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SMART DISASTER MANAGEMENT SYSTEM FOR TALL BUILDINGS

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Abstract: The recent trend of movement and impetus towards realization of smart cities and smart multi-purpose complexes calls for more efficient and safer disaster management systems. Elevators, as the main tool of vertical transportation in high-rise buildings, can potentially propel the advancements towards more competent disaster management systems. Dispatch algorithm of elevators is the dominant factor that determines how smart and efficient they could perform. With recent innovative research on checking the possibility of elevator use for emergency evacuation, the importance of having an expert control system, which would provide a faster and a safer evacuation program, has been observed. In this paper, the importance and feasibility of using Occupant Evacuation Elevators (OEEs) are reviewed. Also, a Smart Disaster Management System (SDMS) is proposed. The main purpose of this system is to simulate all the possible scenarios of emergency in the building and then, through the decision-making capability of the system, select the fastest and safest strategy of egress. To this end, an Agent-Based Modeling (ABM) unit is connected to an Artificial Intelligent (AI) unit to build a thinking engine for the proposed model. Overall, the paper shows how recent technologic advancements can be incorporated in order to form a smart disaster management system.

Keywords: Tall Buildings, Occupant Evacuation Elevator, Disaster Management, Smart Buildings, Agent-Based Modeling, Artificial Intelligence

1 Introduction

Natural and human-caused disasters, such as fires, earthquakes, bomb threats, terrorist attacks, and floods present special dangers for high-rise buildings and unique challenges for risk managers of those buildings (Della-Guistina 1995). Residents of these habitats are prone to being trapped at the time of evacuation if they do not have or are not aware of the emergency plan. In a review of fire fatalities in residential buildings between 2012 and 2014, 19.6% were caused by egress problems and 17.1% were caused by escape problems. Egress problems refer to crowded situations, limited exits, locked exits and mechanical obstacles to the exit. Escape factors refer to unfamiliarity with exits, excessive escape distance, inappropriate choice of exit route, re-entering the building, and clothing catching on fire while escaping (Topical Fire Report Series [TFRS] 2016). There are many examples around the world to show how some catastrophes were a direct result of unsafe and inefficient evacuation at the time of danger. The collapse of the World Trade Center towers 1 and 2 (WTC-1 and WTC-2) (CNN 2001) is recognized as one of the most catastrophic incidents of all time that highlighted the need for building disaster management (Wood 2003). Another recent example is the collapse of Iran's Plasco Tower in January 2017 where twenty firefighters lost their lives. Contributing factors to this tragedy were a failed fire suppression system and an improper disaster management strategy (Bozorgmehr and Smith-Spark 2017). Damage resulting from such disasters include fatalities from structural collapse of the building and injuries from crowd stampedes (Ahn and Han 2012).

The predominance of low-rise residences relative to high-rise buildings and the rarity of disasters during the lifetime of a structure may lead some to underestimate the level of attention required to address the egress of inhabitants from high-rises during emergencies. However, tall buildings and their occupants are highly sensitive to emergency situations. This paper endeavors to 1) examine the feasibility, importance and justification of using occupant evacuation elevators (OEEs) in high-rise buildings; and, 2) propose a smart disaster management system (SDMS) that incorporates OEEs into evacuation systems for tall buildings.

2 Occupant Evacuation Elevators (OEE)

Despite technological advancements, staircases remain the dominant means of egress for occupants during an emergency. Elevators are typically off limits for evacuation, especially in where smoke or fire are involved. Technical provisions for OEEs were very recently added to building codes; as such, insufficient attention has been paid to embed these facilities into building disaster management systems (American Society of Mechanical Engineering Safety Code for Elevators and Escalators 2013 [ASME A17.1-2016]/ Canadian Standards Association Safety Code for Elevators and Escalators 2016 [CSA B44-16]). There are several challenges to the use of elevators in emergencies, such as safety concerns, technical restrictions, and human behavior patterns. At the same time, the unique features of elevators could benefit an evacuation system and justify an investment into the resolution of the challenges.

In the 9/11 disaster, the number of occupants killed in the WTC-2 was half the number of WTC-1. A 2012 federal investigation of the evacuation revealed that the occupants' use of elevators in WTC-2 was part of the reason. This supported the idea that elevators could be very helpful during evacuations, at least under some specific circumstances (Averill et al. 2001). Starting in the 2009 edition of the International Building Code (IBC), buildings with a height of more than 128m are required to have an additional egress stairway (IBC2015 §403.5.2). However, buildings equipped with OEE are exceptions to this clause.

2.1 Benefits

Several unique characteristics make elevators potential routes of egress. The evacuation of a high-rise building using staircases alone could take too much time and be dangerous. High-speed elevators could provide support for occupants who are in imminent danger, are mobility challenged, or find that their movement via the staircases is dangerous or impossible. Stair travel devices to help mobility-impaired evacuees could greatly impede the panicked flow of crowds in the exit route.

A deeper look supports that elevators may be superior to stairway egress routes in some aspects. The biggest advantage of elevators over stairs is their mechanical nature, which could allow them to be automatically controlled using expert systems or automated occupant emergency plans (OEPs). There is a significant capacity in elevator technology that enables the decision maker to redirect the flow of people to somewhere safe, which might not be recognized by the occupants in the danger. With all of the advancements offered by remote sensing technologies, elevators may be the best tools for holding and moving people safely and quickly from danger zone.

Recent innovations in elevator technology disclose some hidden potentials of elevators as evacuation systems. The proposed rope-less elevator from ThyssenKrupp is able to move in both vertical and horizontal directions independent from other elevator cages (ThyssenKrupp AG. 2017). This approach could help the occupants escape the danger zone by providing more degrees of freedom with respect to directional movements. It also provides new possibilities to assist mobility-restricted occupants during an evacuation.

There is evidence that evacuation from higher than 40-storeys can be achieved faster with elevators (Paarlberg 2008). Based on a computer simulation of a hypothetical 50-floor building, the combined use of elevators and stairs and the sole use of OEEs, can respectively reduce the time of evacuation by 50% and 27% compared to the sole use of stairs (Kinsey et al. 2009). In such high-rise structures, even healthy people could tire from running down that many stairs, especially in a panic situation. Slow or exhausted occupants, pregnant women, mobility-impaired occupants, and counter-flow firefighters can noticeably impede the movement of traffic in stairways.

Stair exit routes in high-rise buildings are mainly designed for emergency situations and are not typically used daily by the occupants. Therefore, a considerable area of the building is designated for those rare emergencies. A greater reliance on OEE could deliver more useable floor space to building developers, thereby allowing them to invest more resources on elevator improvements.

The use of elevators could be justified by looking at the general targets defined in any ideal egress exercise and deficiencies in current evacuation routes. Elevators, as one component in an integrated evacuation structure, should help to:

- move people with mobility issues to a safe place;
- transport fire fighters and equipment to the appropriate floor;
- move firefighters between the floors to rescue the occupants;
- perform partial evacuation of occupants to safe floors; and,
- perform full evacuation of a building in coordination with other egress routes, including but not limited to stairs, escalators, and sky-bridges

2.2 Challenges

The design of safe egress routes must consider occupant behavior during emergencies (Kuligowski 2011). Social and cultural norms may be forgotten when the situation appears to be life threatening (Bonabeau 2002). Therefore, one of the biggest challenges to merging OEEs with disaster management systems is to overcome the challenges pertaining to human behavior. For instance, in a building with the two egress options of stairways and elevators, short-term interests may override safety. Because the space within each elevator car is limited, occupants need to be assigned priority and be told who is to use the elevators first. This could create chaos as everyone pushes into the elevator, overloading it and making it inoperable (Kinatedar et al. 2014). In a comparison of evacuation strategies, it was concluded that the combined use of elevators with other egress alternatives could not be effective over the sole use of stairs without further study on occupant behavior when presented with options for escape (Ronchi et al. 2014). The results from such behavioral study could be used to guide the occupants to the most efficient strategy (Ronchi and Nilsson 2014).

There are many technical obstacles to overcome when planning to use OEEs, especially in the case of fire-related emergencies (Chapman 1990). The ultimate goals are to keep smoke out of the elevator shaft, make the elevator system water resistant, enable voice communication between occupants and the command station, have permanent access to stairways, and put the elevator out of the operation as soon as any threat approaches the elevator shafts. The building codes and examples of buildings already equipped with OEEs simply show that these technical concerns have been rectified to a satisfactory extent (Kinatedar et al. 2014), but do not provide guidance on how OEEs should be programmed to effectively improve the evacuation process.

Achieving the technical requirements in the international codes is perceived as an extra investment and builders may not want to invest in OEE unless there are justifications for it. Iconic tall buildings, for example, may justify the cost since the modern features of the building could bring social and economic benefits to the owner.

Evacuation may be implemented as total, staged, or fractional evacuation (Armm and Ross-Sirola 2004). Each of these strategies require a completely different, building-specific, dispatch algorithm. For example, in staged evacuation, one must decide whether to alert the whole building or first alert the occupants with the highest exposure to the threat. The latter stages the evacuation by only letting the danger floor know about the emergency. The rest of the building occupants are given instructions in subsequent stages. The *safe floor* is another strategy in which decisions are made for the elevator to carry evacuees down to the ground level or transfer them to a few floors below the danger zone. For instance, National Institute of Standards and Technology (NIST) Technical Note 1793 describes a phased elevator evacuation as a prioritized evacuation of two floors up and two floors below the danger floor and in the next phase full evacuation of the building (Bokowski 2007). Hence, many scenarios could be examined for a building, depending on its size, geometry, danger location, time of incident, type of incident etc., each of which will result in a distinct elevator dispatch strategy. The effectiveness of these strategies can be evaluated through simulation modelling.

2.3 International Codes

Currently, many building codes and safety regulations acknowledge that elevators in high-rise buildings could be operational and help evacuation during an emergency only if they are carefully managed. Leadership in this area is achieved by the International Code Council's International Building Code (IBC), and the National Fire Protection Association (NFPA) with its Life Safety Code (NFPA 101-2012) and Building Construction and Safety Code (NFPA 5000-2012). All three permit the application of OEE as long as the elevator shafts are designed to divert smoke away from the elevators and they shut down at the first evidence of smoke in the vicinity (IBC 2015, NFPA 101-2012, NFPA 5000-2012). American Society of Mechanical Engineers Safety Code for Elevators and Escalators (ASME A17.1-2013) allows that elevators may be used as a means of evacuation in high-rise buildings (ASME A17.1-2013). Elaboration of the technical details and conditions of these codes is outside of the scope of this paper.

Although most codes reference IBC, NFPA, or ASME, there are few guidelines on procedures of evacuation using elevators. In fairness, details on an OEP could be outside of the scope of these codes, but the need for guidelines on the best practices of OEE usage should not be neglected. Additionally, each building's OEP would highly depend on its case-specific characteristics, so no overarching recommendation can be made without tools to assess their performance and effectiveness.

3 Smart Disaster Management System (SDMS) with OEE

The validation of OEE and its integration into a high-rise building evacuation system aims at rendering a more efficient system that can save lives. The complex, diverse, and immediate threats that exist during an emergency make it very challenging for any building manager to reliably and effectively take control of building systems and their occupants. This opens the possibility for the development of automated and semi-automated disaster management systems within smart buildings that sense, think and operate without the assistance of human operators (Sinopoli 2009, Ronchi and Nilsson 2014). In this context, the smart control system has to sense the building's status as well as the potential hazards, and initiate an evacuation strategy that addresses those specific conditions. The evacuation strategy has to be supported by the building facilities that are electronically controllable from a central command station. These include OEEs, automatic doors, HVAC systems, and adaptive signage throughout the building. The ideal system would also have access to models that reflect the occupants' behavior, building characteristics and the threat itself, and provide decision-making capacity using simulations and some form of artificial intelligence (AI) (Jackson 1986). Agent-based modeling (ABM) is an approach of simulating the actions and interactions of autonomous agents in a modelled environment (Morvan 2012). The ability of ABM to model populations, individual behaviors, and agent interactions make it a very suitable tool for simulation of evacuation scenarios.

In this section, a potential framework for a smart disaster management system (SDMS) for a high-rise building is presented. It takes advantage of the fusion of an agent-based simulation with AI, and uses elevators as a primary means of evacuation (Figure 1). This framework is founded on two-way communication between evacuees and the system, comprehensive modeling of occupant behavior, and a real-time decision-making system to guide and manage the crowd during emergencies. There are three main elements in this framework: emergency detection, strategy selection through the 'thinking engine', and evacuation execution. Each of these elements is explained in the following sections.

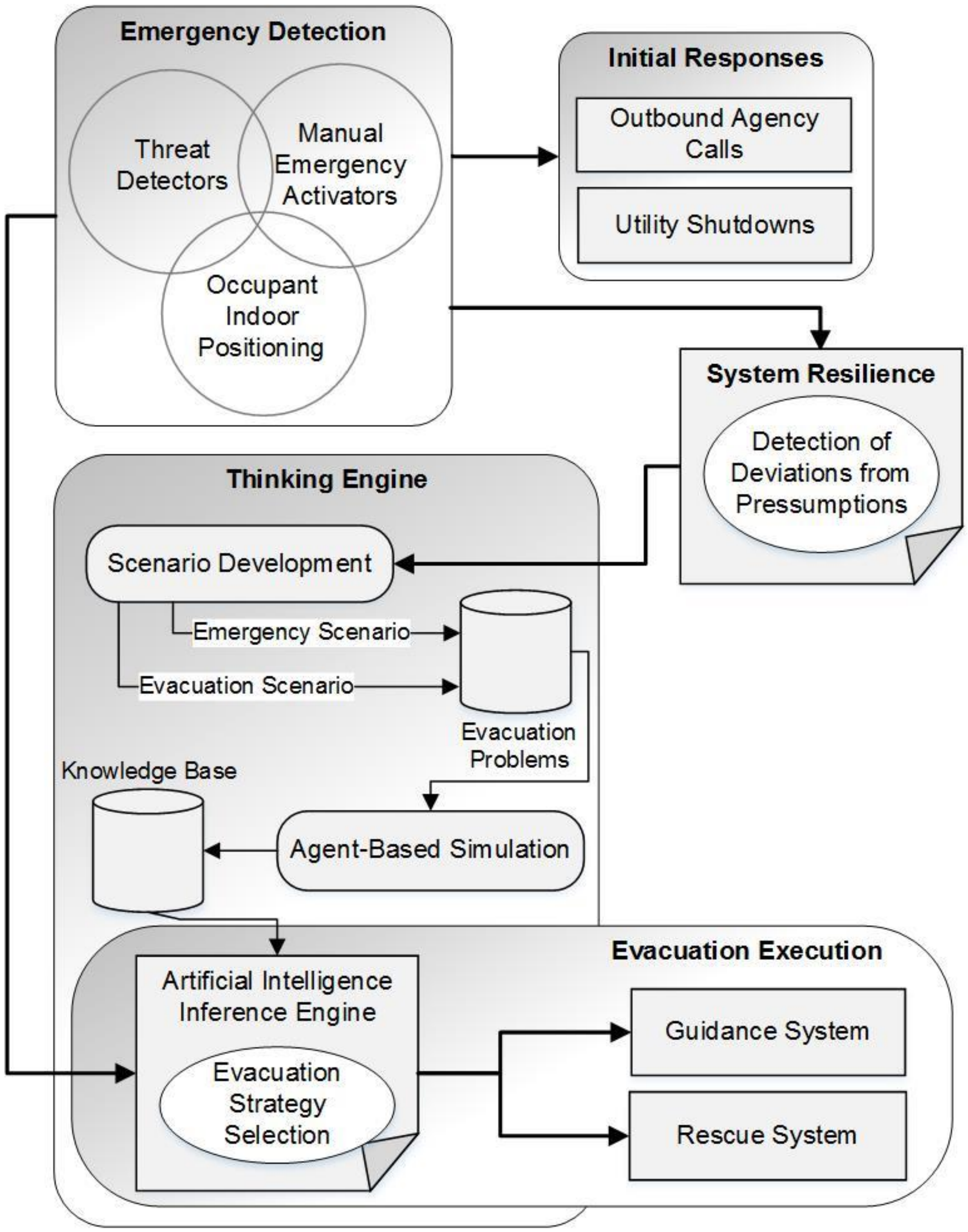

Figure 1: Structure of the proposed SDMS

3.1 Emergency Detection

The proposed SDMS requires different types of sensors, manual activators, and occupant positioning system to both monitor and assess the status of the building systems and to detect the presence of potential hazards. The information obtained from these systems is used in the SDMS to determine the type, location, and severity of an emergency, so that the most suitable response strategy can be determined.

Once a threat is detected using any of the automated or manual activators, the status of the SDMS is changed from “stand-by” to “active”, and the “Initial Responses” and “Evacuation Execution” units of the system are activated, as shown in Figure 1. As an example, smoke detectors inside the elevator lobby on each floor play an important role in the system's strategy selection. At the first evidence of smoke in a lobby enclosure, the SDMS must prevent the elevators from stopping on those floors and neglect them as possible egress paths. The elevators must stop at the first available safe floor and let the evacuees out to use other egress routes. At this point, the system has to change its strategy and look for other alternatives. Combustible gas detectors, heat detectors, and low oxygen detectors are additional devices that would alert the system and differentiate between different hazards (Sutton 2014).

3.1.1 Manual Emergency Activators

There are situations where an emergency system will be activated by manual calls from occupants who identify a threat. For example, if an occupant detects the possibility of a terrorist attack, they must be able to activate the emergency system via a user interface. Manual emergency activators have the same purpose as automated detectors but with a different way of activation via occupant intervention. Currently, manual call points (MCPs) in the buildings exist in the form of break glass activators, pull stations, or call points. However, these activators are usually located somewhere in the corridors and may not be accessible by occupants if they are restricted to their suites during an emergency. In addition, they only activate the emergency alert and cannot make the control station aware of the type of the threat.

An effective disaster management system needs manual emergency activators that would be capable of providing the system with the type and location of the threat. One option could be the use of text messaging to the SDMS. There could be some pre-defined codes recognizable for the SDMS, so that the user can report a specific threat in a particular location of the building using those predefined codes. The smart-phone based alert notifiers are the more advanced and comprehensive versions of these communicators. They can provide a convenient two-way communication between the SDMS and the user. However, not all of the occupants necessarily use smartphones and have the opportunity to benefit from this system (Newman 2011, Robertson and Volk 2008). Another alternative at the middle of the accessibility spectrum is the application of in-unit automation user interfaces that have already been installed by some condominium builders in their high-end residences (Brush et al. 2011).

3.1.2 Occupant Positioning System

Tags and transmitters that declare the location of occupants can significantly improve the process of safe evacuation. Real-time awareness about the location of each evacuee lets the SDMS know the size and distribution of the crowd that needs to be managed (Turgut et al. 2016). There are two main challenges regarding such a system's implementation. One is the occupants' concern about their right of privacy, which understandably limits the extent to which their location and movements can be tracked. The second is the low accuracy of affordable indoor positioning systems. The location of occupants could be estimated through the smartphone-based Wi-Fi/cellular indoor positioning techniques, however, the privacy issue remains a serious concern (Martin et al. 2010). RFID tags and Ultra Wide Band (UWB) systems are other types of indoor positioning techniques that could be considered in this context (Razavi and Haas 2011, Shahi et al. 2012). Another more economical alternative is the use of occupancy sensors that check whether the unit in the building is occupied. Of course, the occupancy sensors cannot offer the same granularity of information that would be acquired from individual transmitters, but it could still function as a viable alternative. It also addresses some of the privacy issues of the occupants, as it would not identify individuals.

The occupant positioning system has three main applications for the system:

1. Real-time update of the system regarding the distribution of the occupants.
2. Having an evacuee guidance system in-place, SDMS can communicate with the occupant and guide them to safety based on their location.
3. Provide guidance to rescue team in localizing trapped or in-need occupants.

3.2 Thinking Engine

As shown in Figure 1, once a threat has been identified through sensors or manual activators, the "Initial Response" elements are activated. These include outbound emergency calls and building utility shutdowns. The SDMS will automatically call fire, police, and ambulances to place a dispatch request. Also, based on the type of emergency that is detected, certain building utilities can be turned off, such as natural gas, electricity, or water to minimize the impact of the threat.

The core of the proposed smart disaster management system (SDMS) is a "thinking engine", which makes decisions with minimal intervention from human operators. The thinking engine is responsible for identifying the best evacuation execution strategy for a given threat. The proposed framework provides the thinking engine with a number of emergency scenarios and the system is required to evaluate and rank the performance of different evacuation strategies for each scenario. There are many factors that contribute to the development of emergency scenarios. These include a number of threat-related factors: 1) Type of threat, 2) Location of threat, 3) Time of emergency, 4) Population of occupants, and 5) Distribution of occupants; in addition to the strategy-related factors: 6) Type of evacuation required (Total, staged, phased or fractional), and 7) Available egress paths.

In each emergency case, threat-related factors act as assumptions of the problem and strategy-related factors are used to develop the solutions. For example, based on the location of the fire, an egress path in the vicinity could be deemed unsafe and it must not be counted as a way of egress during evacuation. Similarly, if the elevators are assumed as OEEs, evacuation scenarios must be developed for both cases of having and not having the elevator, in case smoke reaches the elevator shafts and the elevators become unavailable.

3.2.1 Simulation Phase

The proposed SDMS takes advantage of simulated scenarios to evaluate the performance of each evacuation strategy for every given emergency scenario. A reliable simulation demands a framework in which occupants' behavioral patterns are modeled to the highest possible accuracy. Currently, agent-based modelling (ABM) is the most powerful and accurate tool for modelling individuals' behavior, interactions between the individuals, and interactions between the groups of people. The emergent behaviors in evacuation scenarios are competitive behavior, queuing behavior, herding behavior, kin effect and many other reactions to danger (Pan et al. 2007, Yang et al. 2005). The more of such behavioral patterns a model can simulate, the more effective it can be.

Once the simulations have been completed, the evacuation strategies will be evaluated based on their resultant evacuation time, which represents the overall period between detection of the threat and departure of the last evacuee from the building. Another criterion is the safety factor of each scenario, which measures the success of each evacuation scenario in keeping the occupants away from the hazard. Eventually, all the evacuation strategies are modeled, evacuation time is calculated and safety factor is quantified. Finally, evacuation scenarios corresponding to each emergency scenario would be ranked based on their evacuation time and safety factor.

3.2.2 Artificial Intelligence Inference Engine

Once the system receives a signal reporting the existence of a hazard in the building, the evacuation execution element of the system is activated. The inference engine is shared between the thinking engine and the evacuation execution element. The SDMS system gets updates from all of the sensors and detectors and tries to gather the best information about the status of the building systems and its occupants. Then, it triggers a query among all of the emergency scenarios developed previously in the simulation phase. The simulation phase's product is a set of IF-THEN rules in the form of "If the location of threat is X1, and the time of evacuation is X2, and the possible egress path is Y1, THEN the best evacuation strategy is Z1". By having these scenarios evaluated exhaustively in advance, decisions can be made much more quickly. But, since every emergency scenario may be unique, the SDMS may not find an exact match for a scenario in its simulation database. Therefore, the closest fit between the evacuation strategies can be chosen based on the degree of membership of each case to pre-defined simulated scenarios. Once the system picks the relevant scenario and the corresponding evacuation strategy is loaded, the system mobilize the guidance system to execute the forethought evacuation procedures.

In this stage, a coherent link between the BIM model of the building and SDMS can significantly improve the performance of the system. 3D model of the building will be used as the main environment in which the simulations are performed. BIM model also provides the AI engine with information about vulnerable components or areas of the buildings and lets SDMS recognize high-risk zones during evacuation.

3.3 Evacuation Execution

As shown in Figure 1, the evacuation execution unit performs two important tasks of guiding occupants and assisting with rescue efforts. The primary function of the SDMS during an emergency is to guide the occupants to safety. Dynamic exit signs, automatic doors, and smartphone-oriented user-interactive programs are the tools available for this purpose. Dynamic exit signs are typical exit signs with the ability to adjust their direction in accordance with the evacuation strategy. As an example, it could redirect and prevent the occupants from going to the elevators at the times when the OEE is experiencing safety shutdown by SDMS. Automatic doors are electrically controllable and the system can lock and unlock them to guide the crowd on the desired egress paths. For instance, if the fire takes place in an egress stairway, evacuees should not be allowed to enter the stairway. Smartphone user-interactive programs establishes a real-time communication opportunity between the occupants and the SDMS system. The system can redirect in real time the lost evacuee to a safe location. One possible future solution is the application of Augmented-Reality (AR) based apps on the smartphones, which label the correct way of egress with some flashing arrows on the camera view of the smartphone (Ahn and Han 2012). One of the greatest challenges of this stage is the resilience of the guiding system and its capability to deal with scenarios where it needs to deal with deviations from the expected set of events. Malfunctioning dynamic signs or automatically locked exit doors broken through excess force could be two examples for such deviations. The resilience of the system must be taken into careful consideration during the design, feasibility testing, and implementation of the proposed SDMS and its evacuee guidance system.

A secondary task of the SDMS during an emergency is to assist with rescue efforts. If any occupant is in danger or trapped, the user-interactive program can report the location of the individual to the rescue team. Also, the control of the SDMS can be turned over to the emergency crew during a rescue effort to communicate with the victim and to guide them to the nearest exit or to a safe location.

3.4 System Resilience

Currently, many of the high-rise buildings in major cities are in the format of multi-purpose complexes. These types of buildings dynamically change and consequently increase the dispersion of occupants to different locations of the building. The proposed SDMS, in order to be considered as a resilient design, has to adapt to changing demands of the building during an emergency evacuation. Figure 1 shows how scenario development unit of the system is enabled by the system resilience unit to generate new scenarios based on any considerable change in the occupancy structure of the building. For example, opening of a customer-absorbing store on the third floor can highly distort the traffic flow inside the building and population coming from outside. Therefore, the system must be responsible for detection of conditions that extend beyond the constraints of the scenarios already developed and generate new scenarios to cover these conditions. This forethought is a mandatory requirement for developing a resilient evacuation management system.

4 Conclusion

With the increasing number of high-rise buildings and their exposure to different types of emergency scenarios, there is a need for a reliable disaster management system, and that system could benefit from the various recent technological advancements. In this research, a framework is developed to introduce a smart disaster management system (SDMS) in which occupant evacuation elevator (OEE) is a primary means of evacuation. Most recent versions of international and national codes, such as IBC, NFPA, ASME and CSA, allow the use of OEEs. However, there needs to be an effective and reliable evacuation management system to utilize and combine the use of OEEs and other possible evacuation strategies. The SDMS proposed in this research utilizes automated sensors, manual detectors, and information from occupants and BIM of the building, to evaluate the status of building systems and conditions of its occupants during an emergency situation. It also uses that information to develop, evaluate, and rank evacuation strategies for a number of predefined emergency scenarios using agent based modelling (ABM) and simulation techniques. Finally, at the time of an emergency, SDMS matches the emergency case with pre-simulated evacuation scenarios using fuzzy membership functions and selects the most effective evacuation strategy. The selected strategy will then be implemented by the evacuation execution unit of the SDMS, which is responsible for guiding the occupants to safety and assisting emergency crew in rescue operations.

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