STATUS QUO AND CHALLENGES AND FUTURE DEVELOPMENT OF FIRE EMERGENCY EVACUATION RESEARCH AND APPLICATION IN BUILT ENVIRONMENT

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SUMMARY: *Fire emergency evacuation study has been conducted for decades. In recent two decades, the fire emergency evacuation studies have been incorporating new technologies due to the high demands on efficient and safe evacuation for occupants who have various needs. The proposed fire emergency evacuation system from academic research and solutions from industry practices adopt different technologies to serve various evacuees. Therefore, this study conducts literature review to understand the status quo of current fire emergency evacuation research and practice. It shows that fire emergency evacuation studies mainly focus on the facility operation stage instead of design and construction stages. The facilities include residential buildings, education buildings, subways, shopping centers, etc. Three critical factors affect efficient and safe fire emergency evacuation in a built environment – facility physical features, fire characteristics, and human behavior. This study categories these new technologies, which are incorporated into the fire emergency evacuation research and practices within the recent two decades, into four groups: (1) Facility geometrical analysis, which includes the technologies such as BIM, GIS, VR and the combination of BIM/GIS/VR (2) Fire and smoke simulation, e.g. FDS and Pyrosim. The simulation output such as fire and smoke dynamics is incorporated into intelligent fire evacuation system (3) Crowd evacuation simulation software, e.g. Pathfinder, Massmotion; the output of simulation is used to develop personalized evacuation system (4) Indoor positioning system and mobile device/IoT technology to track and evacuate occupants intelligently. This study presents these new technologies used in the fire emergency evacuation systems and indicates that the development of an intelligent and personalized emergency evacuation system, which may track the evacuees in real time, is the future research trend.*

KEYWORDS: *fire emergency evacuation, building information modeling, geographical information system, fire simulation, evacuation simulation*

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1. INTRODUCTION

There were 1,291,500 fires in 2019 in the United States (Ahrens and Evarts 2019). These fires caused roughly 3,700 civilian deaths, 16,600 civilian injuries and $14.8 billion in property damage. A fire occurs in a structure at the rate of one every 65 seconds, and a home fire occurs every 93 seconds. Researchers have conducted fire emergency evacuation studies for many years in order to evacuate occupants more quickly and safely. As more and more new technologies emerge in the 21st century, it becomes possible to make the casualties and property losses to its minimum. Building information modeling (BIM) and cloud-based BIM are among these popular technologies (Zhang et al. 2019). Currently, some researchers are exploring the concept of translating data between BIM and Geographical Information System (GIS) to plan fire emergency evacuation (Atyabi et al. 2019; Rahman and Maulud 2019). Fire and smoke simulation software such as Fire Dynamics Simulator (FDS) and Pyrosim are used with BIM to predict the building's available safe egress time (Sun and Turkan 2019). Atila et al. (2018) adopted Radio-Frequency Identification (RFID) technology to detect the position of an evacuee, and Zhang et al. (2019) used Bluetooth low energy (BLE) based indoor real-time location system (RTLS) to dynamically push personalized evacuation route recommendations to the smartphone of a building occupant. While academic research applies various technologies to propose and develop the safest fire emergency evacuation systems, there are emergency management systems available on the market, such as WhosOnLocation (WhosOnLocation 2021). Although various technologies are adopted by academic research and industry practices, there lacks a holistic view of the technology application in fire emergency evacuation systems (FEES) within built environments. Researchers and practitioners need to understand the status quo about current available technologies in FEES, the communication protocols among the various technologies of FEES, future development of FEES and the relationship between these strategic developments. Therefore, this study conducts comprehensive literature review to fill the knowledge gap and reinforce the need for enhancement of technology driven fire emergency evacuation systems. The following sections are organized as research methodology, status quo analysis of FEES, communication protocols among various technologies of FEES, future development and challenges of FEES, and conclusion of this study.

2. RESEARCH METHODOLOGY

A comprehensive literature review of fire emergency evacuation studies was conducted. To acquire up-to-date and high-quality papers and analyze them, the steps of a PRISMA 2020 approach was used to systematically identify and screen the publications (see FIG 1). At the identification step, keyword searches were conducted within a few scholarly databases such as Google Scholar, Web of Science, Science Direct, American Society of Civil Engineers (ASCE) Library, Taylor and Francis Online, Wiley Online Library. The search was restricted to English literature. In order to include all fire emergency evacuation studies, the authors started publication search with the keyword "emergency evacuation" instead of "fire emergency evacuation". The other keywords were "disaster", "fire", "building", "construction". On the other hand, the new technologies such as "building information modeling", "geotechnical information system", "virtual reality", "sensors", "IoT", "fire simulation", "smoke simulation" etc. were also used as keywords in searching the relevant publications. In addition, the combinations of the keywords were used to narrow down the search scope. Examples of the combinations are as follows:

- "emergency evacuation" & "building"
- "emergency evacuation" & "construction"
- "emergency evacuation" & "building information modeling"
- "emergency evacuation" & "building" & "sensors"
- "emergency evacuation" & "building" & "fires"
- "emergency evacuation" & "construction" & "sensors"
- "emergency evacuation" & "construction" & "fires"

The query is to target papers which should explicitly or implicitly mention fire emergency evacuation for people in a built environment. Eventually 98 publications were identified.

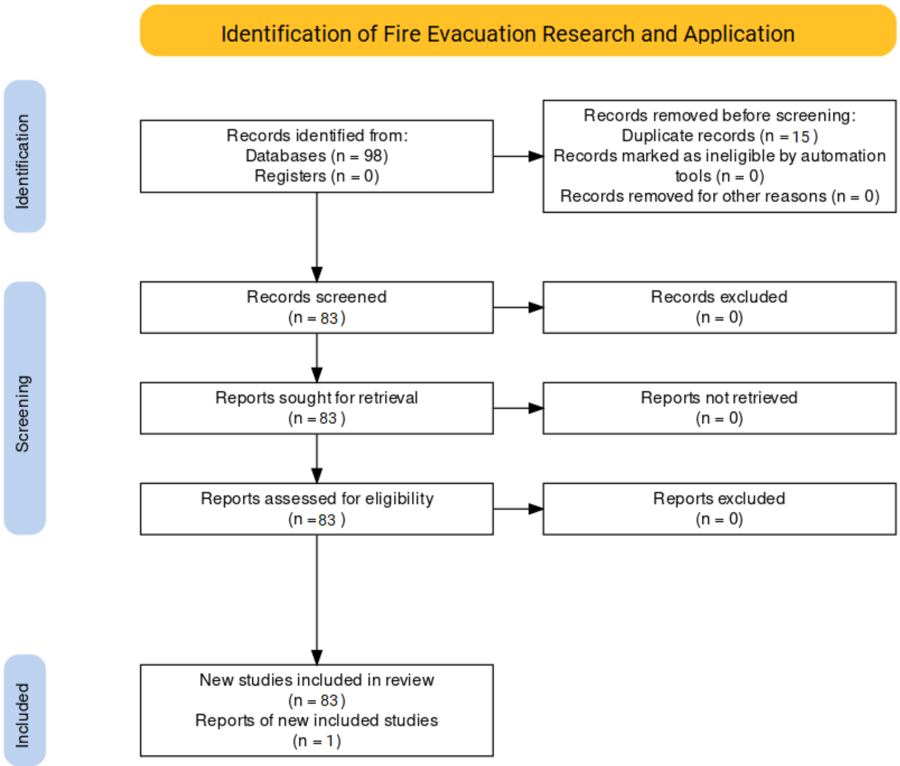

FIG. 1: Publication search with PRISMA 2020 approach.

At the screening step, journal articles and conference proceedings were included in the final sample, but non peer-reviewed publications, such as white papers and industry reports, were excluded in the final database. To determine whether or not a paper met the criteria, the abstract, title, and keywords were first reviewed. If necessary, the body of the text was also scanned. Fifteen irrelevant and duplicated papers were excluded, and 83 papers were selected. The searches were conducted in January 2021, thus this review includes papers published up until that time. The authors restrict the papers' published years ranging from 2000 to 2020, since the fire emergency evacuation studies develop fast along with newly emerging technologies in recent two decades. However, a newly published paper in 2022 was strongly recommended during the manuscript preparation due to the content closely related to literature review. Therefore, 84 publications are included in this study.

The authors then conducted content analysis about these 84 articles and extracted data from them in both qualitative and quantitative aspects. During content analysis, more diverse and detailed fire emergency evacuation studies were explored and organized based on the main categories. The quantitative content analysis was applied to count the number of articles in different journals, years, geographical distribution, building types, etc. The qualitative content analysis was employed to analyze in-depth the main components of fire emergency evacuation systems by literally reviewing the publications one by one by authors. Based on the papers mentioning the structure of the fire evacuation systems, main categories were set as types of emergency (e.g., fire, flood), stages of facility life cycle, usage types of fire evacuation system, and technologies used in the fire emergency evacuation system. The results were summarized and visualized in Sankey charts (FIG 2 and 3)

The Sankey chart provides a graphical overview of the literature study conducted to quantitatively and qualitatively categorize selected articles focused on fire emergency evacuation research and application. This chart depicts the flow from one emergency evacuation category to another providing information about their mapping flow using the colored flow of the bands and depth of the connection using the width of the bands. For instance, the majority of the studies originated out of China (17 out of 84), USA (16 out of 84) and Taiwan (10 out of 84). With the technological advancements in the field of sensing, the chart shows the increases in the frequency of the research (70 out of 84 studies conducted after 2014) conducted towards fire emergency evacuation sensing and modeling suggesting the increase in the use of BIM and web/mobile based applications. And the year 2019 has the highest fire emergency evacuation study publications. 58 out of 84 articles explicitly studied fire emergency evacuation systems. The rest of the articles implicitly address fire emergency evacuation although these articles state their studies of emergency evacuation are for general purposes. An article that focuses on flood emergency evacuation still states that their study can also be applied to fire emergency evacuation as well.

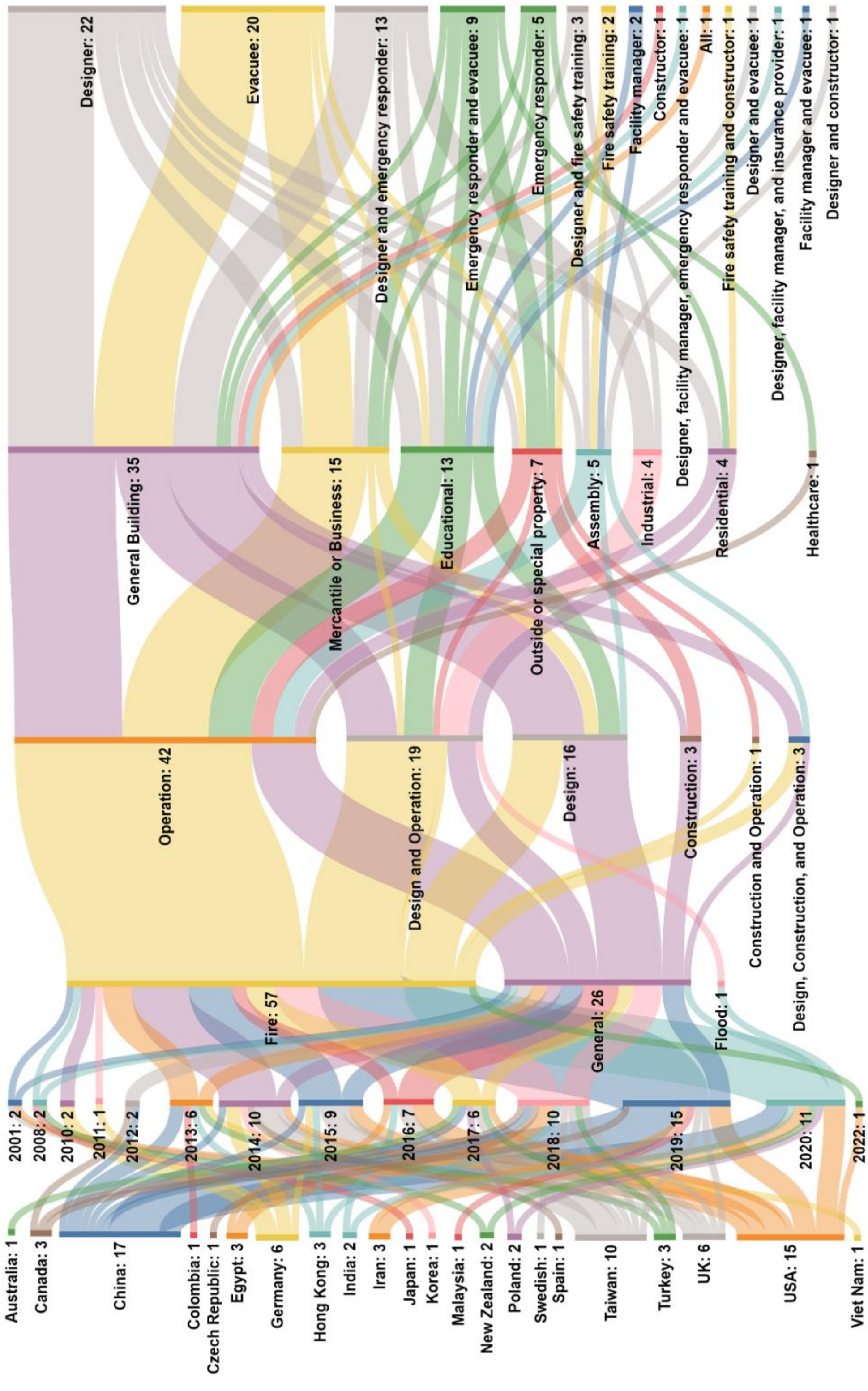

FIG. 2: Collected article summery.

This literature study initiated with understanding the developments in the fire emergency evacuation systems at various stages of facilities. Namely, during the design, construction, and operation phases. The above Sankey chart shows the distribution of the number of articles during each phase of facilities. Most of the literature focused on the operation phase of a facility to aid occupants evacuate safely during fire emergencies. The other major percentage catered towards understanding emergency management systems during the design phase of a facility by implementing fire evacuation simulations and user experienced games/virtual reality.

The authors also have visualized all the literature studies based on the type of facility categorized by the National Fire Protection Association (NFPA), where in the majority of the studies are focused on implementing fire emergency management studies for general buildings, mercantile type occupancy, and educational institutions (NFPA 2021). These facility types are then further classified based on the type of end user/occupant, where in most of the applications are catered towards designers (general building designers, fire engineering designers) and evacuees (building occupants, construction laborers etc.).

The following section discusses in detail the current technologies used in fire emergency evacuation studies.

3. STATUS QUO ANALYSIS OF FIRE EMERGENCY EVACUATION SYSTEMS

Various governmental regulations at federal, state and local levels address safety-related codes and rules in building design, construction, operation, and emergency response. For example, National Fire Protection Association (NFPA) 1710 set the limit for response time as the first engine arrives on scene should be within 240 seconds (4 minutes), second company arrives on scene should not exceed 360 seconds (6 minutes) for 90% of responses with a minimum staffing of 4 personnel (Lexipol 2019). Through reviewing the 84 articles which apply various contemporary technologies to emergency evacuation management systems, it appears that before and after the first responders arrive in the scenes, three critical factors affect occupant evacuation decisions – building

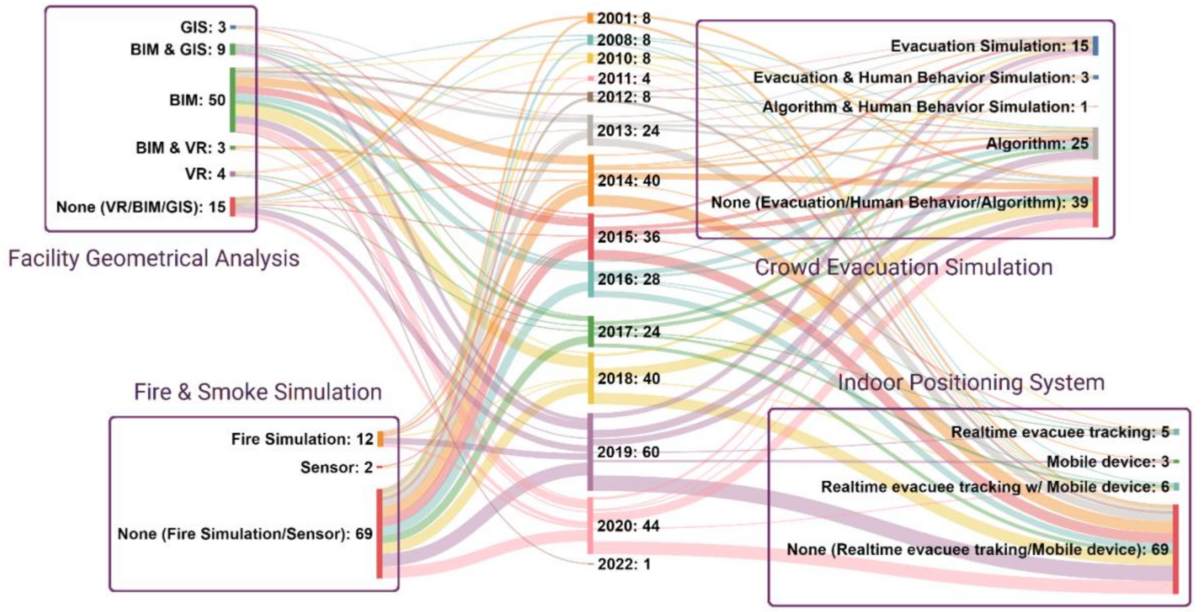

FIG. 3: Contemporary technologies in fire emergency evacuation systems.

3.1 Facility geometrical analysis

One of the major determinants of fire evacuation in built environments is facility physical features. These facility characteristics and geometrical information are represented and stored by the software such as CAD, BIM, GIS, VR and combinations of these technologies. It shows in FIG 3 that the majority (50 out of 84 articles) of fire emergency evacuation study applies BIM technology while the other studies apply GIS (3 out of 84 articles), VR (4 out of 84 articles), GIS with BIM (9 out of 84 articles), VR with BIM (3 out of 84 articles).

Building Information Modeling (BIM) provides graphical interface for user interaction and geometric information of the building scene, which acts as a data input for fire evacuation simulation computing (Bayat et al. 2020; Bina and Moghadas 2020; Chen and Chu 2016; Chen and Huang 2014; Chen et al. 2018; Cheng et al. 2017; Choi et al. 2014; Fu and Liu 2020; Isikdag et al. 2013; Li et al. 2014; Ma and Wu 2020; Mirahadi et al. 2019; Rüppel et al. 2010; Sun and Turkan 2020; Wang et al. 2014; Wang et al. 2012; Yenumula et al. 2015). Bi et al. (2013) stated that BIM has the advantage of 3D visual modeling and detailed geometric information model of the building structure, components, equipment's etc. to develop an idea to integrate BIM with fire emergency planning. Several studies extracted indoor graph networks from the BIM models for aiding emergency evacuation in buildings (Atila et al. 2018; Rüppel et al. 2010; Song et al. 2017; Wang et al. 2014; Xu et al. 2016). Other literature studies utilized network graphs and BIM to both model and simulate emergency evacuation plans for real structures. Weerasekara (2015) utilized the geometric data from the 3D BIM model to create graphs that will aid in providing shortest evacuation paths for large-scale venues. This study used context-based analyses to build a simulation system that combines description of the emergency and different evacuation simulation scenarios to cater safety managers to understand critical situations. The developed simulation system was validated using real time data collected through observations and previously published literature. Lovreglio, Thompson and Feng (2022) pointed out that BIM is a critical component in generative design techniques, which can assist fire safety engineers to generate, compare all possible design options and select the optimal one to meet specific fire safety criteria.

While BIM provides a more detailed 3D indoor geometrical model with rich semantics, geographic information system (GIS) offers powerful spatial analytical tools which are mostly used in open spaces and 3D indoor. The integration of BIM and GIS information for search and rescue operations in both indoor and outdoor environments has become another approach of emergency evacuation research. To simulate the indoor search and rescue teams' movements, Bayat et al. (2020) constructed a three-dimensional indoor building paths network by integrating BIM data into GIS. Their path network coupled with the graph algorithms such as Dijkstra sought the shortest and safest paths in analyzing Plasco's Building in Iran, burned in 2017. Atyabi et al. (2019) applied a similar approach to find the safest evacuation routes in a high-rise commercial building located in the 8th district of Tehran. Other researchers explored open-source software, such as Agent Analyst which are compatible with ArcGIS, to investigate emergency evacuation (Zhu et al. 2018). Tan et al. (2015) applied Agent Analyst to simulate evacuation efficiency in terms of evacuee's knowledge level and the facility accessibility during an emergency.

Although BIM data are an excellent source for a detailed 3D geometrical model with richsemantics, CAD data, in which doors, walls and rooms are in forms of points, polylines and polygons, is more efficient in generating 2D paths for use in GIS. Xu et al. (2016) use Triangulated Irregular Network (TIN) to both increase the efficiency of CAD data usage and decrease the difficulty of generating 2D path processes. Their study was to transfer CAD files into ArcGIS for optimal guided evacuation of crowds. However, the model validation concern still existed in the process of data transferring. In the meantime, Mahdaviparsa and McCuen (2019) used Esri's Campus Viewer Tool, which supported the workflow of producing indoor geodatabase datasets from CAD drawings to GIS. This tool helped them to provide 2D building navigation and 3D overview for the emergency first responders.

Application of virtual reality (VR) in building emergency studies started in 2010. VR enables users to experience certain situations in a digital environment which simulates the real world. The immersive VR technology further makes a user have an immersive feeling in a virtual environment. Therefore, some researchers apply this technology to study the impact of an extreme situation (such as a fire), which are barely possible to conduct experiments in the real world. For example, Rüppel et al. (2010), Rüppel and Schatz (2011), Shaw et al. (2019) proposed BIM-based immersive VR to study human behavior and evacuation decision in a building. Other researchers utilized VR technology coupled with BIM and serious game technologies to provide emergency awareness and fire evacuation training (Shaw et al. 2019; Wang et al. 2014; Wang et al. 2015). Song et al. (2017) proposed to apply VR with geographic information to analyze building fire scenes.

3.2 Fire and smoke characteristics

Another determinant of safe and efficient fire evacuation from a facility is fire characteristics. The fire characteristics describe the fire and smoke development dynamics through a building on fire. These characteristics are usually simulated by software, such as Fire Dynamics Simulator (FDS) and PryroSim, or collected by sensors in a building. The second technology group in FIG 3 shows the contemporary technologies and statistics of corresponding articles which apply these technologies to capture and analyze the characteristics of fire and smoke either in simulation or in real-time.

Fire Dynamics Simulator (FDS) and PyroSim are two popular fire simulation programs. FDS, developed by the National Institute of Standards and Technology (NIST) of the U.S. Department of Commerce, is a computational fire-driven fluid dynamics model. The inputs of FDS simulations include the geometry of a building, building materials, ventilation types, locations of windows, doors, sprinklers and smoke detectors, and combustion types. The FDS generates reports including available local egress time (ALET) which are used to compare required egress time (Mirahadi et al. 2019; Wang et al. 2014; Wang et al. 2015). The FDS also provides the results of temperature, carbon monoxide concentration, and other toxic gas distribution data. These results assist the proposed fire evacuation systems to analyze evacuation routes and display them in BIM (Han et al. 2013; Schatz et al. 2014; Wang et al. 2015) or VR (Yan et al. 2020).

PyroSim is a graphical user interface which enables the users to build fire simulation models. It uses FDS as a fire and smoke simulation engine. It also facilitates the information exchange between BIM and FDS. During the data transfer process, the physical characteristics information of a building is seamlessly imported to represent the building geometry in the simulation program. Meanwhile, building materials and building components (i.e. building zones) are automatically grouped and made ready for users to customize their thermal properties for FDS analysis in PyroSim (Sun and Turkan 2020). The simulation outputs, including temperature, toxicity, and smoke conditions, are then used to visualize the smoke view and fire development in PyroSim and BIM (Sun and Turkan 2019; Sun and Turkan 2020; Zhang et al. 2018). Sun and Turkan (2019) and Chen et al. (2018) assessed the building's fire resistance level by determining its available safe egress time (ASET) for pedestrians.

On the other hand, Han et al. (2013) conducted experimental investigations, through sensors installed in a building, to develop a real-time evacuation route planning method that acquired temperature and carbon monoxide concentration data to evaluate the status and spread of fire. The route planning method utilized several user positioning and sensing methods to integrate real-time data acquisition of temperature of the thermal gas and carbon monoxide concentration of the smoke, risk distribution calculation, and evacuation route formulation for a high-rise building fire.

3.3 Crowd evacuation simulation software and routing algorithm

In case of an emergency in a building structure, evacuation time plays a major role in determining the safety of the building occupant. Several state and national building codes discuss numerous factors in creating a safe and reliable environment for building occupants. Topics such as fire resistive construction, fire protection systems, means of egress, and structural design regulation etc. occupy the prime contents of any national building codes. A building will only receive the certificate of occupancy after a thorough walkthrough to assure that the construction is building code compliance. Every building will be accompanied with a means of egress to guide occupants to evacuate to a safest area during an emergency evacuation. However, several human errors during an emergency tend to deviate and create confusion within the occupants during the evacuation process. There are two research directions through the literature in guiding building occupants evacuate from a building efficiently- crowd evacuation simulation software and evacuation routing algorithm.

3.3.1 Crowd evacuation simulation software

Human behavior and characteristics affect evacuees' decisions during the emergency situations. These characteristics and behavior are usually simulated by evacuation software. According to Kuligowski et al. (2010), the evacuation modeling methods are categorized as movement models, behavioral models, and partial behavior models. Movement models move occupants from one point in one building to another, usually an exit. The purpose of movement models is to optimize (minimize) time in an evacuation. Behavioral models are those models that incorporate occupants performing actions, in addition to movement toward a specified exit. Partial behavior models incorporate occupant behavior under urgent circumstances into building physical features to calculate occupant movement. Kuligowski (2016) further provided computer modeling guidance for fire evacuation scenarios and explained the evacuation modeling configuration in an example.

On the other hand, Santos and Aguirre (2004) categorize emergency evacuation simulation methods as flow-based model, agent-based model, and cellular automata model. The flow-based model enables the user to define walking speed, physical constraints in walkways and stairways, density, and distribution of occupants in a building. It excludes the social behavior of individual evacuees and focuses on estimating the evacuation time of flow of the process. Both movement model and flow-based model are to estimate and optimize evacuation time at macroscopic view. They are interchangeable in a sense. The agent-based model is a microscopic model in which an evacuee is represented by an agent. Each agent has human attributes. The agent-based model can capture the emergent behavior in individuals. Both behavioral model and agent-based model account for evacuee social behavior at a microscopic level. Therefore, these two terminologies are interchangeable. The cellular automata model is also a microscopic model in which an occupant is represented by a cell state. The occupants in this model move from cell/grid space to another cell by the simulated throw of a weighted die. The model is also labeled as partial behavioral because of the individual inputs that the software user can assign to certain occupants, such as patience and reaction (assigned in seconds) and dawdle and sway (assigned stochastically to a certain percentage of the population) (Kuligowski et al. 2005; Kuligowski et al. 2010).

Pathfinder, Pedestrian Dynamics and EVACNET4 are the mostly used movement/flow-based models in building fire evacuation. In Pathfinder the occupants move toward the exits under the constraints of the Society of Fire Protection Engineers (SFPE) Handbook, which incorporates speed reductions based on the density of the space and the capacity of the doors and stairways. The model views the population through a global view only to assess the density of certain areas of the building. The occupants, on the other hand, have a global view of the building because of their route choices. They can choose the shortest route to the exit or the shortest cue route. The software user specifies initial occupant loading by specifying the density in certain areas or by giving discrete numbers of occupants. Examples of the output are the number of people that have used an exit; minimum, maximum, and average time for people to exit from a given room, the times a room, hall, or stair becomes empty; the time a floor becomes empty; and total evacuation time. Pathfinder could be coupled with an external fire model, such as Pyrosim, and building physical feature models, such as Revit and AutoCAD. Zhang et al. (2018) and Liu et al. (2018) used the steering mode in Pathfinder to dynamically simulate evacuation according to personnel distribution, hazards development and collision to design an efficient and more realistic evacuation plan. Chen et al. (2020) applied pathfinder to develop an efficient evacuation plan for a high-rise nursing home whilst Weerasekara (2015) applied Pedestrian Dynamics to simulate the crowd evacuation in a Stadium and compare the total simulated evacuation time with real evacuation time to explore the shortest cleared path.

EVACNET4 is another user-friendly interactive and movement-based model computer program, which instead enables users to describe a building as a network of nodes. A network is composed of nodes and arcs. A node is a spatial description of rooms, stairs, lobbies, and hallways. Certain nodes are designated as “destination nodes” through which occupants exit. An arc connects nodes. Each arc is a passageway between building components (nodes). An arc flow capacity delimits the number of occupants that can traverse the passageway per time period. EVACNET4 takes the completed network model and determines an optimal plan to evacuate the building in a "minimum" amount of time. The results of a simulation model include total time periods, average number of periods for an evacuee to evacuate, and number of successful evacuees. However, the manual inputs of nodes and arcs information of EVACNET4 program is time consuming and mistake prone (Zhu et al. 2018). In addition, the movement/flow-based models lack human behavior and sociological aspects. These models eschew the need of individual’s decision-making processes under emergency evacuations and impede the prospect of more realistic results while agent-based models consider the local dynamics of individuals and interactions between pedestrians with their immediate environments. This literature review finds that Massmotion, Anylogic, EscapeSim and UbikSim are the mostly used agent-based model evacuation software.

In Massmotion an environment is represented as a continuous space and each agent can move freely over all coordinates. There are two types of agents in the Massmotion – bound agents, who follow the assigned routes, and unbound agents. An unbound agent selects a route based the perceived cost in terms of distance, opposing flow, queuing tolerance and congestion. The evacuation model takes into consideration both static and dynamic obstacles. The static obstacles can be walls, formwork, etc. and the dynamic obstacles can be other agents that have their own

speed, size, etc. (Marzouk and Al Daour 2018). Available local egress time (ALET) is calculated for each route and used to compare with required safe egress time (RSET) to design safe building layout (Mirahadi et al. 2019). Marzouk and Al Daour (2018) applied Massmotion model to calculate the total required evacuation time of each floor over a high-rise building construction duration. Their simulation results helped a contractor to develop effective emergency plans during the construction stage. AnyLogic is another agent-based model software. Its pedestrian library is a pedestrian simulation and crowd analysis tool which allows users to accurately model, visualize, and analyze how crowd flows behave in a physical environment, and eliminate its possible inefficiencies

(Bina and Moghadas 2020). Like Massmotion, AnyLogic models calculate available safe egress time (ASET) for each route. The results are used to compare with required safe egress time (RSET) to design safe building layout (Cheng and Gan 2013; Sun and Turkan 2019; Sun and Turkan 2020).

On the other hand, there are open and free agent-based model software, such as EscapeSim (EscapeSim 2013), UbikSim (UbikSim 2016) and GAMA (GIS Agent-based Modeling Architecture). UbikSim enables users to create realistic space models by using a drag and drop editor. However, it lacks some important features of an emergency simulator, such as realistic models of emergencies and evacuation algorithms. The features created in UbikSim can be automatically inherited by EscapeSim in which emergency domain is developed. Therefore, Serrano et al. (2014) used UbikSim and EscapeSim jointly to conduct emergency evacuation simulation and evaluate the evacuation plans. GAMA is mostly applied in the domains of transportation, urban planning, and disaster response. Nguyen et al. (2013) used GAMA to model the Metro supermarket of Hanoi by integrating a model of smoke diffusion. They study the smoke effect on the evacuee's visibility, speed, and evacuation strategy, and optimize the evacuation strategies by taking into account the level of visibility.

Cell-DEVS is a discrete event cellular automata paradigm that allows a hierarchical and modular description of the models. Each DEVS model can be behavioral or structural, consisting of inputs, outputs, state variables, and functions to compute the next states and outputs (Wainer et al. 2004). CD++ is a toolkit for discrete-event modeling and simulation. Wang et al. (2012) used the CD++ with Cell-DEVS, to understand the bottlenecks/congestion and determine the maximum occupation within a satisfactory evacuation time in the design phase. Their simulation output can be used for 2D and 3D visualization. In the meantime, Liu et al. (2014) emphasized the importance of human behavior and reaction to the emergency environment. They developed a framework to build a human library that included validated human egress behavior using a BIM based gaming environment. This framework could be applied to the evacuation simulations and improve the accuracy of the emergency evacuation analysis.

3.3.2 Routing algorithm

The other direction to guide building occupants evacuate from a building is evacuation routing algorithms developed or implemented by researchers and practitioners. Evacuation routing algorithms aid in providing safest and shortest path of occupant evacuation in case of an emergency (Ghorpade and Rudrawar 2019). Several evacuation algorithms in the literature use various principles and computational models to automatically generate the required occupant evacuation paths during an emergency. The evacuation algorithms through our literature review include neural networks, graph theory, shape recognition, agent-based modeling, and serious games.

Neural Networks, graph theory, and shape recognition principles are applied for conducting modeling, segmentation, optimization, and searching on different datasets collected from various sensors in a building structure. Peng et al. (2019) developed a neural network-based path-planning method that utilizes occupants' positions, hazard sources' positions, spatial topologies of the building, and the crowdedness of the area to automatically generate evacuation plans of large public buildings. Under any given environmental circumstances, the developed neural network will learn and calculate the safest and shortest evacuation path. Kim and Lee (2019) studied the changing environment and progress of a construction site to generate emergency evacuation plans for workers safety. This study utilized the A* search algorithm that calculates the shortest path between the workers location to the safest exits in a construction site by defining the workers job spaces and mapping the entire area of the job site as a rectangular grid configured according to distinctive site conditions of a particular workday. This A* path planning algorithm utilizes the mapped grid to find an optimal evacuation path for each assigned job site of a worker. Xu et al. (2016) presented a combination of Triangular Irregular Network (TIN) method to generate a customized network using critical points in a building space using 2D floor plans and an optimal algorithm for crowd evacuation. Using this combination, the presented method aims to develop an automatic way to generate connected network datasets for CAD/BIMs in GIS for developing an efficient optimal crowd evacuation from inside of a building to an outdoor exit. Yan et al. (2019) developed a system utilizing the ant colony optimization algorithm to make the scene and dynamic smoke model lightweight so that public could visualize smooth fire evacuation drills in real-time on Mobile Web3D devices. Several studies integrated network analysis with shape recognition principles for emergency rescue routing and communication. Chen and Chu (2016) utilized medial axis-transform to construct graphs from indoor BIM models for element level network modeling and recuse route mapping using actual building layouts and conditions. These automated approach to map recues routes will assist in-building emergency routing decisions in situations for large infrastructures with complex geometric spaces. The authors of the developed approach aim to assist complicated decision making during such emergency situations by bridging network modeling principles and abundant information stored in BIM.

Some researchers also explored using agent-based modeling principles for modeling and simulation of evacuation of building occupants during an emergency. Mirahadi et al. (2019) developed a tool for designers to create optimized layouts for buildings and facilities based on their evacuation safety performance and to quantify the safety of the egress routes and individual building compartments. This tool integrates fire dynamic simulation, agent-based crowd simulation, and BIM to create a platform for designers to analyze the building layout design under various emergency scenes. Similarly, Marzouk and Mohamed (2018) created a framework that utilizes agents' behavior in emergency situations with the BIM model geometry to visualize the fire evacuation process. This framework will rank and assess the level of safety provided by the building structures during emergency situations.

Serious games and game technology can greatly benefit fire simulation research as it helps in accurately understanding fire environments and visualizing efficient fire rescue operations (Liu et al. 2014; Rüppel and Schatz 2011; Wei et al. 2019). Rüppel and Schatz (2011) evaluated the effect of the building condition on the human behavior during an evacuation process using serious gaming approach and BIM modeling and developed a realistic serious game prototype for engineering simulations.

3.4 Indoor occupant real-time locating/tracking system and mobile device/IoT technology

With the increase in complex nature of architecture and construction, planning and execution of occupants' evacuation during an emergency is becoming intricate. Traditional Emergency evacuation methods offer the same escape route to all evacuee types regardless of the dynamically changing individual evacuee features such as evacuee type, type of emergency, location of the evacuee, and availability of the shortest path (Atila et al. 2018; Inoue et al. 2008; Ma and Wu 2020; Mirahadi et al. 2019). To address such issues, more and more researchers and practitioners are attentive to the intelligent and personalized emergency evacuation systems, which explore using mobile interface-based evacuation system to provide dynamic escape route information that adapts to different emergency situations and evacuee features. Indoor routing system is an indispensable component for the intelligent and personalized building emergency evacuation system since the building occupants have no knowledge about the transiently changing situation of a building. One of the key components of an indoor routing system is to identify occupants' locations within the building in real-time. Indoor occupant real time locating and tracking algorithms aim to accurately identify the exact location of building occupants during an emergency and support emergency response operations. For example, Li et al. (2014) designed an environment aware beacon deployment algorithm to locate building occupants and first responders during fire emergency scenes. The designed method is BIM centered for room-level localization of first responders and trapped occupants and integrates with sequence-based localization (SBL) for timely access to location information. A localization server will communicate with smart devices of the first responders and occupants to provide location information which will be integrated with the emergency response frameworks for reliable communication and collaboration in emergency operations. This designed method was extensively tested in real-time emergency situations in collaboration with first responders from the Los Angeles Fire Department.

Several other authors conducted studies on enhancing complex fire evacuation and simulation data handling capabilities of mobile applications to create a real-time fire emergency evacuation system for building occupants. One such study created a mobile Web3D fire evacuation visualization application using data from BIM and FDS (Yan et al. 2020). This study created a lightweight 3D scene model and dynamic smoke for high quality mobile Web3D visualization that can provide optimal escape routes during an emergency. The developed mobile Web3D interface was tested on building occupants and the results show that experience of a fire evacuation drill was smooth, real-time evacuation systems was efficient, and achieves higher evacuation rates than previous studies.

Both indoor occupant real time locating/tracking system and mobile device service require wireless network technologies as the infrastructure support. This study finds that a few wireless network technologies are applied in the real-time occupant locating - WiFi /WLAN, radio frequency identification (RFID), ultrawide band (UWB), and Bluetooth low energy (BLE).

WiFi/WLAN network is a local area wireless network which connects multiple digital devices. Users remain connected to the network while moving around within limited areas such as a house or a building. Ma and Wu (2020) applied WiFi fingerprint positioning technology to locate the mobile phones in a building to determine the location of the building occupants. In their developed system, building occupants' mobile phones can collect the WiFi signal strength from multiple access point (AP) hotspot points. All data collected in the fingerprinting process needs to be classified and updated according to the people who come and leave the building. When a fire occurs, the system identifies the building occupants’ locations by matching the signal strengths from occupants’ mobile phones and previously established fingerprint data to find the corresponding point based on the nearest neighbor in signal space (NNSS) algorithm.

RFID technology transmits data wirelessly without having a line of sight. Due to this advantage, Costin and Teizer (2015) developed a framework that combined RFID technology with building information model (BIM) to track real-time location of evacuees. Gokceli et al. (2017) proposed using wearable device detection and identification service to identify evacuee’s location. This service stored data which included a list of the RFID readers located in the building. It also stored signal data generated by the RFID Reader and Tag Service for a corresponding reader. This service requested RSSI from the RFID reader to match the data stored in the system, then determined the location of an evacuee. Atila et al. (2018) developed SmartEscape which consisted of a sensor network, positioning system, mobile application with graphical user interface, and intelligent routing engine. The sensor network, which was deployed in a building, sent instant measurement of the building while an RFID positioning system sent the position of the evacuee to the intelligent routing engine periodically.

UWB technology can transmit data between digital devices wirelessly at high data rate within short distance. It also enables accurate three-dimensional positioning. In 2010, Rüppel et al. (2010) proposed using UWB, WLAN, as well as RFID technologies for an airport fire evacuation system. UWB was used in the large areas such as baggage areas of the airport to accurately identify passenger locations and evacuate them in the case of emergencies while WLAN fingerprinting method was applied in offices and passenger areas of the airport to develop real-time location of passengers in order to guide passengers evacuating. In the meantime, the RFID system was utilized in cellars and underground parking garages for real-time evacuee location tracking.

The use of BLE technology in building evacuation systems usually combines with beacons and BIM. For example, Inoue et al. (2008) developed an indoor positioning system which required users to carry beacon receivers to receive signals from beacons installed in the facility. Users’ cell phones estimated the users’ location based on the data of beacon receivers. Park et al. (2017) installed BLE sensors on a construction site and used personal mobile devices to track moving targets. His team also integrated BIM into the moving target tracking system to prevent false detection of movements using boundary constraints. Cheng et al. (2017) and Zhang et al. (2019) also used mobile devices and BLE technology to establish real-time Bluetooth communication with the surrounding sensors, and the locations of the mobile devices are determined based on the received signal strength (RSS) method.

4. COMMUNICATION PROTOCOLS AMONG THE VARIOUS TECHNOLOGIES

Four technology groups are discussed in detail in the above section. To develop an integrated fire emergency evacuation system, communication protocols or data exchanges among the various technologies play a significant role (FIG 4). The following sections present the commonly used data sharing format and data processing tools which are found through our literature review.

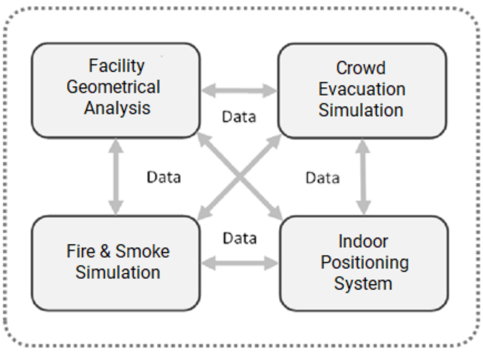

FIG. 4: Data exchanges among the technology groups.

4.1 Data sharing format

Data sharing is critical in emergency evacuation systems since they consist of diverse subsystems such as building models, routing systems, fire simulation systems, evacuation simulation systems and so on. Each system has its own data format and how to make the data exchange more efficient between different systems contributes to effectiveness of the emergency evacuation system. International Finance Corporation (IFC), Extensible Markup Language (XML), Green Building XML (gbXML), City Geography Markup Language (CityGML) are main data sharing formats that are found in the existing studies.

Industry Foundation Class (IFC) is a standard for BIM data exchange. IFC itself is not a data exchange format but a schema, but different systems related to BIM exchange their data more efficiently by following the IFC schema. IFC is one of the most widely used data schema in any systems involving BIM. Ma and Wu (2020) used IFC data structure to connect five modules, monitoring data, personnel information, building information, facility information and mobile data in their fire emergency management system (FEMS). Mirahadi et al. (2019) integrated fire dynamics simulation, agent-based crowd simulation and building information models using IFC data structure in their EvacuSafe system. It enabled users to analyze a building layout, fire scenarios and design layout based on diverse safety criteria. Rüppel and Schatz (2011) designed a BIM-based game for fire safety evacuation simulations and IFC was used for the data exchange between the BIM software and the BIM game engine. Isikdag et al. (2013) developed a new indoor navigation model based on IFC schema, which provides detailed semantic information for efficient indoor navigation, and represents the complex geometries of BIMs and non-georeferenced structures. Choi et al. (2014) suggested the various technologies for quality checks for evacuation regulations based on BIM and IFC. Expandable development methods including the definition of property information and the structure of evacuation regulation are suggested in the IFC-based structure.

Extensible Markup Language (XML) is a markup language designed to store and transport data (W3Schools 2021). It enables effective data transfer between various systems including evacuation systems. Kim and Lee (2019) developed a plug-in consisting of 4D BIM platform that reads the output information for path planning based on XML format. The platform includes site component creation and scheduling creation in the evacuation system. While developing a mobile tracking system, Park et al. (2017) extracted geometry and object information from a BIM model into a XML file to import into their mobile system. Rüppel et al. (2010) used different data formats including IFC, XML, Green Building XML (gbXML), and a manufacturer's own format via a web service. For the data transfer in the area of the Wi-Fi, XML-based format was used.

Green Building XML (gbXML) is the language that enables data transfer between building design software tools, and it is supported by organizations including U.S. Department of Energy (DOE), National Renewable Energy Lab (NREL), Autodesk, and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (gbXML Schema Inc 2021). Since most of evacuation systems include building geometries and associated data, they use gbXML for the data communication between their sub-systems. Also, Revit, one of the most widely used BIM tools, supports gbXML, IFC, and other various design formats. Rüppel et al. (2010) imported building data from the model using gbXML format since it was suitable for their evacuation system in that it can explain complex geometries based on its clear hierarchical structure. Boguslawski et al. (2015) proposed an model integrated BIM and GIS for emergency response based on gbXML, IFC, etc. gbXML was used as the main data format for an input. They simplified a detailed geometry, and the simplified model was exported to the gbXML-based model for the next step analysis. Also, geometry of the indoor building model could be retrieved conveniently from the gbXML format. While developing a BIM-GIS model for automated selection of safe and balanced route. Zverovich et al. (2016) used gbXML format to export the building information and reconstruct for the next step data structure used for GIS.

CityGML is an XML-based open data model to store and exchange data for virtual 3D city models, which is an application schema for the Geography Markup Language (GML). It was developed to define the basic entities, attributes, and relations of a 3D city model (Open Geospatial Consortium 2021). For a large-scale evacuation system covering wider areas and multiple buildings, CityGML can export the building and geographical information effectively. El-Mekawy et al. (2011) used both CityGML and IFC for a bidirectional data conversion between them (Maheshwari and Rajan 2016).

4.2 Data processing tool

.NET is an open source developer platform to develop diverse types of applications using multiple languages, editors, and libraries for games, desktop, web, mobile, and internet of things (IoT) (Microsoft 2021). Revit provides .NET API which can be used to extend the functionality of Revit (Autodesk 2021). Numerous studies used Revit API to develop customized new functions and to process data from different sub-systems in their evacuation systems. Chen and Chu (2016) automatically extracted geometric information from BIM through the Revit API. used Revit API for the interaction between the integrated data and BIM-based 3D visualization capabilities in their evacuation system. Bina and Moghadas (2020) exported the layout of a Revit model to their human behavior simulation through the Revit API. Marzouk and Al Daour (2018) created 4D models using the Revit API that connected Revit and the Timeliner. The tool consists of 6 tasks, (1) Browse File, (2) Assign Selected Elements, (3) Add Selected Elements, (4) View Selected Elements, (5) View Model, (6) Export IFC Model.

Forge is a platform of web service APIs that help to integrate and access design and engineering data via cloud. It embeds some of the components in Autodesk products into the user's customized web of mobile applications (Nagy 2017). In a framework for a fire evacuation management system, Zhang et al. (2019) employed Forge viewer platform where users can display the information of the entity, and operate the view options.

Per our literature review and content analysis, technologies used in fire emergency evacuation are identified and categorized into four groups per geometrical features of a facility, fire and smoke characteristics, evacuation simulation models and routing algorithms, and evacuee location and tracking. The data exchange formats and data processing tools among the various technologies are presented above. The following section presents future development and challenges of fire emergency evacuation studies.

5. FUTURE DEVELOPMENT AND CHALLENGES

With market available wireless technology, the recent research trend on building fire evacuation systems starts to utilize mobile devices and wireless communication technologies to develop intelligent and personalized fire evacuation systems. The main components of these newly developed systems usually include wireless enabled network, facility geometrical module which mainly uses BIM technology, real-time location (RTL) module, evacuation routing module, and mobile device module. The wireless network is the fire evacuation system infrastructure which usually includes gateways, sensors deployed through a building, and cloud service. The BIM module stores building geometrical information, dynamic fire and smoke development which may be collected from sensors, and even sensor information and their locations. A real-time location (RTL) module dynamically identifies occupants' indoor locations and their movements. The evacuation routing module calculates safe routes and updates these routes in case the fire situation changes. All the information of BIM module and RTL module is transmitted by the wireless enabled network to a cloud-based evacuation routing module. Finally, the mobile device module serves as a user interface between the building occupants and the fire evacuation system. The fire evacuation system dynamically pushes personalized turn-by-turn evacuation guidance to the smartphone or mobile device holders and eventually directs them safely exit the building. Each module of an intelligent and personalized fire evacuation system has various technologies available, which have their own pros and cons. Among these technologies, wireless network infrastructure and accurately and quickly locating occupants' position and movement are the key components in developing an intelligent and personalized fire evacuation system. The following sections address the challenges in terms of wireless network and real-time location tracking.

5.1 Data sharing format

Obviously, all modules of an intelligent and personalized fire evacuation system would not function properly without the wireless network infrastructure. Current research in building fire evacuation systems adopts radio frequency identification (RFID), wireless LAN(WLAN)/WiFi, ultra-wide band (UWB), and Bluetooth low energy (BLE) wireless network systems. A RFID system has two basic parts: tags and readers. The reader gives off radio waves and gets signals back from the RFID tag. The system passively identifies a tagged object using radio waves and provides a static position indication with very inexpensive hardware. However, continuous tracking is not possible, but only information about whether an object is registered at a certain moment at a certain location (Favendo 2021). WLAN/WiFi, a popular wireless network in homes and some commercial properties such as office building due to easy system installation, connects two or more than two digital devices through wireless communication within a limited area. However, indoor object tracking and positioning via WLAN/WiFi network has not been proven neither in terms of location accuracy nor in terms of system stability. In addition, the bandwidth is extremely strained by the localization (Favendo 2021). UWB transmits information across a wide bandwidth, which is more than 500 MHz, at a very low energy level for short-range. It allows for the transmission of a large amount of signal energy without interfering with conventional narrowband and carrier wave transmission in the same frequency band. Most recent applications focus on sensor data collection, precision locating and tracking applications. Up to now, the UWB enabled network has achieved the highest accuracy while it is by far the most expensive technology (Favendo 2021). BLE wireless technology provides considerably reduced power consumption and cost as well as easy installation and relocation while transmitting data within a personal area network (PAN). It is natively supported by mobile operating systems, such as iOS, Android, BlackBerry. The use of BLE technology in building evacuation systems usually combines with beacons. BLE wireless technology paired with beacons has emerged as another indoor location technology. Further Long Range Wide Area Networks (LoRaWAN), which is developed as an open standard in unlicensed spectrum, allows anyone to set up their own desired network. This opens up for interesting dynamics in a business area dominated by mobile network operators. Therefore, LoRaWAN technology has been investigated in terms of indoor locating and tracking application. The study of Henriksson (Henriksson 2016) shows developing more complex positioning algorithms is a necessity for indoor locating and tracking applications by using LoRaWAN technology.

While adopting a wireless network for developing fire emergency evacuation systems, the range/coverage, power, bandwidth, cost, easiness of installation and positioning accuracy are the factors to be considered. The factors - range, power and bandwidth - are closely related factors in wireless networks, changing one of these will inevitably have an impact on the other two. The FIG 5 shows the comparison of these wireless network technologies in terms of network coverage, indoor position accuracy, and cost. The cost and coverage of each technology has been scaled from 1 through 5 at horizontal and vertical axes. 5 indicates the most cost-effective and largest-coverage wireless technology respectively. The size of a bubble indicates the positioning accuracy of each technology. A larger bubble indicates a higher positioning accuracy of a wireless network. This FIG 5 provides the factors and information that the researchers and practitioners would consider while adopting wireless network infrastructure for an intelligent and personalized building evacuation system with IoT service. Many studies are competing to provide cheap and easy-to-install solutions meanwhile the network is low power consumption, wide bandwidth, long range, and accurate locating possibility, making for quite a challenging task.

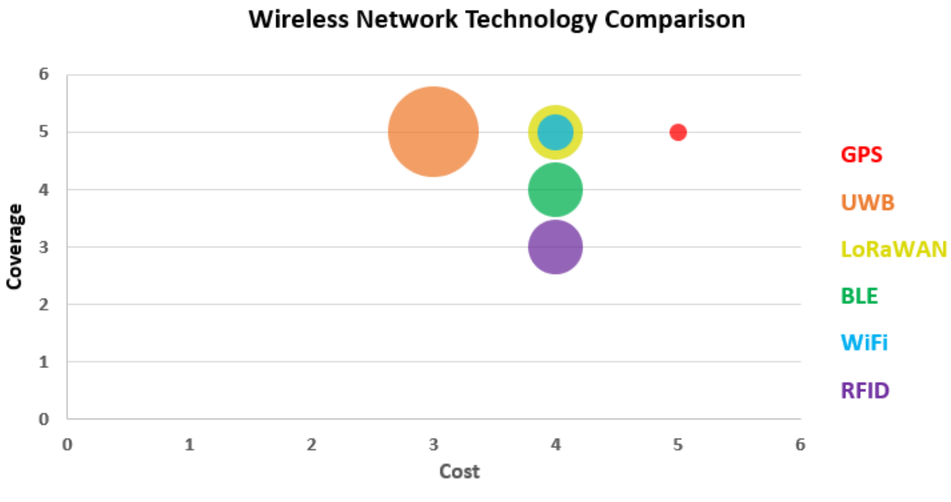

FIG. 5: Comparison of wireless technologies in terms of coverage, cost, and positioning accuracy.

5.2 Data sharing format

The occupant location tracking within a building is another key component in a personalized and intelligent fire evacuation system. Based on the wireless network used in an intelligent and personalized fire evacuation systems, the real-time location and tracking module may use different schemes and algorithms. No matter what wireless network a fire evacuation system uses, there are two phases involved in developing real-time location and tracking module: offline training phase and online location phase (FIG 6). During offline training phase, wireless signal data, e.g. received signal strength indication (RSSI) from BLE beacons and received signal strength (RSS) from

WLAN access points (AP) is collected (called fingerprinting process) and processed. Then location prediction model is constructed with certain algorithm based on the collected and processed data. The existing algorithms to establish location prediction models include k-nearest neighbor (KNN) (Bahl and Padmanabhan 2000; Bhasker et al. 2004), smallest m-vertex polygon method (Prasithsangaree et al. 2002), probabilistic method (Kontkanen et al. 2004), neural networks (Mehmood et al. 2010), decision tree (Yim 2008) and support vector regress (SVR) (Shi et al. 2015). The goal of offline phase is to eliminate abnormal RSSI/RSS data and establish a high quality RSSI/RSS and location database. During online location phase, mobile devices collect the RSSI/RSS information transmitted from BLE beacons/APs. Then, the collected information is input into the location prediction model, which is established in the offline training phase, processed in the online location estimation model to get the best estimated real-time location of occupants. The current algorithms of processing the collected RSSI/RSS at online phase and estimating the real-time occupant location include weighted centroid location (WCL) method (Subedi and Pyun 2017), weighted least-squared method (Tian et al. 2017), adaptive KNN (Oh and Kim 2018), etc. The challenges in real time location and tracking module include:

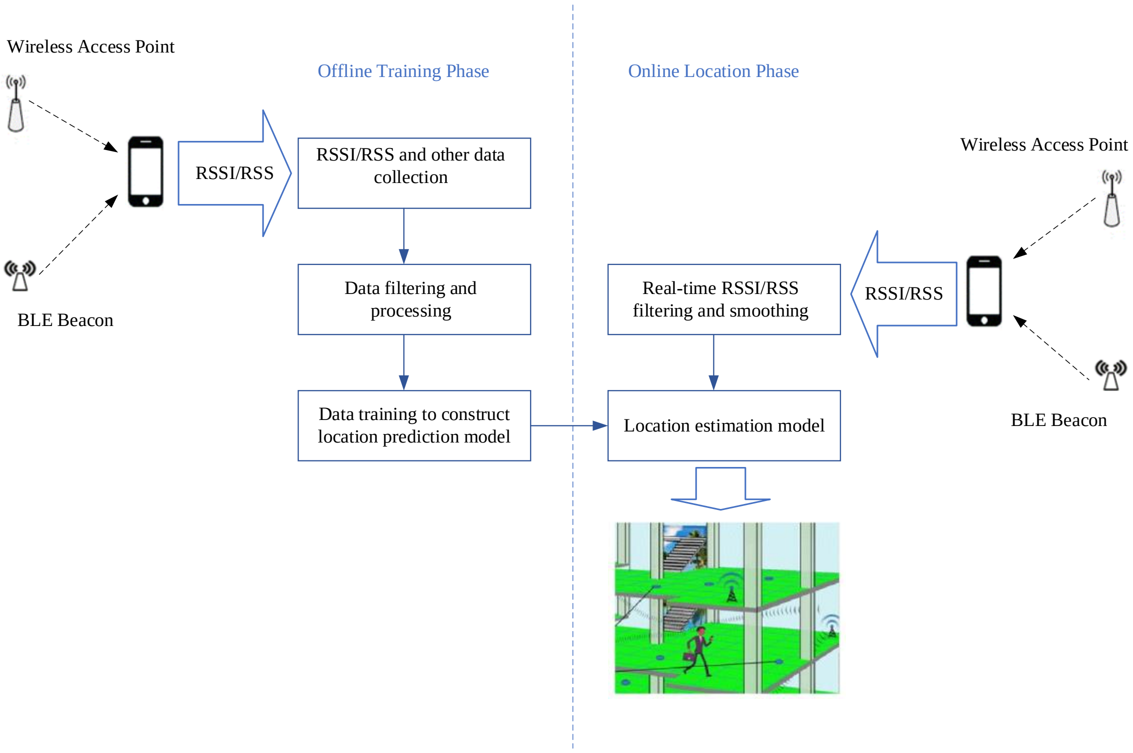

FIG. 6: Real-time location and tracking system.

- Fingerprinting process at offline training phase: fingerprinting is the foundation for constructing location prediction models. Researchers need to collect the information such as the power of the transmit signal, the power of the received signal, propagation parameter, RSSI/RSS at pre-determined reference points at different times and orientations in order to obtain more non-faulty signals. In addition, more reference points in a building area lead to higher possibility of accuracy of location estimate. Therefore, the fingerprinting process is tedious, time consuming and cumbersome.

- Location prediction model at offline training phase: Due to complex indoor environmental noise factors, obstructions as well as attenuation, RSSI/RSS exist high variability even at one reference point. Filtering the collected faulty RSSI/RSS to achieve a high quality location prediction model and database is challenging.

- RSSI/RSS pre-processing at online location phase: the real-time RSSI/RSS received by mobile devices fluctuate due to indoor environmental factors. Therefore, filtering and smoothing the real-time RSSI/RSS becomes a necessity to improve the accuracy of occupants' location estimation. The existing algorithms include Kalman filter, moving average filter, Gaussian filter, etc. Adopting appropriate algorithms according to the selected wireless network whilst reducing computing power is another challenging task.

- Real-time location estimation model at online location phase: The existing algorithms to estimate the occupants' real-time locations according to real-time RSSI/RSS at online phase, e.g. weighted least square method, either consume more computing power or are less accurate. Selecting or developing new algorithms to meet accuracy and promptness of location indication demands future research efforts.

In short, developing less time-consuming data collection and high-quality data training at offline training phase, as well as less computing power consumption and increased location accuracy estimation algorithm at online location phase are the driving forces for accurate real-time occupant location tracking modules. And proper wireless network technology selection catering fire evacuation system design, as well as the integration and communication among the modules of a fire evacuation system are challenges for future intelligent and personalized fire evacuation systems.

6. CONCLUSION

Fire emergency evacuation systems are critical to minimize the casualties and property losses in the built environment during the various types of accidents. Researchers have conducted diverse studies regarding emergency evacuation systems to evacuate occupants more promptly and safely. However, there was a lack of comprehensive review on the components, frameworks and applications of evacuation systems. Thus, this study performed the extensive literature review to investigate the current patterns and trends of research and industry practices in evacuation system, and to provide the guidelines to select appropriate technologies in designing emergency evacuation systems. Existing studies were reviewed and the main categories were summarized with buildings, humans, incidents, and routings.

This study reviewed emergency evacuation systems focusing on fire evacuation systems. Various technologies in evacuation systems were analyzed in depth based on four categories: 1) building-related technologies such as BIM, GIS, VR. 2) human-related technologies such as crowd evaluation simulations, 3) incident-related technologies such as fire and smoke simulations, and 4) routing-related simulations such as indoor positioning systems. This study contributes to academic research and evacuation system development. The findings provide detailed information about the available technologies in the evacuation systems and the main components of the system. These guidelines will help diverse stakeholders to develop evacuation systems based on their specific needs. Furthermore, it will help policy makers to establish evacuation related standards and codes.

REFERENCES

Ahrens, M., and Evarts, B. (2019). "Fire Loss in the United States During 201 9." Quincy, MA: National Fire Protection Association.

Atila, U., Ortakci, Y., Ozacar, K., Demiral, E., and Karas, I. R. (2018). "SmartEscape: A mobile smart individual fire evacuation system based on 3D spatial model." *ISPRS International Journal of Geo-Information*, 7(6), 223.

Atyabi, S., Moghaddam, M. K., and Rajabifard, A. (2019). "Optimization of Emergency Evacuation in Fire Building by Integrated Bim and GIS." *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42, 131-139.

Autodesk (2021). "Revit Developer Center." <https://www.autodesk.com/developer-network/platform-technologies/revit>. (2021).

Bahl, P., and Padmanabhan, V. N. "RADAR: An in-building RF-based user location and tracking system." *Proc., Proceedings IEEE INFOCOM 2000. Conference on computer communications. Nineteenth annual joint conference of the IEEE computer and communications societies (Cat. No. 00CH37064)*, Ieee, 775-784.

Bayat, H., Delavar, M., Barghi, W., EslamiNezhad, S., Hanachi, P., and Zlatanova, S. (2020). "Modeling of emergency evacuation in building fire." *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 43, 321-327.

Bhasker, E. S., Brown, S. W., and Griswold, W. G. "Employing user feedback for fast, accurate, low-maintenance geolocationing." *Proc., Second IEEE Annual Conference on Pervasive Computing and Communications, 2004. Proceedings of the*, IEEE, 111-120.

Bi, X. Y., Wang, J., and Zhang, J. Y. "The Exploration of BIM Technology Application in the Building Fire Emergency Plan." *Proc., Applied Mechanics and Materials*, Trans Tech Publ, 2473-2477.

Bina, K., and Moghadas, N. (2020). "BIM-ABM simulation for emergency evacuation from conference hall, considering gender segregation and architectural design." *Architectural Engineering and Design Management*, 1-15.

Boguslawski, P., Mahdjoubi, L., Zverovich, V., Fadli, F., and Barki, H. (2015). "BIM-GIS modelling in support of emergency response applications." *Building Information Modelling (BIM) in Design, Construction and Operations*, 149, 381.

Chen, A. Y., and Chu, J. C. (2016). "TDVRP and BIM integrated approach for in-building emergency rescue routing." *Journal of Computing in Civil Engineering*, 30(5), C4015003.

Chen, A. Y., and Huang, T. (2014). "BIM-Enabled Decision Making for In-Building Rescue Missions." *Computing in Civil and Building Engineering (2014)*, 121-128.

Chen, X., Liu, C.-C., and Wu, I.-C. (2018). "A BIM-based visualization and warning system for fire rescue." *Advanced Engineering Informatics*, 37, 42-53.

Chen, Y., Wang, C., Yap, J. B. H., Li, H., Hu, H. S., Chen, C.-C., and Lai, K.-K. (2020). "Fire Evacuation Process Using Both Elevators and Staircases for Aging People: Simulation Case Study on Personnel Distribution in High-Rise Nursing Home." *Discrete Dynamics in Nature and Society*, 2020.

Cheng, J. C., and Gan, V. J. (2013). "Integrating agent-based human behavior simulation with building information modeling for building design." *International Journal of Engineering and Technology*, 5(4), 473.

Cheng, M., Chiu, K.-C., Hsieh, Y.-M., Yang, I.-T., Chou, J.-S., and Wu, Y.-W. (2017). "BIM integrated smart monitoring technique for building fire prevention and disaster relief." *Automation in Construction*, 84, 14-30.

Choi, J., Choi, J., and Kim, I. (2014). "Development of BIM-based evacuation regulation checking system for high-rise and complex buildings." *Automation in construction*, 46, 38-49.

Costin, A. M., and Teizer, J. (2015). "Fusing passive RFID and BIM for increased accuracy in indoor localization." *Visualization in Engineering*, 3(1), 1-20.

El-Mekawy, M., Östman, A., and Shahzad, K. (2011). "Towards interoperating CityGML and IFC building models: a unified model based approach." *Advances in 3D geo-information sciences*, Springer, 73-93.

EscapeSim (2013). "gsi-upm / EscapeSim." <https://github.com/gsi-upm/EscapeSim>.

Favendo (2021). "Indoor location tracking – Five technologies in brief." <https://www.favendo.com/rtls/indoor-location-5-technologies>.

Fu, M., and Liu, R. (2020). "BIM-based automated determination of exit sign direction for intelligent building sign systems." *Automation in Construction*, 120, 103353.

gbXML Schema Inc (2021). "gbXML." <https://www.gbxml.org/>. (2021).

Ghorpade, P. S., and Rudrawar, S. K. "Review on Evacuation Systems for Indoor Fire Situation." *Proc., International Conference on Computer Networks and Inventive Communication Technologies*, Springer, 28-37.

Gokceli, S., Zhmurov, N., Kurt, G. K., and Ors, B. (2017). "IoT in action: Design and implementation of a building evacuation service." *Journal of Computer Networks and Communications*, 2017.

Han, Z., Weng, W., Zhao, Q., Ma, X., Liu, Q., and Huang, Q. (2013). "Investigation on an integrated evacuation route planning method based on real-time data acquisition for high-rise building fire." *IEEE Transactions on Intelligent Transportation Systems*, 14(2), 782-795.

Henriksson, R. (2016). "Indoor positioning in LoRaWAN networks."

Inoue, Y., Sashima, A., Ikeda, T., and Kurumatani, K. "Indoor emergency evacuation service on autonomous navigation system using mobile phone." *Proc., 2008 Second International Symposium on Universal Communication*, IEEE, 79-85.

Isikdag, U., Zlatanova, S., and Underwood, J. (2013). "A BIM-Oriented Model for supporting indoor navigation requirements." *Computers, Environment and Urban Systems*, 41, 112-123.

Kim, K., and Lee, Y.-C. (2019). "Automated generation of daily evacuation paths in 4D BIM." *Applied Sciences*, 9(9), 1789.

Kontkanen, P., Myllymaki, P., Roos, T., Tirri, H., Valtonen, K., and Wettig, H. "Topics in probabilistic location estimation in wireless networks." *Proc., 2004 IEEE 15th International Symposium on Personal, Indoor and Mobile Radio Communications (IEEE Cat. No. 04TH8754)*, IEEE, 1052-1056.

Kuligowski, E. D., Peacock, R. D., and Hoskins, B. L. (2005). *A review of building evacuation models*, US Department of Commerce, National Institute of Standards and Technology ….

Kuligowski, E. D., Peacock, R. D., and Hoskins, B. L. (2010). "A Review of Building Evacuation Models; 2nd Edition." U. S. D. o. Commerce, ed., National Institute of Standards and Technology.

Kuligowski, E. D. (2016). Computer evacuation models for buildings. In SFPE handbook of fire protection engineering (pp. 2152-2180). Springer, New York, NY.

Lexipol (2019). "Understanding and Measuring Fire Department Response Times." <https://www.lexipol.com/resources/blog/understanding-and-measuring-fire-department-response-times/>.

Li, N., Becerik-Gerber, B., Krishnamachari, B., and Soibelman, L. (2014). "A BIM centered indoor localization algorithm to support building fire emergency response operations." *Automation in Construction*, 42, 78-89.

Liu, R., Du, J., and Issa, R. R. (2014). "Human library for emergency evacuation in BIM-based serious game environment." *Computing in Civil and Building Engineering (2014)*, 544-551.

Liu, X., Zhang, H., and Zhang, P. "Simulation Study on Collaborative Evacuation Among Stairs and Elevators in High-Rise Building." *Proc., International Conference on Smart City and Intelligent Building*, Springer, Singapore, 163-172.

Lovreglio, R., Thompson, P., and Feng, Z. (2022). "Automation in Fire Safety Engineering Using BIM and Generative Design." Fire Technology, 58(1), 1-5.

Ma, G., and Wu, Z. (2020). "BIM-based building fire emergency management: Combining building users' behavior decisions." *Automation in Construction*, 109, 102975.

Mahdaviparsa, A., and McCuen, T. (2019). "Comparison Between Current Methods of Indoor Network Analysis for Emergency Response Through BIM/CAD-GIS Integration." *Advances in Informatics and Computing in Civil and Construction Engineering*, Springer, 627-635.

Maheshwari, N., and Rajan, K. (2016). "A Semantic Model to Define Indoor Space in Content of Emergency Evacuation." *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, 41.

Marzouk, M., and Al Daour, I. (2018). "Planning labor evacuation for construction sites using BIM and agent-based simulation." *Safety science*, 109, 174-185.

Marzouk, M., and Mohamed, B. "Multi-criteria ranking tool for evaluating buildings evacuation using agent-based simulation." *Proc., Construction Research Congress 2018*, 472-481.

Mehmood, H., Tripathi, N. K., and Tipdecho, T. (2010). "Indoor positioning system using artificial neural network." *Journal of Computer science*, 6(10), 1219.

Microsoft (2021). "What is .NET?", <https://dotnet.microsoft.com/learn/dotnet/what-is-dotnet>. (2021).

Mirahadi, F., McCabe, B., and Shahi, A. (2019). "IFC-centric performance-based evaluation of building evacuations using fire dynamics simulation and agent-based modeling." *Automation in Construction*, 101, 1-16.

Nagy, A. (2017). "What is Forge?", <https://www.autodesk.com/autodesk-university/class/What-Heck-Forge-2017>. (2021).

NFPA (2021). "National Fire Protection Association: Fires by occupancy or Property Type." <https://www.nfpa.org/News-and-Research/Data-research-and-tools/US-Fire-Problem/Fires-by-occupancy-or-property-type>.

Nguyen, M. H., Ho, T. V., and Zucker, J.-D. (2013). "Integration of smoke effect and blind evacuation strategy (SEBES) within fire evacuation simulation." *Simulation Modelling Practice and Theory*, 36, 44-59.

Oh, J., and Kim, J. (2018). "Adaptive K-nearest neighbour algorithm for WiFi fingerprint positioning." *Ict Express*, 4(2), 91-94.

Open Geospatial Consortium (2021). "CityGML Overview." <https://www.ogc.org/standards/citygml>. (2021).

Park, J., Chen, J., and Cho, Y. K. (2017). "Self-corrective knowledge-based hybrid tracking system using BIM and multimodal sensors." *Advanced Engineering Informatics*, 32, 126-138.

Peng, Y., Li, S.-W., and Hu, Z.-Z. (2019). "A self-learning dynamic path planning method for evacuation in large public buildings based on neural networks." *Neurocomputing*, 365, 71-85.

Prasithsangaree, P., Krishnamurthy, P., and Chrysanthis, P. "On indoor position location with wireless LANs." *Proc., The 13th IEEE international symposium on personal, indoor and mobile radio communications*, IEEE, 720-724.

Rahman, S. S. A., and Maulud, K. A. "Approaching BIM-GIS Integration for 3D Evacuation Planning Requirement Using Multipatch Geometry Data Format." *Proc., IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 012033.

Rüppel, U., Abolghasemzadeh, P., and Stübbe, K. "BIM-based immersive indoor graph networks for emergency situations in buildings." *Proc., Proceedings of the International Conference on Computing in Civil and Building Engineering*, University of Nottingham Press.

Rüppel, U., and Schatz, K. (2011). "Designing a BIM-based serious game for fire safety evacuation simulations." *Advanced engineering informatics*, 25(4), 600-611.

Rüppel, U., Stübbe, K. M., and Zwinger, U. "Indoor navigation integration platform for firefighting purposes." *Proc., 2010 International Conference on Indoor Positioning and Indoor Navigation*, IEEE, 1-6.

Santos, G., and Aguirre, B. E. (2004). "A critical review of emergency evacuation simulation models."

Schatz, K., Schlittenlacher, J., Ullrich, D., Rüppel, U., and Ellermeier, W. (2014). "Investigating human factors in fire evacuation: a serious-gaming approach." *Pedestrian and Evacuation Dynamics 2012*, Springer, 1113-1121.

Serrano, E., Poveda, G., and Garijo, M. (2014). "Towards a holistic framework for the evaluation of emergency plans in indoor environments." *Sensors*, 14(3), 4513-4535.

Shaw, E., Roper, T., Nilsson, T., Lawson, G., Cobb, S. V., and Miller, D. "The heat is on: Exploring user behaviour in a multisensory virtual environment for fire evacuation." *Proc., Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 1-13.

Shi, K., Ma, Z., Zhang, R., Hu, W., and Chen, H. (2015). "Support vector regression based indoor location in IEEE 802.11 environments." *Mobile Information Systems*, 2015.

Song, Y., Zhao, L., Wei, M., Zhang, H., and Liu, W. (2017). "Modelling Technology for Building Fire Scene with Virtual Geographic Environment." *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, 42.

Subedi, S., and Pyun, J.-Y. (2017). "Practical fingerprinting localization for indoor positioning system by using beacons." *Journal of Sensors*, 2017.

Sun, Q., and Turkan, Y. (2019). "A BIM based simulation framework for fire evacuation planning." *Advances in Informatics and Computing in Civil and Construction Engineering*, Springer, 431-438.

Sun, Q., and Turkan, Y. (2020). "A BIM-based simulation framework for fire safety management and investigation of the critical factors affecting human evacuation performance." *Advanced Engineering Informatics*, 44, 101093.

Tan, L., Hu, M., and Lin, H. (2015). "Agent-based simulation of building evacuation: Combining human behavior with predictable spatial accessibility in a fire emergency." *Information Sciences*, 295, 53-66.

Tian, Y., Shigaki, D., Wang, W., and Ahn, C.-J. "A weighted least-squares method using received signal strength measurements for WLAN indoor positioning system." *Proc., 2017 20th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, IEEE, 310-314.

UbikSim (2016). "emilioserra / UbikSim."

W3Schools (2021). "Introduction to XML." <https://www.w3schools.com/xml/xml_whatis.asp>. (2021).

Wainer, G., Chen, W., Cidre, J. I., Glinsky, E., Leon, S., Monadi, A., and Troccoli, A. (2004). "CD++ A tool for and DEVS and Cell-DEVS Modelling and Simulation." Carleton University.

Wang, B., Li, H., Rezgui, Y., Bradley, A., and Ong, H. N. (2014). "BIM based virtual environment for fire emergency evacuation." *The Scientific World Journal*, 2014.

Wang, K. C., Shih, S. Y., Chan, W. S., Wang, W.-C., Wang, S. H., Gansonre, A. A., Liu, J. J., Lee, M. T., Cheng, Y. Y., and Yeh, M. F. "Application of building information modeling in designing fire evacuation-a case study." *Proc., 31st International Symposium on Automation and Robotics in Construction and Mining, ISARC 2014*, University of Technology Sydney, 593-601.

Wang, S.-H., Wang, W.-C., Wang, K.-C., and Shih, S.-Y. (2015). "Applying building information modeling to support fire safety management." *Automation in construction*, 59, 158-167.

Wang, S., Van Schyndel, M., Wainer, G., Rajus, V. S., and Woodbury, R. "DEVS-based building information modeling and simulation for emergency evacuation." *Proc., Proceedings of the 2012 Winter Simulation Conference (WSC)*, IEEE, 1-12.

Weerasekara, N. N. (2015). *Modeling and simulation of evacuation plan for Hancock Stadium*, Illinois State University.

Wei, L., Zhang, N., Feng, J., Wang, Y., and Zhu, G. "Research on Intelligent Evacuation APP of Mobile Phone under BIM Platform." *Proc., 3rd International Conference on Computer Engineering, Information Science & Application Technology (ICCIA 2019)*, Atlantis Press, 365-368.

WhosOnLocation (2021). "WhosOnLocation Product Suite." <https://whosonlocation.com/productsuite/>.

Xu, M., Hijazi, I., Mebarki, A., Meouche, R. E., and Abune'meh, M. (2016). "Indoor guided evacuation: TIN for graph generation and crowd evacuation." *Geomatics, Natural Hazards and Risk*, 7(sup1), 47-56.

Yan, F., Hu, Y.-h., Jia, J.-y., Guo, Q.-h., Zhu, H.-h., and Pan, Z.-g. (2019). "RFES: a real-time fire evacuation system for Mobile Web3D." *Frontiers of Information Technology & Electronic Engineering*, 20(8), 1061-1074.

Yan, F., Hu, Y., Jia, J., Ai, Z., Tang, K., Shi, Z., and Liu, X. (2020). "Interactive WebVR visualization for online fire evacuation training." *Multimedia Tools and Applications*, 79(41), 31541-31565.

Yenumula, K., Kolmer, C., Pan, J., and Su, X. (2015). "BIM-controlled signage system for building evacuation." *Procedia engineering*, 118, 284-289.

Yim, J. (2008). "Introducing a decision tree-based indoor positioning technique." *Expert Systems with Applications*, 34(2), 1296-1302.

Zhang, J., Guo, J., Xiong, H., Liu, X., and Zhang, D. (2019). "A framework for an intelligent and personalized fire evacuation management system." *Sensors*, 19(14), 3128.

Zhang, Y., Yan, Z., Zhu, X., and Piao, W. "Dynamic Emergency Evacuation System for Large Public Building." *Proc., International Conference on Smart City and Intelligent Building*, Springer, Singapore, 173-182.

Zhu, Z., Zhou, L., Zhang, C., Lin, B., Cui, Y., and Che, M. (2018). "Modeling of macroscopic building evacuation using IFC data." *ISPRS International Journal of Geo-Information*, 7(8), 302.

Zverovich, V., Mahdjoubi, L., Boguslawski, P., Fadli, F., and Barki, H. (2016). "Emergency response in complex buildings: automated selection of safest and balanced routes." *Computer-Aided Civil and Infrastructure Engineering*, 31(8), 617-632.