM can be enriched with sensory data related to occupants' information (e.g. ID, location, and time) as well as the environmental hazard conditions. Industry Foundation Classes (IFC), as an open BIM standard, includes IfcSpace and IfcBuildingElement entities, which can be employed to represent physical/spatial components of a building (such as walls, doors, stairs, rooms and exits) as well as their conceptual attributes (such as volume, use, accessibility, etc.). The current IFC 4 version is also offering basic definitions of sensors, time series, and occupant entities under IfcSensor, IfcTimeSeries, and

IfcOccupant, respectively. However, these entities are missing details to provide the desired level of dynamism.

In addition to the above-mentioned approach in context of emergency management, evaluating evacuation time under emergency conditions and renovation projects in the buildings which effects decision making of occupants and first responders. For this purpose, an Agent-Based Model (ABM) co-simulation framework is defined that utilizes workspace management to represent the occupied spaces during construction, and to evaluate their impact on evacuation under fire incidents.

## 1.2 Research Objectives

This thesis aims to improve fire emergency management using occupant information and BIM-based simulation. For this purpose, a dynamic BIM for fire emergency real-time management is developed that captures enough dynamism regarding the building condition as well as environmental conditions and occupants' behavior. Also, an ABM is used to assist in the analysis of the static and dynamic behavior of the environment and occupants in BIM.

The specific objectives of the research are: (1) extending IfcSensor entity for occupant's sensors; (2) adding new attributes to IfcOccupant to support emergency response operations and defining a new entity for occupancy; (3) defining the relationships between sensors, occupants, occupancy, time series, and building components in the context of building evacuation; (4) creating dynamic BIM for tracking occupants and environmental states; and (5) evaluating the evacuation time for specific scenarios where additional spatio-temporal constraints exist during a fire incidence. Renovation construction operations are considered as such constraint and an ABM co-simulation framework will be developed under emergency conditions. The feasibility of the proposed methods is discussed using different case studies.

### 1.3 Thesis Organization

This research is structured as follows:

Chapter 1 *Introduction*: this chapter introduces the research topic and objectives, and presents the structure of the thesis.

Chapter 2 *Literature Review*: this chapter reviews the existing literature on the concepts, methods and standards that are used in the research. The literature review comprises the information about building fire and evacuation planning, BIM technology, Internet of Things (IoT), sensors and sensory data, and fire and evacuation simulation.

Chapter 3 *Proposed Methodology*: this chapter proposes the model for improving fire emergency management using occupant information and BIM-based simulation.

Chapter 4 *Improving Fire Emergency Real-Time Management by Integrating Occupant Information and BIM*: this chapter elaborates on the proposed approach to extend IFC and link sensory data to BIM for fire emergency real-time management.

Chapter 5 *Planning Building Renovation Projects for Safe Evacuation Provisions*: this chapter elaborates on the proposed approach to simulate safe fire evacuation using agent-based simulation during building renovation projects and evacuation in the buildings.

Chapter 6 *Conclusions and Future Works*: this chapter summarizes the present work and concludes the findings.

# CHAPTER 2 Literature Review

## 2.1 Introduction

Statistics show 1,345,500 fires reported in the United States in 2015; out of which, 37.27% are structure fire that have caused 2,685 civilian deaths, 13,000 civilian injuries, and $10.3 billion in property damage (NFPA 2013). During a fire evacuation, the lack of comprehensive information affects the success and efficiency of emergency management and results in increasing the number of casualties (Leite et al. 2009).

Wei-Guo et al. (2006) stated that the availability of core information about buildings and infrastructure systems improves the effectiveness of managing disasters (Wei-Guo et al. 2006). Moreover, Tsai et al. emphasized the need of critical building information, such as building evacuation plans and electrical and mechanical equipment (Tsai et al. 2008). Walder and Bernoulli (2009) emphasized the need for critical spatial information and semantic information related to the structure and equipment, as well as the disaster (Walder et al. 2009). An approach to enable rapid and safe evacuation in building emergencies requires accessing the dynamic information about the buildings, occupants and fire propagation. Building facilities' information includes building's structure; floor plans; location of stairs, ramps, exits, doors and windows; facility's materials; and fire protective equipment. On the other hand, the attributes of occupants are presence, number, location, age, mobility condition, ID, etc. In addition, the required information regarding fire propagation includes sensory data about smoke, heat, and toxic gases.

## 2.2 Building Fire and Evacuation Planning

In disaster management applications, time is one of the most critical factors to decrease casualties and properties' damages. Furthermore, precise information about an incident, structure and human's behavior can decrease the risk of life threats and asset damages (Yang et al. 2009; Tashakkori et al. 2015; Xiong, Q. et al. 2017). Dilo and Zlatanova (2011) showed that the success of emergency response is related to the perception of environmental elements and events (Dilo and Zlatanova 2011). This awareness is directly linked to the dynamic information in the emergency event. Situational awareness about changes in building components' conditions can minimize the uncertainty in finding directions and improve safety (Holmberg et al. 2013). Many studies have focused on network modeling, indoor navigation and route finding based on the shortest path (Kobes et al. 2010; Karas et al. 2012). In addition, some studies have used dynamic data about people, to find less congested paths (Pelechano and Malkawi 2008; Xiong, Q. et al. 2017).

In the context of indoor emergency response, Tashakkori et al. argued that indoor situational awareness helps in effective emergency management (Tashakkori et al. 2015). They used a set of required information for route finding to develop a 3D spatial indoor-outdoor model. However, their solution did not include dynamic information. Tangs and Ren provided a simulation spatial indoor model for fire (Tang and Ren 2012). This model includes static and dynamic information, such as occupants, fire field, and building geometry.

To summarize, a safe fire evacuation depends on an awareness of the static and dynamic features, especially geometric obstacles, smoke spread and occupants' behavior. These features have a critical effect on individuals' decisions and the evacuation process (Tang and Ren 2012). Therefore, the provision of a dynamic indoor emergency spatial model that supports situational awareness for building evacuation is vital. Such a model will cover both static and dynamic information including both occupants' behavior and indoor spatial information (e.g., building's structural layout, and fire propagation).

### 2.3 Building Information Modelling (BIM)

BIM is emerging as a digital representation of a building with the geometric/topological and semantic entities that describe the elements, materials, and relationships between them. Also, highly accurate and detailed data about the current state of building elements can be provided by BIM (Isikdag et al. 2008). BIM-based models include spatial data, semantic, and the component relationships that allow to visualize construction processes through 4D simulation and gives an opportunity to manage cost and time effectively (Eastman et al. 2008). Recently, BIM has been used to improve building disaster management by understanding physical and functional characteristics of objects and visualizing building spatial information in three dimensions (Liu et al. 2015). However, effective fire emergency methods should rely on the real-time and dynamic information (Cheng et al. 2017).

BIM, as the base model of a building, can integrate with sensory data to have real-time information about the disaster and occupants. Consequently, occupants can be guided to safe exits rapidly form risky locations. Kensek (2014) investigated the feasibility of integrating BIM and sensors such as light, $CO_2$ and heat (Kensek 2014). She used Arduino as a single board) computer, Revit Architecture as a BIM software, and Dynamo as a visual programming environment to demonstrate how sensory data could change the 3D model. Also, the changes in the 3D model could be actuated on the physical model.

One of the primary goals of BIM is to provide interoperability between different platforms for data exchange, which is currently achieved by the IFC as a common open standard. This standard is used to share physical and functional features of buildings among stakeholders (Young et al. 2007).

### 2.3.1 Industry Foundation Classes (IFC)

IFC as a platform-independent standard for BIM, is an object-based file format that has been developed by Building SMART Alliance (BSA). IFC is based on a taxonomy standard that describes building ontology (Wix 1999). Besides, IFC can facilitate interoperability in the Architecture, Engineering, Construction, and Facilities Management (AEC/FM) industry (Isikdag et al. 2008). Moreover, IFC as a data standard of BIM has a hierarchical and modular framework consisting different entities. These entities represent tangible components (e.g. walls, doors and windows), as well as conceptual components (e.g. schedules, activities, and spaces). Each entity has common properties (including ID, name, geometry, etc.) as well as relationships to other components (Ma et al. 2011). Currently, the final official version of IFC is IFC4. This version covers eight domains: 1) Architecture, 2) Building Controls, 3) Construction Mgmt., 4) Electrical, 5) HVAC, 6) Plumbing Fire Protection, 7) Structural Analysis, 8) Structural Elements (Liu et al. 2015). Although IFC is an object-oriented building model, modeling all objects related to the building is complicated. Thus, BSA presents an extensible architecture for extending IFC (Motamedi et al. 2016).

### 2.3.2 Extending IFC

IFC 4 contains 1609 entities including objects, attributes and relationships (Xue et al. 2015). This model is an abject oriented approach that can be improved extensibility of the data structure. Thus, new entities and types should be defined according to the overall IFC architecture and shall reuse existing specifications.

There are three mechanisms to extend IFC if the current release does not support a specific need: (1) defining new entities, (2) using proxy elements; and (3) using the property sets (Weise et al. 2009). Among the three alternatives, defining new entities can be the best method to extend the IFC standard because the newly defined entities can be used in the same way as the existing ones (Motamedi et al. 2016). However, adding new entities to an IFC release can only happen after availability of some "proof of concept", followed by long discussions within the Model Support Group of the BSA; hence, does not really fit the aim of research projects (Weise et al. 2009). The other two alternative mechanisms can extend the scope of IFC without changing the schema, although they require additional implementation agreements about the definition of property sets and proxies when they are used to share data with other software. Therefore, the other two alternatives are more practical to meet specific local requirements (Weise et al. 2009; Ma et al. 2011; Motamedi et al. 2016).

Several research projects proposed new objects, entities, and relationships for extending the IFC standard (Weise et al. 2009; Fairgrieve and Falke 2011; Motamedi et al. 2016). However, there is limited research about an extension for occupants. Also, IFC still has challenges to represent the live sensor readings.

## 2.4 Occupant and Occupancy Information

In disaster management, in order to have occupancy-based control, different sensors are used to accurately determine the occupancy of building spaces and the parameters concerning occupants in real time, such as number of occupants in the spaces of the building. Melfi et al. proposed occupancy resolutions at four levels (occupancy, count, identity, and activity) in three aspects (spatial resolution, temporal resolution, and occupancy resolution) (Melfi et al. 2011). A fifth level was suggested by Labeodan et al. for tracking occupants' movement in different zones, as shown in Table 2-1 (Labeodan et al. 2015). The higher level of accuracy in occupancy detection will lead to better decisions improving safety (Shen et al. 2017).

**Table 2-1 Occupancy Resolution in Three Dimensions (Modified from (Melfi et al. 2011; Labeodan et al. 2015))**

| Dimension / Level | Spatial Resolution | Temperoral Resolution | Occupancy Resolution |
|---|---|---|---|
| 1 | Building | Day | Occupancy<br>At least one person in a zone |
| 2 | Floor | Hour | Count<br>How many people are in a zone? |
| 3 | Room | Minute | Identity<br>Who they are? |
| 4 | | Second | Activity<br>What they are doing? |
| 5 | | | Track<br>Particular occupant's movement history across different zones |

Wang et al. (2013) focused on BIM and Discreet Event System Specification (DEVS) for occupancy analysis. In this research, authors proposed a solution of a uniform BIM and DEVS/Cell-DEVS simulation process. For this purpose, they generated initial data files for the DEVS simulator by extracting information from the IFC file ((x, y, z) coordinates of elements, such as outside walls, inside pillar walls, entrance, exit and stair). Then, they built a DEVS simulation model based on collected data. In the simulation part, they used a Cell-DEVS for simulating the visitors moving behavior in three dimensions/ eight directions with different probabilities. As shown in Figure 2-1, each floor is converted to cell network, and each cell represents a square place associated with physical horizontal coordinates. Also, each cell has five state variables: Movement, Phase, Pathway, Layout, and Hot zone.

The result of this research showed that among several properties (coming rate, stairs number, door location/stair, movement direction probability and hot zone), coming rate and stair number had more effect on the occupancy level (Wang et al. 2013).

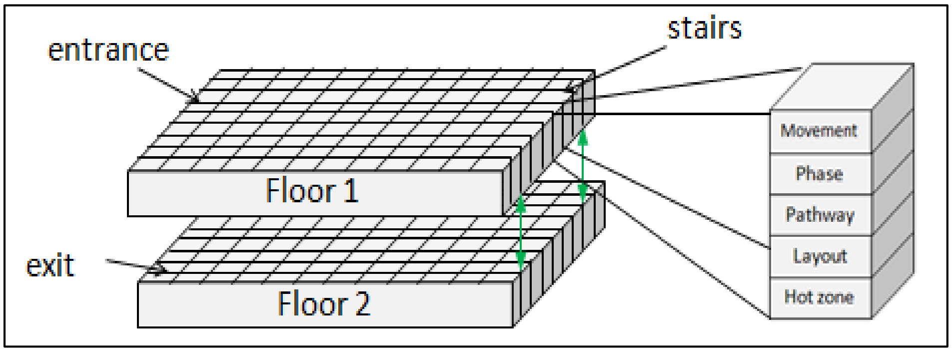



**Figure 2-1. Four-Dimensional Cells (Wang et al. 2013)**

## 2.5 Internet of Things (IoT)

IoT can be defined as a dynamic global network that aims to connect the objects for communicating and interacting with each other and with the human by using internet and computing devices (Fu et al. 2011; Li et al. 2014). IoT is a combination of three paradigms: (1) internet-oriented paradigm (middleware), (2) thing-oriented paradigm (sensors), and (3) semantic-oriented (knowledge). IoT can collect and analyze information to create an appropriate action, or learn from a process based on the three paradigms (Atzori et al. 2010).

There are two main types of device in IoT: (1) sensors that can perceive the objects as well as translate the result into understandable information, and (2) actuators that trigger actions to respond the changes or collected data (Bi and Kang 2014; Li et al. 2014).

Using IoT technologies can be helpful for disaster management, such as fire emergency management. For instance, the prediction of fire is investigated by the sensors' measurements. Then, the information of risk is sent to firefighters (Saha et al. 2017) and other actuators to control the fire.

## 2.6 Sensors and Sensory Data

Integration of BIM and sensor networks for increasing the accuracy and effectiveness of disaster-response decision-making has been discussed extensively in building disaster management (Choi et al. 2014; Cheng et al. 2017).

With the spread of IoT technologies and intelligent buildings, the need for integrating sensors and sensory data with BIM has also increased. Advanced sensors can collect real-time information about occupants, occupancy, surrounding environment and incidents. Among other applications, such sensory data can provide accurate and useful information to support building evacuation planning and emergency response (Shen et al. 2017).

## 2.7 Integrating Real-Time Information in BIM

An intelligent building is a building with smart technologies installation. In such buildings, there is usually a network of sensors and actuators with access to Internet, which can automatically control building components using knowledge-based algorithms and environmental data. For instance, intelligent buildings can monitor occupant's behavior and control building response to decrease energy consumption (Weise et al. 2009).

The first step towards modelling and managing an intelligent building is adding real-time information to BIM because the current BIM uses static information only. A dynamic BIM, which integrates real-time information and BIM, provides the opportunity of reacting to emergencies in real time by visualizing and monitoring the current situation in the building (Chen et al. 2014).

Two different methods have been explored for integrating real-time information in BIM. The first one is using IFC for modifying and updating information stored in a BIM database through sensors. In this method, the format of real-time information gathered through monitoring systems is changed to IFC. Then, the IFC source file can be used for visualization, analysis, and control. In the second approach, the BIM model is linked to an external database of sensory data. The connection between BIM and external database can be created by a third party (such as a visual programming environment). This linkage establishes a real-time bi-directional coordination between as-designed virtual models and as-delivered physical building (Pasini et al. 2016).

Currently, there are several kinds of BIM software (e.g., Autodesk Revit, ArchiCAD, Bentley Building, Solibri, and Vectorworks among other most commonly used tools). Revit is a widely used BIM software for visual analysis, documentation, and design, which also supports IFC. However, these tools can not store and visualize sensory data. To achieve a dynamic BIM with the ability to store and manage real-time information, some add-ins should be developed (Chen et al. 2014).

## 2.8 BIM- Based Simulation

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

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

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 (Boukerche et al., 2009; Wang et al., 2012; Sun and Turkan, 2019).

## 2.9 Evacuation Simulation

Improving the building evacuation modeling procedures can help effective occupant evacuation and efficient decision making. Simulation can be useful for understanding the occupant's behavior and evaluating the evacuation strategies.

Many research studies have proposed different models on human behavior and movement that focus on agent's reactive behavior using pre-determined static rules or pre-determined domain knowledge. However, currently there is an increase in the use of intelligent agents in emergency evacuations scenarios (Sharma et al. 2017).

Recently, BIM has been used to improve building disaster management by visualizing 3D building information. Moreover, BIM is a rich data resource of spatial and semantic information that facilitates the design of simulation, data integration, and analysis support. Thus, BIM can be applied on fire simulation for human safety and property security (Boukerche et al. 2009; Wang et al. 2012; Sun and Turkan 2019).

### 2.9.1 Agent Based Modelling for Evacuation

There are three approaches to characterize the real world in simulation: (1) coarse networks, (2) fine networks, and (3) continuous networks (Kuligowski et al. 2010; 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 (Ronchi and Nilsson 2013). 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' behaviors. Fine networks are able to represent a space as a grid of uniform cells, where nodes and tiles usually cover the space of enclosure (Gwynne et al. 1999; 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.

Using numerical simulation is a popular method in the context of building fire and evacuation (Gao et al. 2012; Ayala et al. 2013; Zhilei et al. 2014; Tan et al. 2015). Ronchi and Nilsson (2013) presented a list of most frequently software tools designed to simulate the building evacuation. These software tools include: STEPS (MacDonald 2011), Pathfinder (Thunderhead Engineering 2011) buildingEXODUS (Galea et al. 2004), FDS+Evac (Korhonen and Hostikka 2009) and EXIT89 (Fahy 1991).

### 2.9.2 Agents Behavior

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; Karas et al. 2012; Luo et al. 2014); they have not investigated the effects of occupants' attributes. Recently, limited studies have focused on occupants' behavioral factors and their impact on the efficiency of building evacuation (Xiong, Q. et al. 2017; Eftekharirad et al. 2018). One of the building evacuation models that has the capability of including occupant's behavioral 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 with 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).

Behavior of agents can be classified in nine general categories consisting of: seek, flee, arrive, pursuit, wander, path following, cohesion, alignment, and separation, as shown in Table 2-2 (Ogunlana and Sharma 2014).

**Table 2-2. Agent Behavior Categories**

| Type of behavior | Description |
|---|---|
| Seek | An agent is directed towards a target position. |
| Flee | An agent is directed away from a target position. |
| Arrive | A variant of seeking where agent decelerates towards a target position. |
| Pursuit | An agent goes after another agent. |
| Wander | An agent randomly walks through the environment. |
| Path following | An agent moves through a series of waypoints. |
| Cohesion | An agent keeps a group of agents together. |
| Alignment | An agent aligns with other neighbor agents. |
| Separation | An agent maintains a comfortable distance from its neighbors. |

Each agent has a set of certain behaviors 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 behavior of other agents.

### 2.9.3 Evacuation Planning for Occupants with Disability

There is a growing interest in evacuation planning for occupants who have physical or mental limitations (Proulx 2002). Based on the statistics of Canada in 2017, the number of Canadian individuals with disabilities in 10 domains of functioning, such as mobility, seeing, hearing, and mental health is 6,246,640, as shown in Figure 2-2 (Statistics Canada 2017).

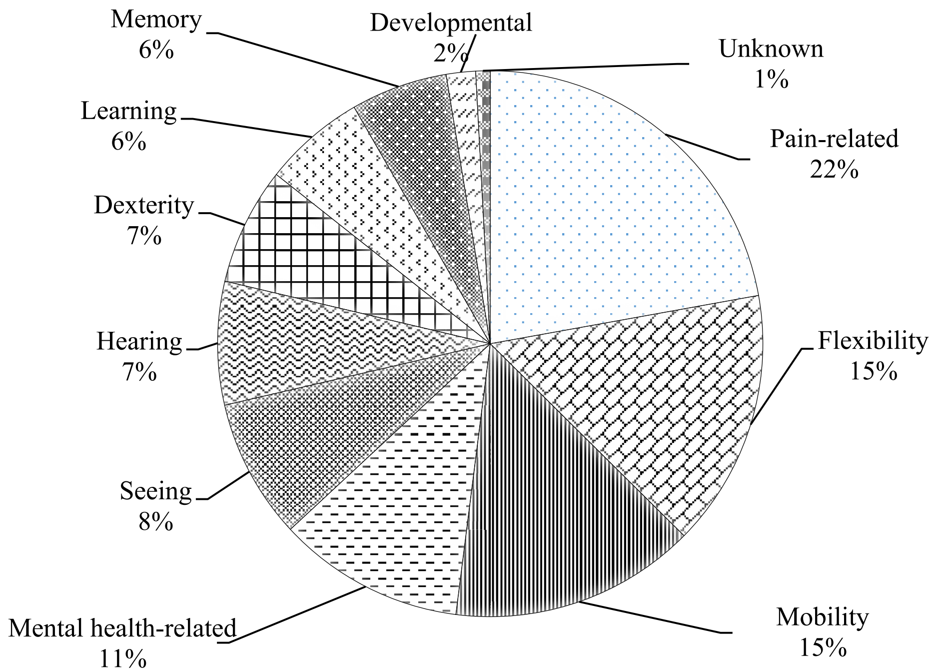



**Figure 2-2. Type of Disability for Persons with Disabilities Aged 15 Years and Over in Canada (Generated Based on Statistics Canada, 2017)**

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 (Centers for Disease Control and Prevention (CDC) 1998; Hall 2000; Shokouhi et al. 2019). 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 (PublicWorks 1981; Shields et al. 1998; Proulx 2001), as shown in Tables 2-3 and 2-4.

**Table 2-3. Occupant Characteristics for Developing the Evacuation Strategy (Proulx 2002)**

| Occupant Characteristics | |
|---|---|
| Profile | Gender |
| | Age |
| | Ability |
| | Limitation |
| Knowledge and Experience | Familiarity with the building |
| | Fire safety training |
| | Other emergency training |
| Condition | Alone vs. with others |
| | Active vs. passive |
| | Alert |
| | Alcohol+Drug – Medication |
| Role | Visitor |
| | Employee |
| | Owner |

**Table 2-4. Building Characteristics for Developing the Evacuation Strategy (Proulx 2002)**

| **Building Characteristics** | |
|---|---|
| Occupancy | Residential (lowrise, midrise, highrise) |
| | Office |
| | Factory |
| | Hotel |
| | Cinema |
| | College and University |
| | Shopping Centre |
| Architecture | Number of floors |
| | Floor area |
| | Location of exits |
| | Location of stairwells |
| | Complexity of space/ Wayfinding |
| | Building shape |
| | Visual access |
| | Balcony |
| Activities in the Building | Working |
| | Sleeping |
| | Eating |
| | Shopping |
| | Watching a show, a play, a film, etc. |
| Fire Safety Features | Fire alarm signal |
| | Voice communication system |
| | Fire safety plan |
| | Trained staff |
| | Refuge area |
| | Elevator |
| | Sprinklers, Smoke control sys., etc. |

The evacuation strategies 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.

## 2.10 Construction Works in Renovation Projects

Statistics show average 2,560 fires in structures undergoing renovation in the United States each year. Fires in structures undergoing renovation have caused annual averages of 4 civilian deaths, 65 civilian injuries, and $108 million in direct property damage (Campbell 2017).

Renovation projects can increase the risk of fire in buildings because of combustible materials and ignition sources used in the renovation works. Moreover, building renovation projects affect the evacuation routes and exits by workers, equipment, materials and other obstructions (Garis et al. 2015).

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. 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.

Workspace modelling in construction is the simulation of the spaces that labor 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 behavior can be modelled statically (occupying the same space throughout activity execution) or dynamically (occupying different spaces throughout activity execution) (Hosny et al. 2013). 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 labor and equipment can be considered as extra physical obstacles that impact occupants' behavior during evacuation. Moreover, since workspace modelling is done for the entire project duration, the most vulnerable moments with most obstruction are detected and analyzed.

## 2.11 Summary and Conclusions

This chapter reviewed the concepts, methods and technologies involved in the current body of research on improving fire emergency management using occupant information and BIM-based simulation.

It is found that comprehensive and timely information related to occupants, occupancy, fire and its products, and building condition is of great importance for the effective emergency management; however, most of the research projects studied safe fire evacuation based on the static models. In this research, a dynamic BIM-based model that covers both static and dynamic information including both occupants' behavior and indoor spatial information (e.g., building's structural layout, and fire propagation) will be generated. Then, a co-simulation including building fire and evacuation simulation will be applied to calculate the evacuation time and to analyze the impact of the fire on occupants with different attributes, under a building renovation project.

# CHAPTER 3 Overview of the Proposed Methodology

## 3.1 Introduction

As explained in Sections 2.2, 2.3 and 2.9, fire emergency management can be improved by using occupant information and BIM-based simulation. In this chapter, an extended IFC model to identify the entities, attributes, and relationships between sensors, occupants, occupancy, time series, and building components will be developed, as explained in Section 3.2. Then, an ABM-based co-simulation that uses BIM to improve building fire safety management will be proposed in Section 3.3.

## 3.2 Extending IFC for Fire Emergency Real-Time Management Using Sensors and Occupant Information

To have a real-time fire emergency management, related information can be classified into two main classes: indoor and outdoor. In both classes, the information at the highest level can be divided into static and dynamic information. To provide the classes with comprehensive data, they should be connected to external databases. For example, occupants' ID can extract more detailed information from the external database, such as age, mobility and health condition. Furthermore, indoor static information can be modeled in BIM as well as dynamic information collected through various sensors, as shown in Figure 3-1. Then, sensory data should be fused with the spatial and semantic information in the BIM platform.

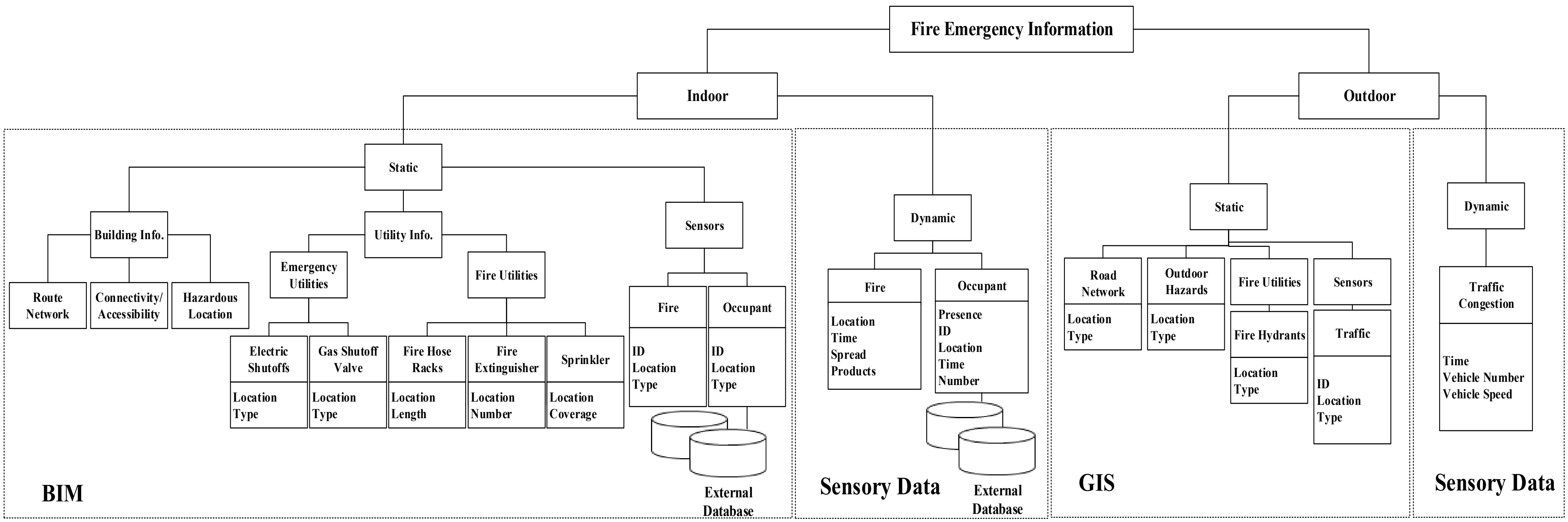



**Figure 3-1. Information Classification in Fire Emergency**

As shown in Figure 3-2, there are two main methods to visualize the real-time sensory data in BIM. The first alternative is creating a link between BIM software tools and sensory data stored in an external database. The link can be created using APIs, plug-ins or add-ins normally offered by software tools. For instance, the occupants' information can be linked to BIM using tools such as visual programming plug-in Dynamo for Autodesk Revit. The output of this method is a real-time model that visualize the sensory data related to fire, building spaces, and occupants. However, the model is not fully semantic. Also, using this method can cause challenges of exchanging the data and interoperability because it is not standardized.

The second alternative is integrating the sensory data, such as the real-time location of occupants, with IFC, as IFC objects. In IFC, basic occupants' infor-mation, such as ID, name, and type of actor are defined in IfcPerson and IfcOccupant classes. How-ever, other detailed occupants' information should be added to IFC. In addition, IfcTimeSeries is an entity for a time-stamped data entries that allows a natural association of data collected over intervals of time (Liebich et al. 2013). This entity does not currently have a relationship with IfcSensor and IfcOccupant. Therefore, defining the new relationships between IfcSensor, IfcOccupant, and fcTimeSeries is needed to facilitate the development of real-time occupant tracking in BIM.

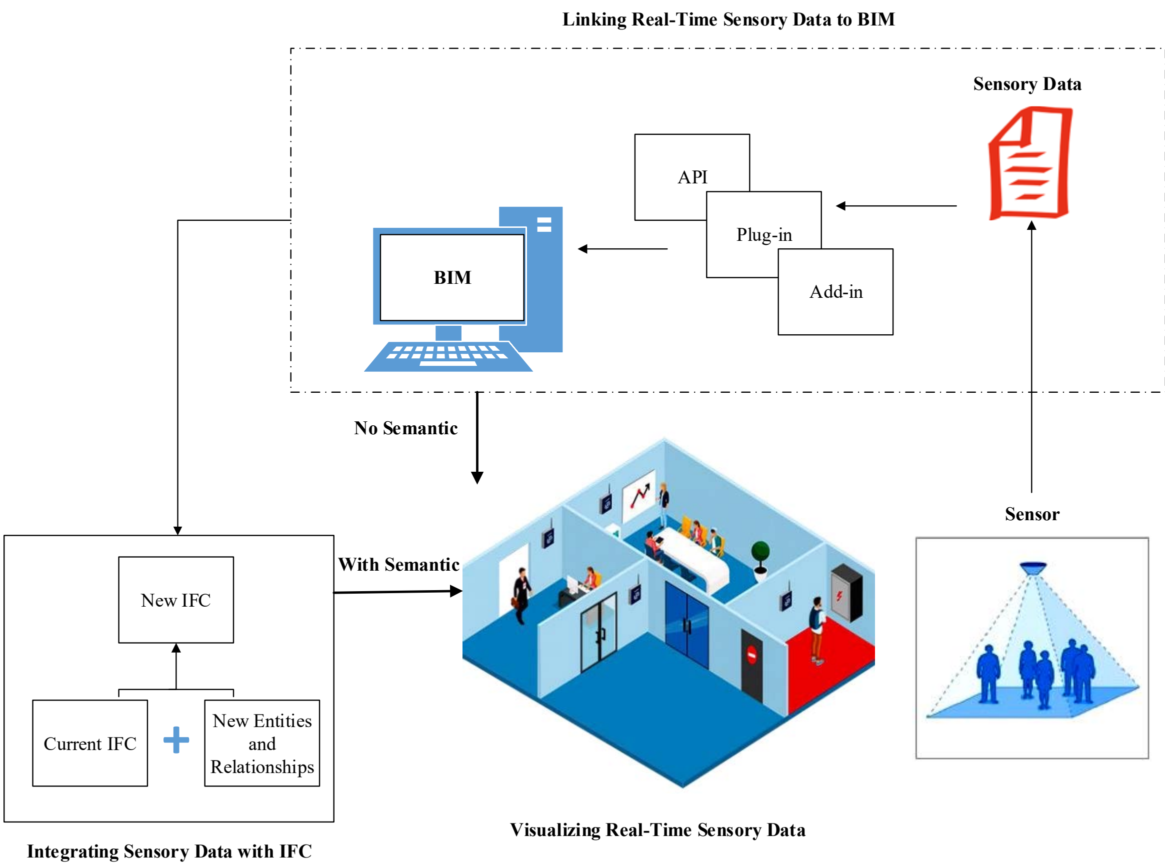



**Figure 3-2. Two Methods for Real-Time Sensory Data in BIM**

Figure 3-3 shows how the BIM model can be overlaid by the real-time information and how datasets can be related to each other. Occupants and fire sensory data can be enriched by connecting to long-term static data. The static data are rarely changed, such as ID, mobility condition, and heath condition. Thus, a comprehensive and real-time dataset containing sensory data and static data can be added to BIM.

After checking the available information in IFC4 EXPRESS diagrams, an extended data model, including the required attributes and the relations, is prepared using the Unified Modeling Language (UML) format.

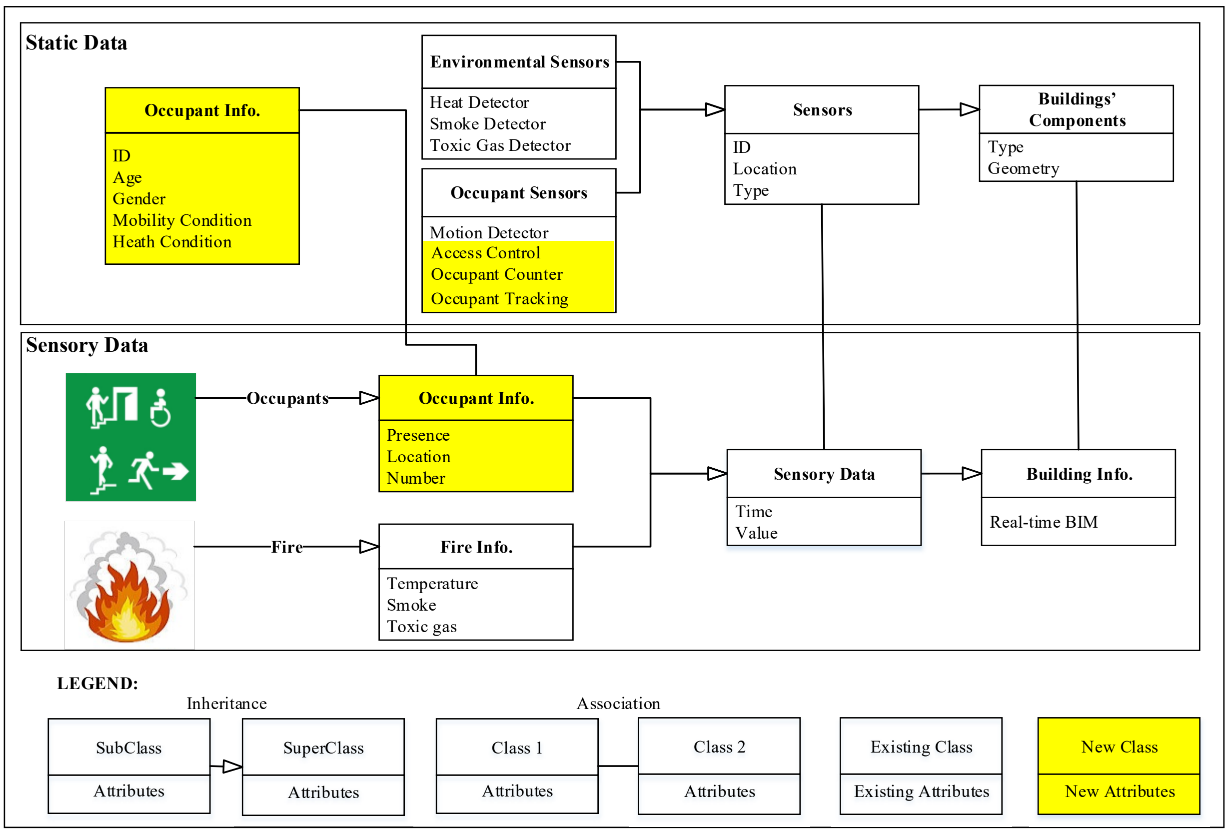



**Figure 3-3. Relationship between Sensory Data and Static Data**

### 3.2.1 Occupant and Occupancy Data

Basic occupants' information, such as name and type of actor are availble in IfcOccupant. However, the following detailed occupants' information should be added to IfcOccupant: (1) ID; (2) age; (3) location; (4) mobility condition (e.g., wheelchair users); and (5) health condition (e.g., occupants with heart and breathing problems need special help). In addition, the occupancy of a space can be defiend at a lower spatial resolution. For this purpose, a new entity, IfcOccupancy, is defiend with the following attributes: presence of occupant and number of occupant. Figure 3-4 shows the relationships between existing and new entites.

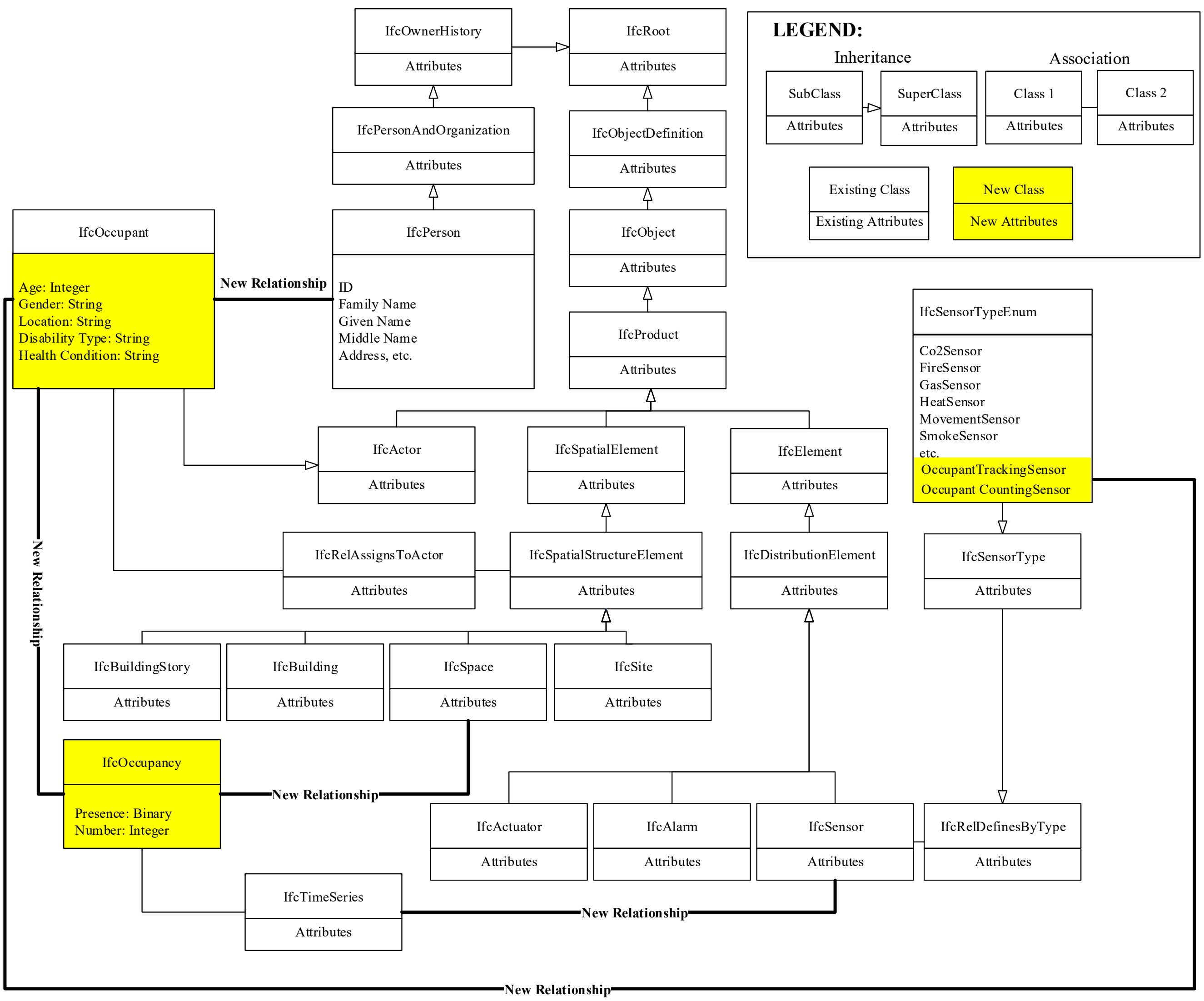



**Figure 3-4. Data Model for Sensor Types and Building Occupants' Information**

### 3.2.2 Sensors and Sensory Data

Using sensors helps to have awareness about the surrounding conditions (BuildingSMART 2018). The following relationships should be captured and modeled: (1) the relationship between sensors and building physical/conceptual elements, (2) the relationship between sensors and sensory data expressed by time series, and (3) the relationship between sensory data and occupants' information.

In the current version of IFC, the geometry and definition of all types of spaces (e.g., room spaces) are described by IfcSpace entity. IfcSpace represents a bounded area or volume that provides a certain function within a building. Also, definitions of building elements, such as walls and ceilings, are described by IfcWall and IfcCovering. Furthermore, some mechanical and electrical devices, such as sensors and actuators are available. The sensor is defined as IfcSensor and the sensor type is defined by IfcSensorType, such as gas sensors, temperature sensors, and fire sensors. The static properties relating to the IfcSensorType are defined by the IfcPropertySet. Each property set includes common attributes, such as name, usage, materials, ports, composition, assignments, and representations (Isikdag et al. 2008).

To define the dynamic information for the sensors, sensory data should be measured in real-time. IfcMeasureValue is defined to keep different types of measured values, such as volume, time, ratio, mass, count, and area. Also, in order to collect real-time data, IfcTimeSeries entity can be used. This entity describes a set of time-stamped data entries and allows a natural association of data collected over intervals of time (IFC4 2017; BuildingSMART 2018). Creating a relationship between IfcSensor and IfcTimeSeries provides a dynamic BIM.

Various types of sensors are defined in IfcSensorType. However, sensors for counting the number of occupants (OccupantCountingSensor) and sensors for determining occupants' location (OccupantTrackingSensor) are proposed by this research to be added. Adding these sensors to IFC and defining a relationship between sensors and time series can help to have dynamic occupants' information in the context of disaster management.

### 3.3 Planning Building Projects for Safe Evacuation Provisions - An Agent-Based Model Approach

Figure 3-5 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, and 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.

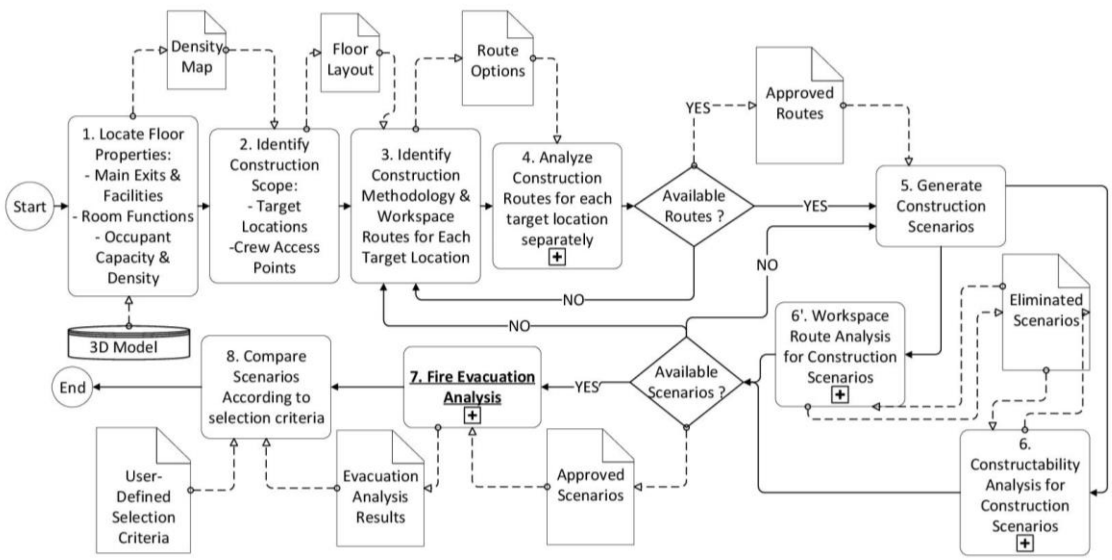



**Figure 3-5. Fire Evacuation Analysis for Workspace Planning**

Next, the evaluation of scenarios is branched into two parts: (1) route analysis (as in step 4) for activities executed simultaneously at different locations; and (2) 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). The concluding scenarios are analyzed 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 behavioral 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 3-5 (i.e. the simulation engine) is explained in the section 5.3.

### 3.4 Summary and Conclusions

For BIM-based fire evacuation planning, several relevant elements along with their common attributes have already been introduced in IFC (e.g., actuators, sensors and occupants). However, creating smart disaster-response decision-making applications requires enhancement of the current standard in at least two major directions. Firstly, to migrate from a static (stateless) to a dynamic (state-full) BIM by adding the sensory data history and associating it with the elements of BIM. Secondly, since having access to comprehensive and accurate data is critical in disaster management, the attributes of some entities (such as IfcSensor and IfcOccupant) need to be enriched and also relationships among such entities must be established. Therefore, a model was proposed that includes: (1) extending IfcSensor entity for occupant's sensors; (2) adding new attributes to IfcOccupant to support emergency response operations and defining a new entity for occupancy; and (3) defining the relationships between sensors, occupants, occupancy, time series, and building components in the context of building evacuation, as explained in Section 3.2.

In addition, the safety and wellbeing of the occupants should be considered during renovation planning because the construction works change the building layout and movement flow, which increase the occupants' vulnerability, affecting their evacuation behavior under emergency conditions. Accordingly, an 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 presented in Section 3.3. This framework was used to evaluate the construction plan alternatives and evacuation time in a building.

# CHAPTER 4 Improving Fire Emergency Real-Time Management by Integrating Occupant Information and BIM

## 4.1 Introduction

As explained in Section 2.3, BIM is becoming a repository of building related data. To represent the building's real-time information, a dynamic BIM for recording and storing timely and accurate sensory data of building's components, spaces and occupants is required. Such a dynamic BIM can improve the building emergency management and enhance effective survival services in emergency conditions. In this chapter, it is proposed to link sensory data to BIM, using the IFC standard, to capture, record and up-date the state of building elements, spaces and occupants. For this purpose, an extended IFC model to identify the entities, attributes, and relationships between sensors, occupants, occupancy, time series, and building components are proposed, as explained in Section 3.2. Two case studies to highlight the feasibility of the proposed model are presented (Section 4.2.4).

## 4.2 Extending IFC for Fire Emergency Real-Time Management Using Sensors and Occupant Information

Smart buildings use sensors to measure the parameters that indicate the conditions related to the buildings, such as building assets, occupants, and incidents. In emergency conditions, the timely critical information measured by sensors can decrease the fatalities and damages. For instance, when a fire occurs in the building, having access to real-time information for occupants' location, fire propagation and dangerous zones can increase the awareness of occupants and first responders. Consequently, the building can be evacuated effectively and efficiently.

Recently, there has been an increase in the use of sensing technologies and the IoT in the construction and building management industry. Thus, the construction industry deals with large volumes of sensory data (also known as "Big Data") to support decision making (Bilal et al. 2016; Delgado et al. 2018). However, several challenges limit an effective use of data (including compiling, organizing and analyzing) in the construction and building management domain.

As explained in Section 1.1, sensors as hardware specifications can be mapped by existing standards, but there is a limitation to map the sensory data. The limitations are: (1) BIM is mainly used for design and construction phases (Becerik-Gerber et al. 2011). (2) BIM cannot store and manage the large data sets. (3) Updating models based on sensory datasets is not possible by BIM (Delgado et al. 2018). Therefore, current research efforts have been focusing on linking sensory data with BIM (Chen et al. 2014; Delgado et al. 2015; Delgado et al. 2016; Delgado et al. 2018) to have a dynamic BIM (Cahill et al. 2012; Abrishami et al. 2014; Agdas and Srinivasan 2014; Volkov and Batov 2015; Park and Cai 2017).

In the context of an emergency condition, the changes of the information related to the occupant, occupancy, fire and building components must be captured, analyzed and visualized in real-time or near real-time.

### 4.2.1 Linking Sensory Data to BIM

Several studies have tried to visualize the changes sensed in a facility, through BIM and by the aid of colors, adding charts, or even animations. For instance, Chen et al. (2014) offered an approach to connect the sensory data to a BIM model. They graphed changes of temperature sensed by sensors locations on a bridge deck (Chen et al. 2014). Also, Delgado et al. (2018) presented a bridge monitoring system including fiber optic based strain sensors to monitor the structural performance. A dynamic BIM environment for structural monitoring was suggested that enabled displaying the dynamic strain response of main girders in a bridge under trains load. In this work, the collected data (including the strains and stresses) were visualized by using colors and charts in several time steps. Moreover, they partially developed the IFC for defending the fiber optic sensors for structural health monitoring (Delgado et al. 2018).

Similarly, Attar et al. (2011) proposed a model to combine BIM with sensors for the captured data of occupant-centric performance in a building. They mapped the sensed values of temperature by color coding, and those of light sensors through charts. Also, they provided a user-friendly interface to communicate with different stakeholders. However, the output of the mentioned research study is not a fully semantic BIM (Attar et al. 2011).

Since BIM is originally a static information source of building data, using it to react to emergencies in a timely and effective manner is a challenge. Also, BIM software tools are initially developed for the design and construction phases and lack capabilities to record and use sensory data. As an example, most of the software tools and IFC editors commercially available fail to accurately process/interpret data stored as IfcTimeSeries. In response to this gap, several studies have addressed some of the limitations by developing dynamic BIM (Ajayi et al. 2014; Srinivasan et al. 2014; Al-Shalabi and Turkan 2015; Francisco et al. 2018). To implement a dynamic BIM, the real-time information, such as data received from various types of sensors should be infused in the current static BIM. For this purpose, two main approaches have been suggested: (1) creating a stand-alone application; and (2) developing a plug-in or add-in to the BIM software (Delgado et al. 2018).

In the first approach, a dynamic BIM is developed as a stand-alone application that does not require another software to run in parallel. This option can provide more capabilities to BIM, although it needs considerable programming experience and it is time-consuming (Delgado et al. 2018).

In the second approach, the capabilities of the current BIM are expanded by using APIs (Application Programming Interfaces) to add additional features to the software. For instance, a dynamic BIM was developed by using a Revit's .NET API.

Although the two approaches can be used for visualizing the information of changes in sensory data, such as temperature, strain, light, and $CO_2$, they have some limitations to demonstrate the changes in the fire and occupants' attributes, such as location. The methods are not fully semantic BIM and they do not facilitate data exchange because the generating models are not compliant with IFC.

### 4.2.2 Extending IFC

As explained in Section 2.3, providing Interoperability between different platforms for exchange of information is one of the main high level goals of BIM. IFC standard currently contributes to achieving such goal. IFC is an open standard developed by BuildingSMART to share physical and functional features of buildings among stakeholders and various platforms (Liebich et al. 2013). IFC has a hierarchical and modular framework containing different entities with the different attributes. Also, there are several relationships between the entities to model data related to different phases of building life cycle (Ma et al. 2011).

IFC specifications can be extended to describe new use cases (Akinci and Boukamp 2003; Zhiliang et al. 2011; Motamedi et al. 2016; Eftekharirad et al. 2018). For example, there are extensions for infrastructures assets, such as IFC Bridge, IFC Road, and IFC Tunnel. However, there are few research projects that extended the IFC (Weise et al. 2009; Fairgrieve and Falke 2011; Motamedi et al. 2016; Eftekharirad et al. 2018). Also, extending IFC for emergency management to represent the live occupants' sensory data (e.g., occupant's location) has not been yet explored.

With regards to real-time monitoring in the emergency condition, IFC has some main entities, such as sensor, occupant and time series. However, new entities and relationships should be identified to consider the challenges of real-time monitoring. Those challenges are: (1) size of data, (2) accuracy of sensory data, (3) data storing, and (4) data interoperability with existing formats (Gerrish et al. 2015).

As explained in Section 2.3.2 , three mechanisms can supposedly extend IFC: (1) defining new entities; (2) using proxy elements; and (3) using property sets. Extending the IFC through the first method can be considered the best option, because the new entities can be used in the same way as the existing ones; however it normally takes a long time for the new entities to be approved by Model Support Group of the Building SMART Alliance BSA (Weise et al. 2009).

The other two alternative mechanisms are more practical because IFC can be extended without changing its schema. However, they require additional implementation agreements about the definition of property sets and proxies when they are used to exchange data with other software (Weise et al. 2009; Zhiliang et al. 2011; Motamedi et al. 2016).

### 4.2.3 Proposed Approach

As explained in Section 3.2, the sensory data related to occupants, occupancy, fire and building components should be integrated with IFC. First the sets of information are defined in the existing entities of IFC, such as IfcPerson and IfcOccupant classes, and then the more detailed information as new attributes for the IFC entities should be added. Besides, the new relationships with different entities, such as IfcTimeSeries and IfcSensor, and IfcTimeSeries and IfcOccupant should be defined to have access to real-time data collected by the sensors. Furthermore, the mentioned new relationships can be facilitated the real-time fire emergency in BIM.

### 4.2.4 Implementation and Case Study

In order to implement the proposed method in Section 3.2 , two case studies are designed. In the case study, the 9$^{th}$ floor of the EV (Engineering and Visual Arts) building and a students' lab at Concordia University were chosen as experimentation area. Then, different types of sensors, including smoke detectors, temperature sensors and occupant's sensors, installed in the facility were used to collect sensory data of fire and occupants.

In the first case study, collected sensory data from Siemens-Room Temperature Sensor was used to test the proposed method for extending IFC. Then, a fire was simulated based on the assumptions in the floor as well as the fire propagation. In order to data acquisition and modeling, temperature measurement based on date and time were collected by temperature sensors installed in each room and corridor. The floor was modeled in Autodesk Revit Architecture 2018. Sensors were added to Revit under the electrical category (as shown in Figure 4-1). Then, the model was exported to IFC format.

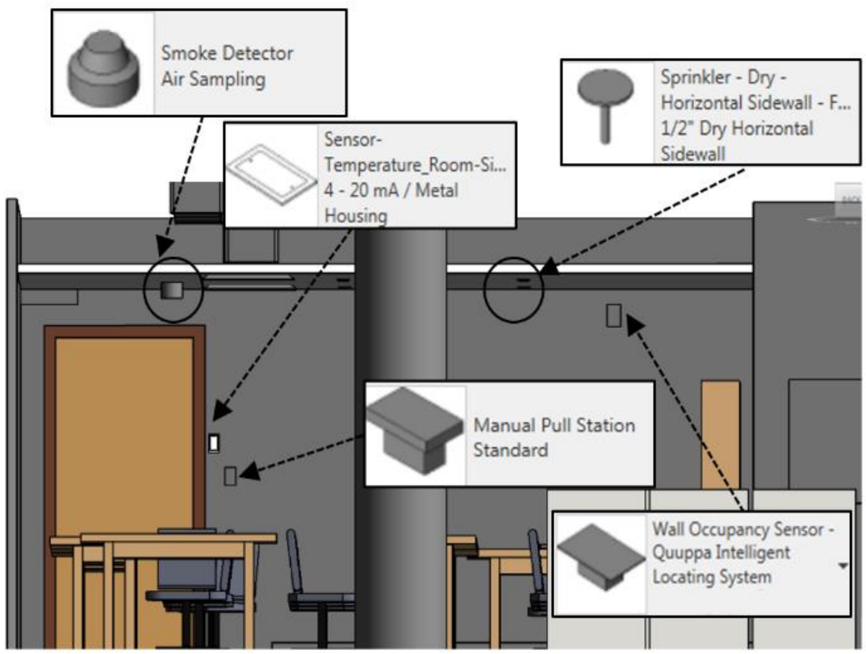



**Figure 4-1. Revit Model of a Students' Lab**

In the IFC format, new attributes and relationships for sensors and occupants were added to the EXPRESS file, based on the IFC4 standard. Then, the modified IFC model was viewed by BIM Vision as a freeware IFC model viewer that enables users to work on the file in the format IFC4.

In order to visualize sensory data in BIM as well as linking sensory data to the Revit model, the visual programming tool Dynamo was used. The following steps were taken: (1) modelling 9th floor of the EV building, (2) assigning a number to each space; (3) defining parameters of the model, such as temperature and spaces for visual programing; (4) classifying the space temperature as shown in Table 4-1; (5) assigning a certain color to each class of temperature; and (6) visualizing the color of the space automatically based on the temperature classification on the Revit model.

Figure 4-2 shows the condition of spaces on the floor. Occupant information can be visualized in a similar way.

**Table 4-1. Space Classification Based on Temperature (Thompson 2018)**

| Temperature (°C ) | Zone Color | Condition |
|---|---|---|
| $T < 37$ | Green | Very safe |
| $37 \leq T \leq 43$ | Yellow | Safe |
| $48 \leq T \leq 55$ | Orange | Near dangerous |
| $T > 55$ | Red | Fire/ dangerous |

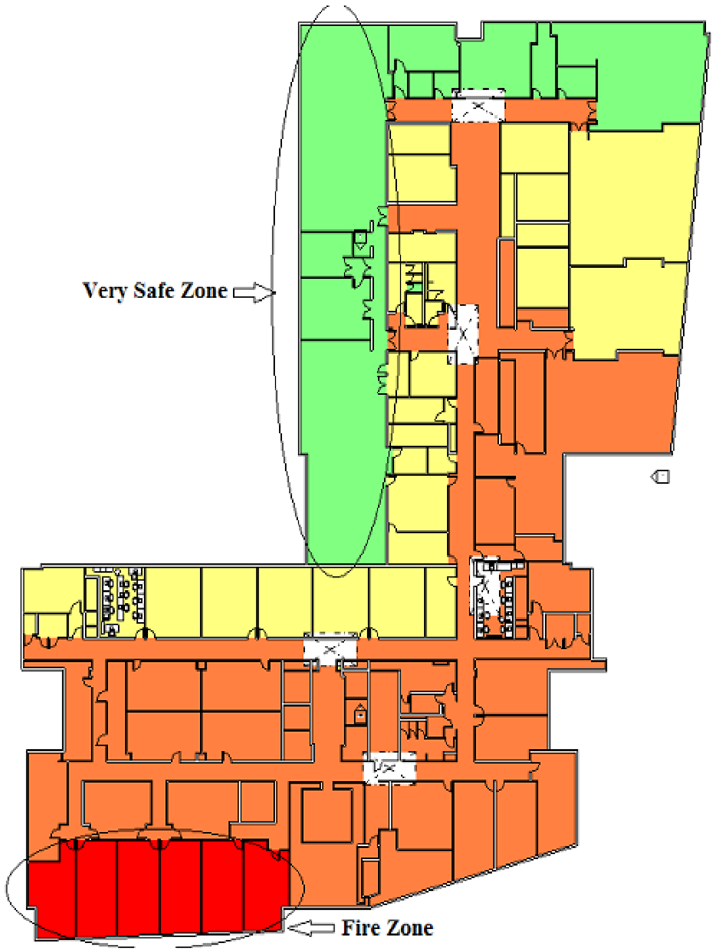



**Figure 4-2. Space Classification Based On Temperature in Revit**

In the second case study, a shared office for graduate students on the 9th floor of the EV building was chosen. To collect the real-time sensory data of the occupants' locations, a Quuppa Intelligent Locating System was installed at the office. Quuppa system uses Bluetooth Low Energy (BLE) technology to gather the real-time tracking data, such as ID, date/time and X-Y-Z coordinates with accuracy of 50 centimeters. The area in which case study carry out, there were no privacy issues for collecting the data by Quuppa because the data were used for the research project.

A fire alarm went on in EV building on April 24th, 2018 at 3:10 PM (false alarm). The locations of occupants in the office were tracked using Quuppa system and the data were stored as time series. The mentioned data were linked to the 3D model of the office (created in Autodesk Revit Architecture 2018). For the linking and visualizing the occupants' locations, the following three main steps were taken: (1) adjusting the office model to Quuppa system; (2) defining the time, occupants' locations and occupants' attributes including ID and mobility limitation; and (3) visualizing the dynamic model.

Firstly, the coordinate system of the 3D model was changed to match the local coordinate system used by Quuppa. The information of three different occupants was then added to the model, as shown in Figure 4-3.

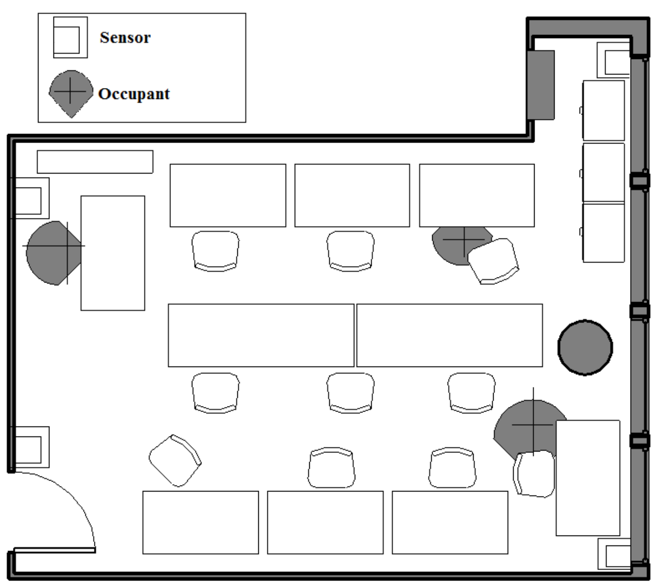



**Figure 4-3. Revit Model of the Office and Three Occupants' Locations before the Fire Alert**

Secondly, the real-time locations of occupants were visualized in BIM by developing a Python scripts in Dynamo. Dynamo, as a visual programming plugin, helped to link the sensory data of Quuppa system to Autodesk Revit. In Dynamo, the following steps were followed: (1) the Excel file containing occupants' data was selected. This file has several parameters including ID, date/time and X-Y-Z coordinates, and health condition of occupants. (2) A certain color and shape were assigned to each occupant. (3) A relationship between location point (X-Y coordinates) and each occupant was defined. (4) ID, time, and disability conditions of occupants were defined using the Python script in Dynamo. (5) A filtering system was generated in Revit, using Dynamo, to filter occupants based on their attributes (such as age, gender, and most importantly, disabilities and physical conditions). The filtering system can be particularly helpful to the first responders to facilitate finding the location of disabled occupants. (6) The real-time tracking of the occupants was automatically visualized during the fire in both 2D and 3D views as shown in Figures 4-4 and 4-5. These figures show the locations of three occupants that were present in the office. The 3D model can be used to find the real-time condition of occupants. For instance, firefighters can find the occupants who are injured and/or laying down on the ground under the fire products such as heat, smoke and toxic gases.

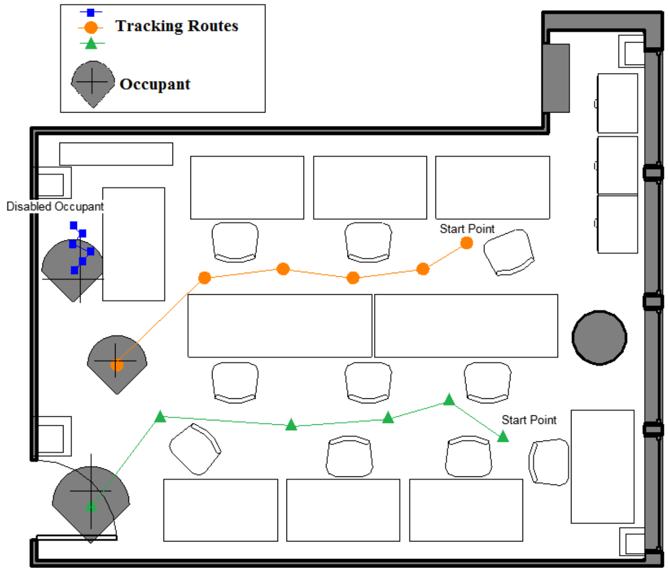



**Figure 4-4. 2D View of Tracking the Occupants, Evacuating the Office during the Fire Alert**

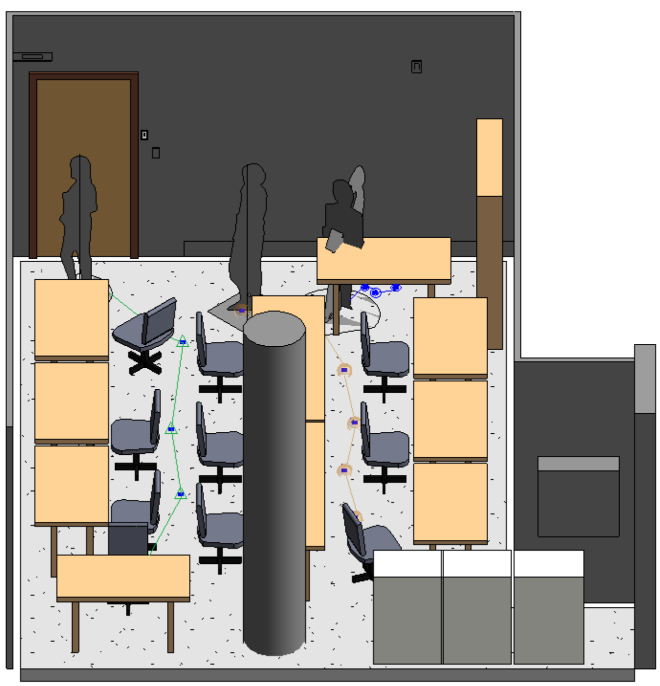


**Figure 4-5. 3D View of Tracking the Three Occupants' Locations at the 6th Second of the Evacuation**

## 4.3 Summary and Conclusions

This chapter elaborated on the motivations and needs of new types of occupants' sensors and new occupants' attributes to have comprehensive real-time awareness in case of a fire in a building. An extended IFC model was developed to identify the entities, attributes, and relationships between sensors, occupants, occupancy, time series, and building components. The proposed model was tested in two case studies. The first one is a hypothetical case study that temperature data were added to BIM for visualizing the space conditions under a fire. The second case study is linking the occupants' sensory data to BIM and visualize real-time occupants' tracking under a fire.

The proposed method was effective in providing real-time information for effective fire emergency management. Moreover, this work can be used to enhance the emergency first responders' perception by using 3D visualization of the dynamic conditions of the building under fire and occupants' condition.

# CHAPTER 5 Planning Building Renovation Projects for Safe Evacuation Provisions - An Agent-Based Model Approach

## 5.1 Introduction

Several studies have represented that building features and lack of space increase the risk of fire-related injuries and damages (Istre et al. 2001; Xiong, L. et al. 2015; Shokouhi et al. 2019). Renovation projects as the constraints can increase the risk of fire in buildings due to the two main reasons; (1) combustible materials and ignition sources are used in the renovation works; and, (2) evacuation routes and exits are changed or blocked due to the workers, equipment, materials and other obstructions.

Renovation projects include reconstruction, rehabilitation and remodeling 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. 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 chapter. 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 behavior, 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 behavior 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 scenario scenarios for construction operations are defined, while a building is in operation. Then, the requirements of modelling evacuation behavior in each scenario under emergency condition are set.

## 5.2 Methodology

As Explained in Section 3.3 a methodology for developing a construction plan that considers the impact on occupants' evacuation as the objective function is suggested.

The detailed implementation and transformation of building information from BIM to the fire evacuation analysis system (i.e. the simulation engine) is explained in Section 5.3 through a case study.

## 5.3 Case Study

The 9$^{th}$ 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 center. 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 9$^{th}$ 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 5-1. The expected scope of construction work is the complete renovation for the labs (A through F in Figure 5-2) and routine maintenance work in the corridors of the student offices (the solid line at student office in Figure 5-1). The access points for the construction crew were the two service elevators (marked with arrows in Figure 5-1).

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 due to having a worst-case scenario; (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 neighboring 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).

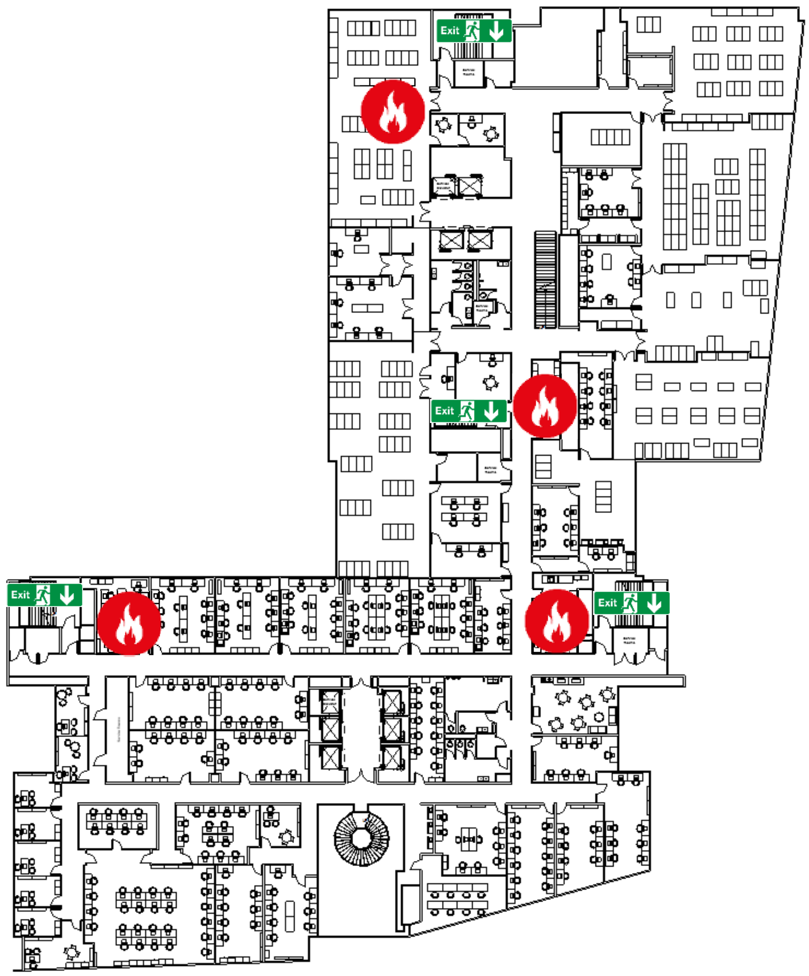



**Figure 5-1. 9$^{th}$ Floor Plan of EV Building With Fire Locations**

Figure 5-2 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.

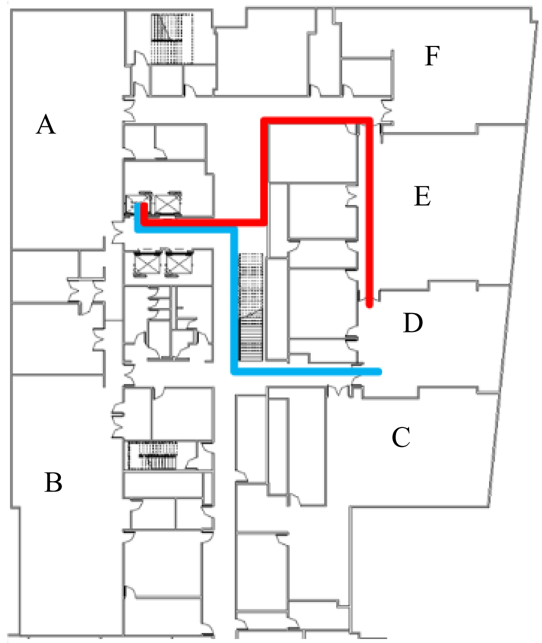


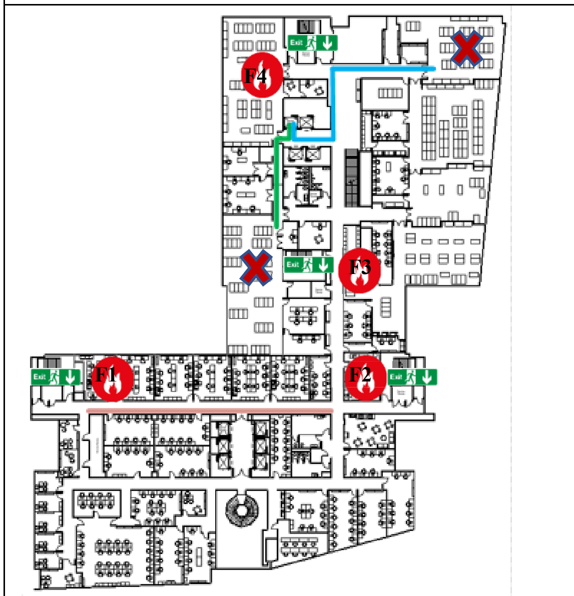

**Figure 5-2. Lab D Route Analysis**

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).

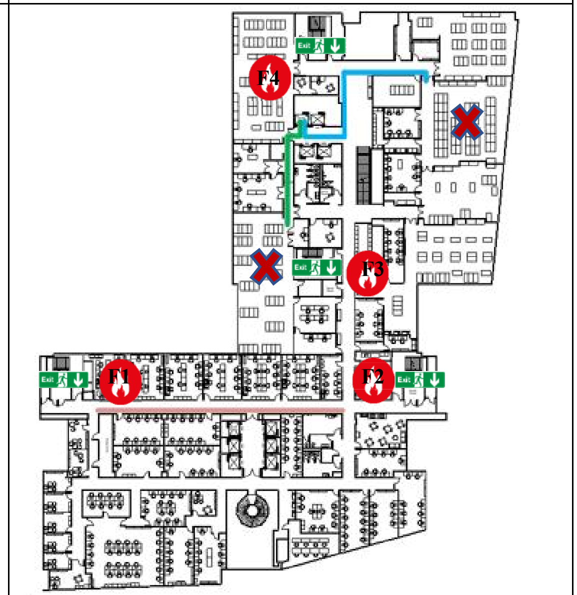
The construction alternatives revealed forty-six route movements. Upon the analysis, it was determined that the four route options shown in Figure 5-3 cover all the possible route blockages and are the most critical ones (in terms of corridor blockage duration and distance).

As Figure 5-3 shows four fire instances were created, each near to one exit, and each of the workspaces was tested to investigate their influence to occupants' behavior in the evacuation time and probability of occupants' injuries and death.

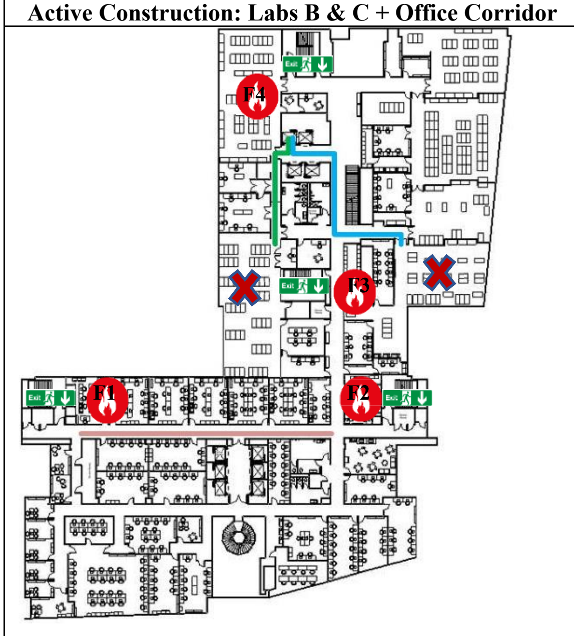
**Scenario 1**
**Active Construction: Labs B & F + Office Corridor**




**Scenario 2**
**Active Construction: Labs B & E + Office Corridor**




**Scenario 3**
**Active Construction: Labs B & C + Office Corridor**




**Scenario 4**
**Active Construction: Labs B & D + Office Corridor**

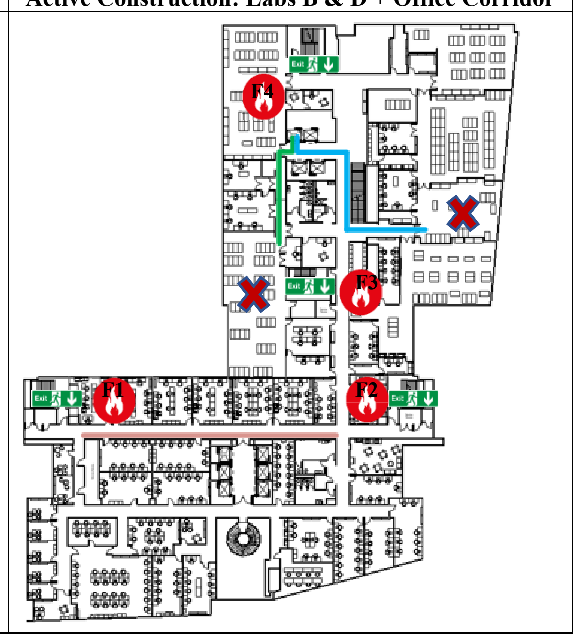



**Figure 5-3. Final Route Snapshots for Fire Evacuation Analysis**

### 5.3.1 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 modeled 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 5-4.

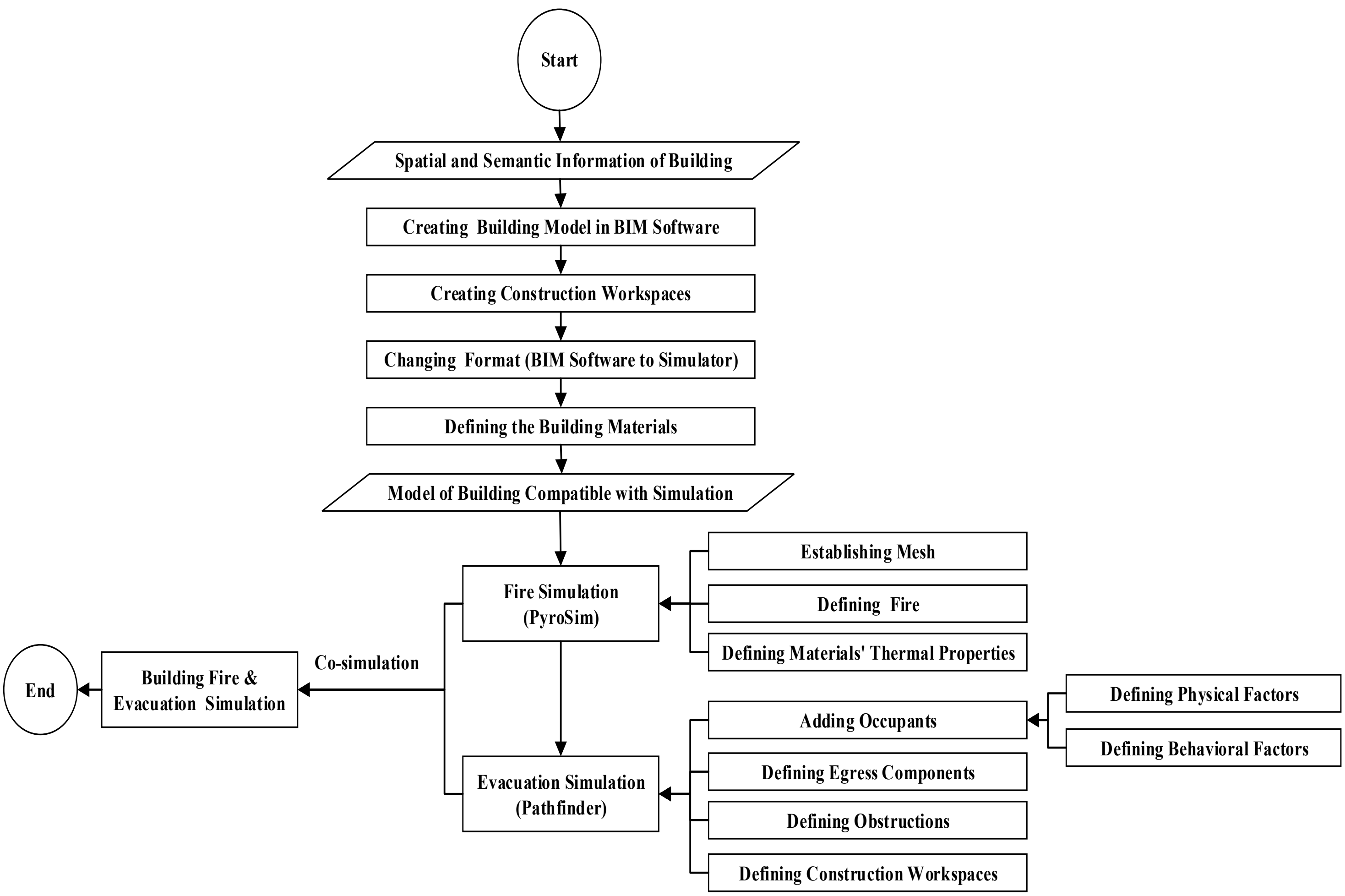



**Figure 5-4. Flowchart of Developing a Building Fire and Evacuation Simulation Using BIM Model**

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 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 Fire Dynamics Simulator (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 5-1. 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 5-1. Type of Occupant's Attributes**

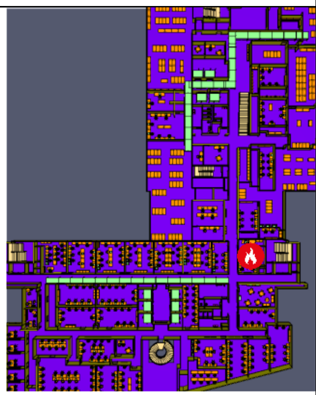
| Attributes type | |
|---|---|
| Physical Attributes | Age<br>Gender<br>Speed<br>Size of body<br>Mobility condition |
| Behavioral Attributes | Exit Familiarity<br>Delay time to start |
| Other Attributes | Number of occupants<br>Initial location of occupants<br>Role of occupants (Assistant, firefighter, etc.) |

### 5.3.2 Building Fire and Evacuation Simulation

At a high level, two main fire scenarios were implemented. In the first scenario, fire occurred on the $12^{th}$ floor of EV Building. In the second scenario, four critical locations with maximum impact on main exit doors were chosen on the $9^{th}$ floor of the building, as shown in Figure 5-3.

In each fire scenario, the Revit model (with all information about materials and textures) was imported to PyroSim. Then, 1.00 m length cubic mesh was created to balance the computation time and accuracy. Moreover, polyurethane foam as a fuel material for creating combustion was defined because the foam results in a quick-fire propagation. The thermal property of the material has been referenced from SFPE Handbook, GM27.

To reflect the changes of fire conditions, 2D and 3D slices including temperature and visibility were added in the model. Finally, the output results, such as temperature, visibility, toxicity density, and smoke were visualized. Figures 5-5 and 5-6 show the fire simulation of the 4 different locations of fire for the first construction case in sequence times.

| Fire Scenario | Time: 0 secs | Time: 10 secs | Time: 50 secs | Time: 100 secs | Time: 700 secs |
|---|---|---|---|---|---|
| **F1 CS 1** |  |  |  |  |  |
| **F2 CS1** |  |  |  |  |  |

| | | | | | |
|---|---|---|---|---|---|
| **F3 CS1** |  |  |  |  |  |
| **F4 CS1** |  |  |  |  |  |

* The green areas are renovation operations and elevators.

* The black areas are smoke propagation.

**Figure 5-5. Simulation of Four Fire Scenarios and the Smoke View during Construction CS1**

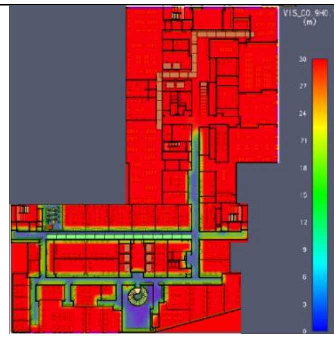
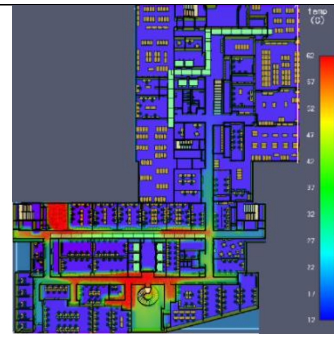
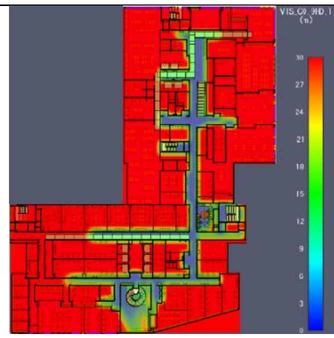
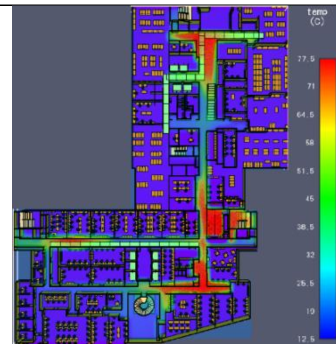
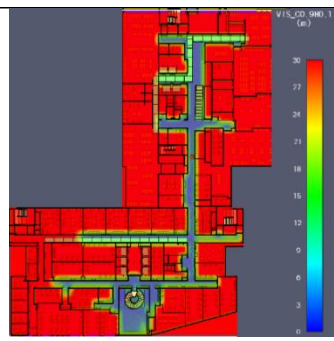
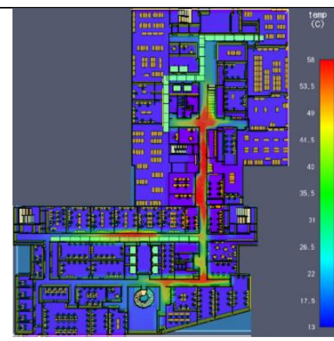
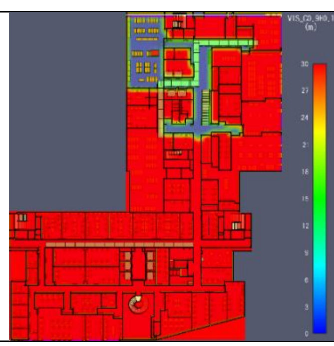
| Fire Scenario | Visibility at 300th second | Temperature at 700th Second |
|---|---|---|
| **F1 CS 1** |  |  |
| **F2 CS1** |  |  |
| **F3 CS1** |  |  |
| **F4 CS1** |  |  |

**Figure 5-6. Temperature and Visibility of the Fire Simulation in the Construction's Scenario (CS1)**

### 5.3.3 Evacuation Simulation

Pathfinder as an agent-based egress evacuation simulator was chosen for defining the occupants' behavior and movements to select the path to an exit. The simulation in Pathfinder software is deterministic. In pathfinder each occupant is an agent that can make independent decisions. Each occupant have profiles and behaviors. A profile describes the physical attributes and decision-making preferences of the agent, such as size and walking speed, movement options and door choice. The behavior of agent defines the actions can be arranged in any logical order, such as waiting for assistance or going to an exit.

In this software, a movement model is based on the fundamental diagram of walking speed-density relationship in SFPE. Moreover, "locally quickest algorithm" is used for the path planning that the agent has knowledge of the time to evacuate the current room and reach each door, current room queues, density, and global building. In fact, occupants act as an independent agents that choose an initial exit based on shortest estimated total exit times. However, they monitor the queues forming at the exits and will switch to a different exit if they perceive that to be advantageous. In addition, they avoid obstructions, such as other occupants and barriers.

In the evacuation model, some movement simulation modes were supported by Pathfinder, such as Steering, and SFPE (which was chosen in this study). In steering mode, occupants' behavior and movement are more realistic although this mode does not support the door flow rate limits. SFPE mode is designed based on a set of assumptions and hand-calculations of

Engineering Guide to Human Behavior in Fire (Galea Edwin 2003) that occupants do not attempt to avoid one another, but doors impose a strict flow rate limit and the room density affects occupant velocity (Thunderhead Engineering 2018).

For all 24 scenarios, the following steps were performed.

- Importing the building model as a FBX file.
- Defining the elevation for the model (since the model was related to the 9th floor);
- Adding stairs to the model and defining the capacity for the stairs;
- Creating four main exits of the building in the ground floor;
- Defining desks, tables, etc. as obstructions;
- Determining construction workspaces as obstructions;
- Defining the doors and the door properties, such as flow rate, state and accepted list of occupants;
- Adding occupants and determining the capacity of each occupancy in the building; Table 5-2 shows average and maximum occupant density based on the type of existing occupancy in the 9th floor of the building.

**Table 5-2. Occupant Density Based On the Occupancy Type**

| Occupancy type | Average capacity | Maximum capacity |
|---|---|---|
| Professor Offices | 1 | 2 |
| Student Offices | 6 | 12 |
| General Computer Labs | 15 | 30 |
| Lab A | 20 | 40 |
| Lab B | 20 | 40 |
| Lab C | 15 | 30 |
| Lab D | 10 | 20 |
| Lab E | 15 | 30 |
| Lab F | 10 | 20 |

- Defining 300 occupants including 12 firefighters, 2 occupants with wheelchair and 286 other occupants and defining the physical and behavioral factors, as shown in Tables 5-3 and 5-4.

**Table 5-3. Number of Occupants Based On Age and Gender**

| Attribute | Category | Number |
|---|---|---|
| Gender | Female | 143 |
| | Male | 157 |
| Age | < 30y | 103 |
| | 30y-50y | 100 |
| | > 50y | 97 |

**Table 5-4. Occupant Mean Speed Based On Age and Gender**

| **Occupant mean speed (m/s)** | | |
|---|---|---|
| Age | Gender | |
| | Female | Male |
| < 30y | 0.76 | 1.01 |
| 30y-50y | 0.67 | 0.88 |
| > 50y | 0.6 | 0.67 |

- Re-allocating the occupants due to the renovation scenarios. Table 5-5 shows the re-allocation plans for labs. In addition, occupants in the offices that are affected by renovation works were re-allocated to the nearest offices.

**Table 5-5. Re-Allocation Plans for Labs**

| Scenario | Occupancy | Capacity | Total |
|---|---|---|---|
| CS1 | Lab A | 20 + 20 from Lab B | 40 |
| | Lab B | _ | 0 |
| | Lab C | 15 | 15 |
| | Lab D | 10 + 7 from Lab F | 17 |
| | Lab E | 15 + 3 from Lab F | 18 |
| | Lab F | _ | 0 |
| CS2 | Lab A | 20 + 20 from Lab B | 40 |
| | Lab B | _ | 0 |
| | Lab C | 15 | 15 |
| | Lab D | 10 + 7 from Lab E | 17 |
| | Lab E | _ | 0 |
| | Lab F | 10 + 8 from Lab E | 18 |
| CS3 | Lab A | 20 + 20 from Lab B | 40 |
| | Lab B | _ | 0 |
| | Lab C | _ | 0 |
| | Lab D | 10 + 7 from Lab C | 17 |
| | Lab E | 15 | 15 |
| | Lab F | 10 + 8 from Lab C | 18 |
| CS4 | Lab A | 20 + 20 from Lab B | 40 |
| | Lab B | _ | 0 |
| | Lab C | 15 + 2 from Lab D | 17 |
| | Lab D | _ | 0 |
| | Lab E | 15 | 15 |
| | Lab F | 10 + 8 from Lab D | 18 |

- Defining the parameters of the simulation, such as time, output and behavior; Table 5-6 shows the simulation parameters in this study; and finally:

- Simulating.

**Table 5-6. Simulation Parameters**

| Category | Parameter | value |
|---|---|---|
| Time | Time Limit | 3600 s |
| | Time Step Size | 0.025 s |
| Output | 3D Output Freq. | 0.25 s |
| | CSV Output Freq. | 1.0 s |
| | Runtime Output Freq. | 0.5 s |
| | Jam Velocity | 0.25 m/s |
| Behavior (SFPE Mode) | Max Room Density | 1.88 pers/m² |
| | Door Flow Rate/ Boundary Layer | 15.0 cm |
| | Minimum Speed Fraction | 0.15 |

### 5.3.4 Fire and Evacuation Co-Simulation

To have a co-simulation of fire and evacuation, the results of fire simulation in PyroSim were coupled with evacuation simulation in Pathfinder. The 24 scenarios of fire and workspaces were modeled in PyroSim and their results were used to calculate Fractional Effective Dose (FED) during the evacuation. To calculate FED during evacuation, the required data, such as concentrations of the narcotic gases $CO$, $CO_2$ and $O_2$were saved in the fire simulation and these data were used by Pathfinder for the evacuation simulation. The following steps were taken to integrate the fire results as a Smokeview file (*.smv) in PyroSim to calculate FED during evacuation in Pathfinder.

1. Preparing PyroSim calculation. In this step, the Plot3D data file written by FDS was created as the output of the fire simulation. In Plot3D data, five quantities including temperature, soot visibility, and $CO$, $CO_2$ and $O_2$ volume fractions were chosen.
2. Preparing Pathfinder Calculation. The Smokeview files written during the PyroSim simulation were integrated with the Pathfinder. Then, the simulation was run.
3. Display Results. Finally, the results of the two simulations were displayed simultaneously. Also, the FED results were exported as CSV files for each occupant. It must be mentioned that this co-simulation does not represent full coupling of the fire and evacuation simulation. For instance, this co-simulation does not include navigation to avoid fire, change in speed due to smoke, dynamic display of exposures, and the ability to track exposure for all occupants (Pathfinder, 2018).

### 5.3.5 Results and Discussion

After running the simulation, as shown in Tables 5-7, 5-8 and 5-9, the results of the 24 scenarios (in terms of evacuation time) were obtained. Each fire incident was tested alone against each workspace route (shown in Figure 5-3), 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.

**Table 5-7. 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 | –* | –* | –* | –* |

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 5-10.

**Table 5-8. 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 5-9. 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 a number of occupants were stuck.

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 and 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 5-10. Occupant Number Based On the Scenario**

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

## 5.4 Conclusion

This chapter proposed an ABM-based co-simulation that uses BIM to improve building fire safety management. By analyzing 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 death. Additionally, the simulation results revealed the risk of developing construction plans that satisfy the minimum fire code requirements without testing them using simulation.

The workspace modeling 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.

# CHAPTER 6 Conclusions, Limitations, and Future Work

## 6.1 Summary of the Research

Reviewing the literature concerning emergency management concluded that limited perception regarding the disaster area and occupants can increase the probability of injuries and damages. Thus, the availability of comprehensive and timely information can help understand the existing conditions and plan an efficient evacuation. For this purpose, BIM should be integrated with three sets of information: (1) occupancy that defines the type of space usage; (2) occupants' information; and (3) sensory data. IFC, as a standard of BIM, has the physical and spatial information, such as areas, volumes, and elements of a building. IFC also has the basic definitions of sensor and occupant entities. However, these entities do not provide enough dynamic and accurate information for supporting emergency management systems.

This thesis aimed to improve fire emergency management using occupant information and BIM-based simulation. For this purpose, a dynamic BIM for fire emergency real-time management was developed that captures enough dynamism regarding the building condition as well as environmental conditions and occupants' behavior. Also, an ABM was used to assist in the analysis of the static and dynamic behavior of the environment and occupants in BIM.

For the extending IFC, the following main steps were taken: (1) the IfcSensor entity for occupant's sensors is extended; (2) new attributes to IfcOccupant to support emergency response operations are added and a new entity for occupancy is defined; and (3) the relationships between sensors, occupants, occupancy, time series, and building components are defined in the context of building evacuation. The feasibility of the proposed method is discussed using two case studies.

In Case Study 1, the sensory data related to temperature of the 9th floor of EV Building were added to BIM for visualizing the space conditions under a fire. The second case study is linking the occupants' sensory data to BIM and visualize real-time occupants' tracking under a fire.

In Case Study 2, the occupants' sensory data are linked to BIM and the real-time occupants' tracking are visualized under a fire.

For the evaluating the impact of various construction plans, the following main steps are taken: (1) a dynamic BIM for tracking occupants and environmental states is created; and (2) the specific scenarios for construction operations are defined in a building under emergency condition, and the requirements of modelling evacuation behavior are set in each scenario. Finally, this framework are 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.

## 6.2 Research Contributions

The contributions of this research are:

(1) Integrating sensory data with BIM as proposed by this research is effective in providing real-time information for effective fire emergency management, and is useful for enhancing the occupants and emergency first responders' perception because they can use 3D visualization of the dynamic conditions of the building under fire and

occupants' condition. The using of integrating real-time sensory data with BIM in the field of fire emergency management is relatively new.

(2) Integrating sensory data with BIM is becoming a frequently discussed topic, but few research projects involve the IFC extension approach. As shown in Section 3.2, the new entities, attributes and relationships between sensors, occupants, occupancy, time series, and building components are defined to improve in the context of building evacuation and fire emergency real-time management.

(3) The BIM-based co-simulation in this research is used to improve building fire safety management. Based on the simulation results in Section 5.3.5 , the renovation works increased the evacuation time (maximum of 17% delay in evacuation time) under emergency conditions and increased the probability of injuries and death.

(4) The ABM co-simulation framework that was proposed in this research is effective for the workspace management to represent the occupied spaces during construction, and to evaluate their impact on evacuation under fire incidents. The framework is relatively new because it brings together attributes of agents, rules governing their behavior, and decision models for occupants of an under-renovation building, under emergency conditions.

## 6.3 Limitations and Future Work

This research aimed to fill the gaps in the existing research background. However, there are some limitations, which are considered as future work:

(1) An extended IFC model was developed to identify the entities, attributes, and relationships between sensors, occupants, occupancy, time series, and building components. However, the model should be approved by Model Support Group of the Building SMART Alliance BSA.

(2) The proposed IFC-based model was based on the occupants' view. However, an IFC-based model based on the first responders' view of indoor/outdoor fire emergency management will be proposed as a future work.

(3) A BIM-based co-simulation model was proposed to evaluate the impact of renovation operations on evacuation under fire incidents. In the fire simulation model, flames were not propagated for different materials. However, smoke and other products of fire were spread. Therefore, fire propagation should be considered as a future work.

(4) Future work will include the implementation and testing of the proposed method, including the interaction between the occupants and the simulated fire propagation during the building evacuation, as well as developing a platform for the next generation of intelligent building emergency management that can seamlessly integrate with BIM and IoT.

(5) The BIM-based co-simulation model was designed for a floor of building (the 9$^{th}$ floor of EV Building at Concordia University). However, further implementation and testing of the simulation including the interaction between the occupants and the simulated fire

propagation during building evacuation in a multi-store high rise building will be accomplished.

(6) In the BIM-based co-simulation model, the impact of occupants on fire simulation was neglected, however this impact should be considered as a future work.

(7) Regarding the fire analysis, the proposed co-simulation model has some assumptions. 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 behavior of occupants in the mentioned co-simulations will be analyzed to improve fire safety management.

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# APPENDICES

## Appendix A - List of Related Publications

1. **Eftekharirad, R.**, Nik-Bakht, M., and Hammad, A. (2018). "Extending IFC for Fire Emergency Real-Time Management Using Sensors and Occupant Information", *Proceedings of 35$^{th}$ International Symposium on Automation and Robotics in Construction (ISARC 2018)*, Berlin, Germany, 35, 1-8.
2. **Eftekharirad, R.**, Nik-Bakht, M., and Hammad, A. (2018). "Linking sensory Data to BIM by Extending IFC – Case Study of Fire Evacuation", *Proceedings of 12$^{th}$ European Conference on Product and Process Modelling (ECPPM 2018),* Copenhagen, Denmark, 8, 9-14.
3. **Eftekharirad, R.**, Hosny, A., Nik-Bakht, M., and Hammad, A., and Moselhi, O. (2019). "Planning Building Renovation Projects for Safe Evacuation Provisions - An Agent-Based Model Approach", *Proceedings of 15$^{th}$ IBPSA Conference, Rome, Italy*.

## Appendix B - Current and Desired Target State of Fire Emergency in Buildings

Tables A-1 and A-2 show the current and desired target state of devises, sings, materials and systems are used to manage fire emergency.

**Table B-1. Current State of Fire Emergency in Semi-Smart Buildings**

| Scope | Devise/sign/document/system | Function |
|---|---|---|
| Fire Sensors | Heat Detector/ Smoke Detector/ Flame Detector/ CO Gas Detector | * Combine with alarm system.<br>* Send information to central monitoring and control.<br>* Alarm to evacuation.<br>* Connect to firefighters/fire department. |
| Occupants Sensing | Motion Detector | * Use for energy saving (lighting turn on/off). |
| | Access Control | * Access to enter rooms based on ID. |
| | Camera | * Monitoring for security and control. |
| | Security Patrol RFID Tags | * Checking the presence of security personnel/ Guard Tour System. |
| Fire Emergency Equipment | Alarms | * Waring the occupants to building of outbreak of fire and call for assistance. |
| | Manual Pull Station | * A user must activate the device.<br>Activation: Sending an alarm to the fire alarm control panel. |
| | Fire Fighter's Telephone | * Call for assistance. |
| | Sprinkler | * Sensitive to heat.<br>* Spreading water automatically when temperature reaches in around 70° C. |
| | Plan of Building | * Paper-based maps that contains floor plan with highlighted locations to respond to incident:<br>(1) Elevator, staircase, elevator hoist, escalator and emergency exit doors, etc.<br>(2) Location of hazardous materials and items, gas, electric and water input, fire emergency equipment such as fire |

| | | |
|---|---|---|
| | | pump, firefighter telephone and evacuation chair parts. |
| | Fire Hose | * Fire protection device used to extinguish or control fire |
| | Fire Extinguishers | |
| | Evacuation Map | * Floor plan on the wall to find the exit door, safe place and emergency equipment. |
| | Emergency Lighting and Signs | * Showing the direct path to or the exact location of the exit door.<br>* Need to test Periodically to batteries and operation. |
| Inspection of Fire Equipment | All Type of Emergency Equipment and Sensors | * Need to test Periodically by expertise. |
| Evacuation Procedure | Alarm/ Plan | * Occupants evacuate individually based on signs and paper map in each corridor (static information)/ self-evacuate.<br>* Persons with mobility issues or who are unable to safely evacuate should call and wait for assistance first responders will be assigned to assist.<br>* Personnel and emergency team: Help to evacuate and injuries based on emergency training.<br>* Firefighter: Using paper-based map and building plan to response. |
| Information | Map/ Sensor | * There is static information about:<br>(1) Fire: location<br>(2) Building condition: floor plan and emergency equipment's locations. |

**Table B-2. Desired Target State in Smart Buildings**

| Scope | Devise/sign/materials/system | Function |
|---|---|---|
| Fire Sensors | Heat Detector/ Smoke Detector/ Flame Detector/ CO Gas Detector | * Use compact sensors or data sharing among several fire sensors to increase accuracy of fire detection.<br>* Real-time, detailed and accurate information about heat, smoke, flame and toxic gas such as value, type, volume.<br>* Detect the real-time location of fire.<br>*Measure real-time speed of fire spread. |
| Occupants Sensing | Motion Detector | * Use for emergency management/ presence of occupant in each room |
| | Access Control | * Use other individual information such as presence in assigned rooms (yes/no), age, mobility condition, heath condition (breath/ heart disease, etc.), male or female (average walking speed, body size, etc.) that help to evacuate properly. |
| | Camera | * Use to track people [presence, number of occupants, location] |
| Fire Emergency Equipment | Alarms | * Add online systems to alert and keep occupants informed of fire such as sending massage to students and personnel (cell phone, email, PC on the labs and other screens). |
| | Manual Pull Station, Fire Fighter's Telephone | * Remove manual systems such as pull station and firefighter's Telephone System.<br>Use IoT network to connection sensors, alarms.<br>*Digital applications that have comprehensive static and dynamic information about occupants, fire, emergency equipment, building condition and surrounding environment to make effective decisions to control and extinguish fire, rescue occupants and organize first responders' team working. [IoT based applications] |
| | Sprinkler | * Using IoT to actuate based on all information |

| | | |
|---|---|---|
| | Plan of Building | * Real-time and digital map that contains spatial and semantic information.<br>(1) BIM.<br>(2) Dynamic and real-time information about occupants, fire, building condition and surrounding environment. |
| | Evacuation Map | * Application on cell phone to guide persons to find the safest and shortest path based on real time information. [IoT based applications] |
| | Emergency Lighting and Signs | * Replace by application on cell phone.<br>(or)<br>* Existing lighting and signs connect to internet for online testing. |
| Inspection of Fire Equipment | All Type of Emergency Equipment and Sensors | * Online monitoring, control and testing equipment that connect to internet |
| Evacuation Procedure | Alarm/ Plan | * Occupants evacuate by using cell phone application.<br>* Identify the number and location of persons with mobility issues or who are unable to safely evacuate and send first responders to assist, quickly.<br>* Personnel and emergency team use applications that use real time fire disaster to evacuate effectively.<br>* Firefighter: Use digital applications that have comprehensive static and dynamic information about occupants, fire, emergency equipment, building condition and surrounding environment to make effective decisions to control and extinguish fire, rescue occupants and organize team working. [IoT based applications] |
| Information | Map/ Sensor | * There is static and dynamic information about:<br>(1) Fire: location, spread speed.<br>(2) Building condition: spatial and semantic information, real time information about structure, MEP and material, equipment, etc.<br>(3) Occupants: presence, number, ID, mobility and health condition, location, tracking, etc.<br>(4) evacuate route: safe and short. |

## Appendix C - Fire Emergency Tools, System and Equipment in Concordia University

## EV Building

**Table C- 1. Fire Emergency Tools, System and Equipment**

| Class/ Tool | Photo | Description |
|---|---|---|
| **1. Building Security** | | |
| Security Patrol RFID Tags for Guard Tour System |   | It is the wireless non-contact use of radio-frequency electromagnetic fields to transfer data, for the purposes of automatically identifying security personnel. |
| Security Camera |  | It records activities in place to detect unusual condition. |
| **2. Fire Detection and Alarm System** | | |
| Smoke Detector |  | It is a device that senses smoke, typically as an indicator of fire. |
| Temperature Sensor |   | It is a thermocouple or Resistance Temperature Detector (RTD) that provides for temperature measurement through an electrical signal. |
| Manual Pull Station |   | When a user activates the alarm by pulling the handle down, an alarm sends to the fire alarm control panel. |

| | | |
|---|---|---|
| **3. First Aid Firefighting Equipment** | | |
| Fire Extinguisher |  | It is an active fire protection device used to extinguish or control small fires, often in emergency situations. |
| Fire Hose Box |  | It is an intervention system that carries water or other fire retardant to extinguish fire. |
| **4. Fire Suppression Equipment** | | |
| An Automatic Sprinkler System |  | It is an active fire protection method (sensitive to heat) consisting of a water supply system, providing adequate pressure and flowrate to a water distribution piping system. |
| **5. Occupant Sensors** | | |
| Access Control |  | It is the selective restriction of access to a place or other resource. |
| Motion Detector |  | It is a device that detects moving objects, particularly people. |
| **6. Emergency Evacuation Tools** | | |
| Exist sign/ Emergency Lighting |  | - |

| | | |
|---|---|---|
| Evacuation Map |  | It is a map to guide users to safety, providing feature locations like fire extinguishers or exists. |
| Firefighter’s Telephone |  | It is a communication device during the fire. |