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Research Issues in Agent-Based Simulation for Pedestrians Evacuation

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ABSTRACT Crowd evacuation in emergencies may lead to fatalities if the evacuation plans were not tested and evaluated. Traditionally, evacuation drills have been, and still are, being used to assess evacuation plans. However, in recent years the simulation of evacuation plans during emergencies has emerged as a strong alternative that is cost effective and potentially more accurate. Agent-Based Simulation (ABS) is the preferred type of simulation for evacuation scenarios, due to its ability to model individual decision-making and social behaviour. In this paper we conduct meta-analysis of eighty-one peer-reviewed papers published between 2009 and 2019 that used ABS to model pedestrian evacuation. Our analysis assesses the current state-of-art and identifies opportunities for improvement. We identify seven dimensions over which the surveyed papers agree or differ. The dimensions include purpose of the simulation, type of emergency and environment considerations, type and scale of evacuated space, simulation software used, agents' characteristics and behaviour, support of evacuation policies, and analysis and validation. We conduct meta-analysis of the surveyed papers along the identified dimensions. One of the main findings of our analysis is the lack of a standardized validation methodology for ABS of emergency evacuation.

INDEX TERMS Agent-based simulation, evacuation models, pedestrians behavior modeling, pedestrians evacuation, simulation validation.

I. INTRODUCTION

Emergency management is a key activity in the planning for life-threatening events. The first step of emergency management includes developing an emergency evacuation plan to identify possible emergency scenarios [1]. Emergency evacuation involves moving a large number of people in response to natural disasters such as fire or flood, or terrorist attacks. If not planned well, evacuations may cause casualties due to jostling and congestions at exits [2]. Testing evacuation plans using drills or mock evacuations is considered expensive and in many cases ineffective, as it does not accurately model the behaviour of individuals during panic [3]. Computer simulation provides a promising alternative. Not only are computer simulations more cost-effective, but they also allow studying the impact of different factors, such as building structure and authority figures placement, on the evacuation time and safety [4].

In this paper we conduct meta-analysis of eighty-one peer-reviewed papers published from 2009 to 2019 that used Agent-Based simulation to model pedestrian evacuation. Papers simulating non-emergency scenarios were not included in this survey. Studies that used other simulation techniques along with ABS were included. While there has been previous works that surveyed simulation of pedestrian evacuation, the works either did not focus on agent-based simulation for evacuation [5] or have become obsolete due to lapse of time [6]. We aim to answer the following questions in this paper:

- What are the main common dimensions that describe and distinguish recent research in ABS for emergency evacuation?
- What are the open challenges that researchers on ABS need to focus on?

To help answer these questions, we survey 81 peer-reviewed published articles in which agent-based models were built for pedestrian evacuation. From the surveyed papers, we identify the dimensions over which we can compare the different papers against one another, which include purpose of the simulation, type of emergency, type of building, scale, simulation software, type of agents,

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the combination of modelling approaches, analysis of results, model validation, environment characteristics, evacuation policies applied, and modelling sociological, psychological and physical factors of individuals and groups.

The literature contains a myriad of studies and reviews on agent-based simulations. For example, authors in [5] surveyed ABS models published between 1998 and 2008. Their main concern was the philosophy of the model and how it was developed and validated. Additionally, the models were surveyed in terms of their field of study, simulation software used and simulation purpose. Domains of interest included social science, economics, biology, military, and traffic. In regards of pedestrians behaviour, the authors in [7] outlined the fundamental features of pedestrian detection techniques, including manual counting, video, RGB cameras, infrared, laser, GPD, and ultrasonic sensors. Focusing on pedestrian evacuation, the authors in [6] reviewed 26 evacuation models. The models were categorized according to their availability, overarching method of simulating pedestrians, purpose, type of structure, pedestrians' and buildings' perspective, internal algorithms for modelling pedestrians' movement, fire effects incorporation, the use of computer-aided design, visualization methods, and validation methods. Additionally, models were categorized based upon whether they considered special features of evacuations, such as counterflow, exit blockage, fire conditions, group behaviour, disabled and low-stamina pedestrians' impact, evacuation delays, elevator use, and route choice.

Our survey is similar to the paper by Kuligowski *et al.* [6]. However, there is a need for an updated review as new models have been built since the publishing of the paper. Contrary to Heath *et al.* [5], this survey is focused on just one domain, which is pedestrians' evacuation. This is considered a contribution to the body of literature as ABS issues and challenges are quite domain dependent.

Section 2 presents the main research directions for simulating pedestrian evacuation, outlining the advantages of using ABS. Section 3 discusses the different dimensions of ABS for pedestrian evacuation. In Section 4, we draw some conclusions based on the surveyed papers and we provide direction for future work.

II. SIMULATION MODELS FOR EVACUATIONS

Evacuation models can be mainly classified as either macroscopic, microscopic, or a hybrid of both [8]. Agent based simulation falls under microscopic models, as we explain in the remainder of this section.

A. MACROSCOPIC MODELS

At the macro-level, the concern is general pedestrians' dynamics as a homogenous flow such as spatial density or average speed. Macroscopic simulation is efficient in representing large-scale scenarios but fails to explain certain emergent behaviours such as congestion at narrow passageways [9]–[11]. Pedestrians are represented in a collective manner using unique key features such spatial density, average velocity, and flow rate in relation to the time and location. These models are mostly used to generate reasonable lower bounds for the evacuation time, which can be used to analyse existing buildings or aid in planning new ones. Most of the macroscopic models depend on mathematical or analytical models to solve evacuation problems [8].

Macroscopic models include regression models, route-choice models, queuing models, and gas-kinetic models. ***Regression models*** utilize statistically established relations between flow variables to predict pedestrian flow in different conditions, such as passages, stairs, ramps and walkways [12]. In ***route-choice models***, pedestrians choose the best route according to the travel time, safety, and comfort. In ***queuing models***, Markov chains are used to describe how pedestrians move in the network from one node to another. Nodes represent rooms while doors are the links between the nodes [13]. On the other hand, ***gas-kinetics models*** use an equivalence of fluid or gas dynamics to control how crowd density and speed parameters change over time using partial differential equations [14].

While macroscopic models are suitable at producing general evacuation flow profiles, they are unable to describe emergent crowd phenomena arising from complex interactions at lower levels [15].

B. MICROSCOPIC MODELS

Microscopic simulations consider individual pedestrians' behaviour, movements of evacuees, and the interactions among individuals. Pedestrians are modelled as entities with individual characteristics such as age, gender, physical abilities, body size, and walking speeds [8]. The main disadvantage of micro-level modelling is their need of intensive computational processes [9]–[11]. However, this issue can be solved with parallel computing techniques [8].

Zhao et al. [16] reviews seven methodological approaches for modelling pedestrians evacuations; cellular automata (CA), lattice gas models (LG), social force models (SF), fluid-dynamics models (FD), game theory models, approaching based on experiments with animals, and agent-based simulations (ABS). ***Cellular automata***, proposed by Von Neumann, are discrete dynamic systems consisting of a grid of cells. CA progress at each time step, changing the variables of each cell according to the neighbouring cells. CA can be useful in studying the impact of exits width and obstacles on pedestrians' evacuation. They can also be used to model friction forces and congestion. CA models can simulate two kinds of interactions; interactions between environments and pedestrians and interactions among pedestrians. Models simulating interactions between environments and pedestrians are useful to demonstrate the impact of environment characteristics, such as exit width and obstacles, on evacuees' movement. Models simulating interaction among pedestrians allow the study of friction effects of pedestrian behaviour, bi-direction behaviour, and herding behaviour [16]. ***Lattice gas model*** are a special case of cellular automata. In lattice gas models, each individual is considered as an active particle on the grid. The future location of an individual is probabilistically determined by the current configuration of its neighbourhood. Advances of this model include Extended Floor Field Model and SWARM information model [17]. In ***social force models***, pedestrians movement is determined by various needs including the desire to reach a certain destination, to keep a certain distance from other individuals, and to keep a distance from other objects or obstacles [18]. In ***fluid dynamic models***, pedestrians' movement is described with fluid-like behaviour, assuming that crowds behave as gases or fluids. Fluid dynamics can be useful in modelling how crowds' density and speed change over time [16]. ***Game theory models*** can be adopted if the interactive decision model of the evacuees is rational. In this case, the evacuees assess all the available options and select the one that maximizes their utility. Each evacuee's final utility payoffs depend on the actions chosen by all evacuees [16].

All the aforementioned methods are characterized for modelling pedestrians in a homogenous way. ***Agent-based models***, on the other hand, simulate individuals as autonomous agents that have their own characteristics and behaviours and act according to the situation encountered in the environment [19].

However, this results in ABSs being computationally more expensive than other models. ABSs are computational models that simulate individuals with virtual agents. On the other hand, the heterogeneity of humans character can only be accurately represented in a system that considers the differences at individual level [17]. The emergent phenomenon that results from individuals' complex behaviours as well as the interaction among individuals is referred to as collective behaviour. ABS are characterized as being able to represent large systems consisting of the interaction of subsystems that are categorised as being unpredictable, distributed and almost decomposable [16]. A key advantage of ABSs is their ability to model individual decision-making and social behaviour of groups and how such behaviour is affected by structural properties of buildings [10]. The aforementioned capabilities made ABSs one of the most realistic simulation techniques that are used to model a large number of dependent moving objects [1], [10], [20], [21]. ABSs can also be combined with other simulation models to accurately simulate physical and social forces that impact evacuees' behaviour [18], [20].

C. MESOSCOPIC MODELS

Mesoscopic, or hybrid simulation is the combination of both macro and micro techniques [9]–[11]. In this approach, individuals' spatial movement is independently specified but still dependent on collective flow conditions rather than the interaction with other pedestrians [11], [22].

Because of the complexity in modelling pedestrian behaviour during evacuation, as well as the limitations in computer resources, there is a tendency of combining ABS with other modelling approaches benefitting from the advantages of each model in regards of crowds dynamics [16], [23]. Many studies modelled pedestrians' evacuation by combining the basic principles of ABS with other rules from cellular automata [1], [10], [11], [24]–[29], social force [18], [30]–[44], fluid dynamics [45]–[48], finite state automata (FSA) [49], scalar field method (SFM) [50], and particle swarm optimization [51].

For instance, the combination of cellular automata and multi-agent systems is termed as Situated Cellular Agents (SCA). In SCA, a set of agents are situated in an environment (space) and interact through the propagation of a set of fields [28]. In [50], the agent's motion is controlled by the scalar field method (SFM), which can consider the effects of social level and manage a complex network of agent. SFM is based on the notion that interactions exist between each object in the simulation (i.e. agent-to-agent, agent-to-wall, etc). Such interactions can be quantified as scalar fields of virtual potential energy. Agents are attracted to other related agents and exits while repelled by barriers that hinder their motion.

III. DIMENSIONS OF SIMULATING EMERGENCY EVACUATION

The studies included in this survey deliberate the development of an agent-based model for pedestrian evacuation, are peer-reviewed papers, and were published within a 10-year time frame, as shown in **Fig. 1**. Google Scholar electronic database was searched using the keywords "Agent-based emergency evacuation simulation" and "Agent-based emergency evacuation model". Peer-reviewed articles published between January 1st 2009 and August 30th 2019 were included, considering they modelled an emergency evacuation scenario for pedestrians using agent-based simulation. Articles that did not use ABS or that modelled non-emergency evacuations were excluded. This resulted in 81 articles.

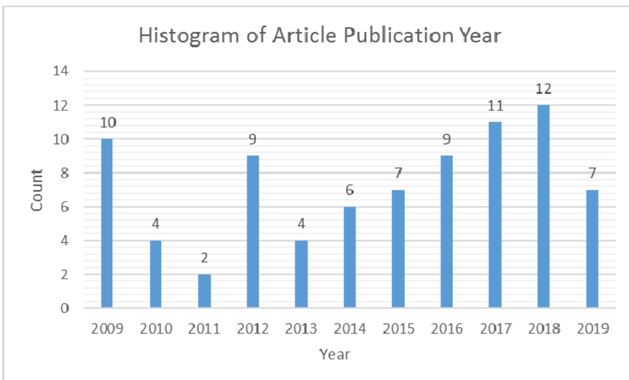

FIGURE 1. Number of Surveyed Articles per Year.

In this section, the dimensions of simulating emergency evacuations found in the literature are summarized and discussed.

In a previous survey, Kuligowski *et al.* [6] divided the aspects into two categories; main features and special features. Main features include model availability, modelling method, purpose, grid/structure, movement, fire data, Computer-Aided Design (CAD) and validation method. Special features include the consideration of exit blocks, fire conditions affecting pedestrian behaviour, toxicity, groups, disabled/slow occupants delays and pre-evacuation times, elevator use and route choice.

Cassol *et al.* [52] categorized the evacuation aspects into four key components: environmental physical structure, environmental functionality, population data, and environmental condition. Environmental physical structure includes building features aspects such as the dimensions, number of floors, number of rooms, and number and location of exits and stairs. Environmental functionality defines the functionality of the place, such as an office, hospital, school, airport, stadium, or arena. Population data includes the number of pedestrians in the environment, their spatial distribution, and their demographics, such as age, gender, and relationships among them. Environmental condition defines the factors that can affect the navigability of a building, such as time of day or the presence of smoke, fire, or heat.

Santos [53] categorized aspects into three main different dimensions; the characteristics of the evacuation environment, the policies and procedures of the evacuation, and the psychological and social characteristics impacting evacuees' response.

In our study, we categorize the aspects of evacuation simulation into seven main dimensions: purpose of the simulation, emergency type and environment considerations, type and scale of evacuated spaces, simulation software used, agents' characteristics and behaviour, the support of evacuation policies, and analysis and validation of the simulation.

A. PURPOSE

Pedestrians evacuation simulations have been the focus of many researches. The different papers have differed with respect to the purpose: creating evacuation plans [9], [23], [54], evaluating and optimizing evacuation plans [2], [11], [24], [30]–[32], [45], [50], [52], [55]–[65], evaluating buildings structure [1], [10], [25], [33], [33], [46], [47], [51], [59], [60], [66]–[70], allocating authority figures [4], [18], planning paths for rescuers [71], determining the factors that impact fire evacuations and model them [26], [48], and studying human behaviour during emergency [3], [27]–[29], [31], [34]–[39], [49], [51], [51], [58], [72]–[88]. **Fig. 2** shows the number of surveyed articles according to their main purpose, considering that many papers have more than one main purpose. The figure clearly shows that most of the simulation models aimed at studying human behaviour during emergency evacuations, which indicates the importance of the human behaviour dimension for evacuation simulations.

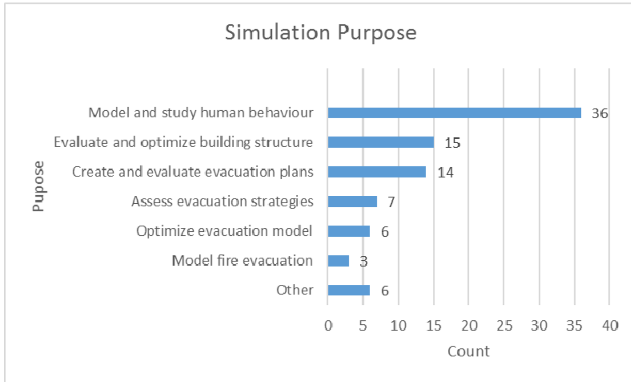

FIGURE 2. Number of Surveyed Articles per Purpose.

B. EMERGENCY TYPE AND ENVIRONMENT CONSIDERATIONS

The type of **emergency** being simulated influences the features of the evacuation model. Fire evacuation was the focus of many studies that considered the impact of fire and/or smoke on the evacuation process [1], [3], [30]–[32], [39], [43], [49], [51], [52], [55], [57], [62], [67], [68], [71], [75], [82], [90]–[93]. **Fires** impact the environment as they may block exits or impact evacuees vision because of **smokes** [26]. Fire evacuation simulations should consider the impact of buildings material on the fire spread rate. Moreover, fire cues and the building architecture impact the decision-making and responding behaviours of evacuees [92]. Authors in [1] created a model that allows for customization of number of fires, fire spread rate, and smoke production rate. A Fire Dynamic Simulator (FDS) is a computational tool developed by NIST to simulate fire-driven flow. [93] When designing fire evacuation simulations, FDS measurements should be considered. These include measures of heat produced, toxicity concentration, and smoke density. [46] In the case of fire emergencies, it is also reasonable to consider the time needed to receive a fire alarm. This pre-alarm period depends on the location of the fire and the sensitivity of the alarm system. [46], [90] Additionally, the interaction between evacuees and the environment should be considered as agents opening the doors or windows may also impact the fire and smoke spread rate [48].

Other studies simulated the evacuation of earthquake and blasts evacuations and the resulting damage on buildings and infrastructures [10], [43], [60], [64], [67], [83], [84]. During emergency evacuations, damage can occur to the **building structure** caused by earthquakes, bomb blasts, or fires. The ability to simulate a dynamic environment creates more realistic simulations as agents have to avoid obstacles [43] or find alternative exit routes [11]. Some authors studied the impact of structural characteristics on the evacuation. For instance, [10] modelled the damage of structural and non-structural components, while [33], [51] studied the impact of room and door size on evacuation time. Other simulations allowed the user to modify the environment by rearranging obstacles [25] or customize the furniture quantity and place, number of exits, and aisle space [1], [69].

Others studies modelled the evacuation of cities during a tsunami [9], [61], [62], [64], while other models considered

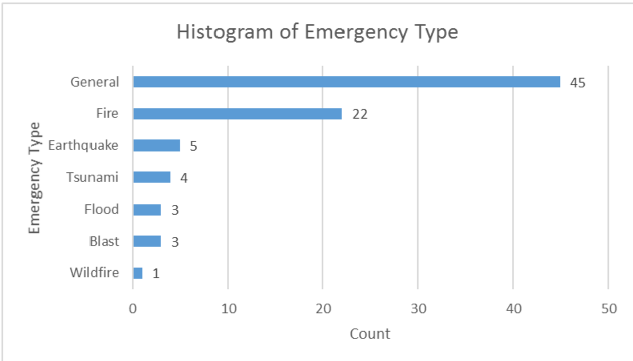

FIGURE 3. Number of Surveyed Articles per Emergency Type.

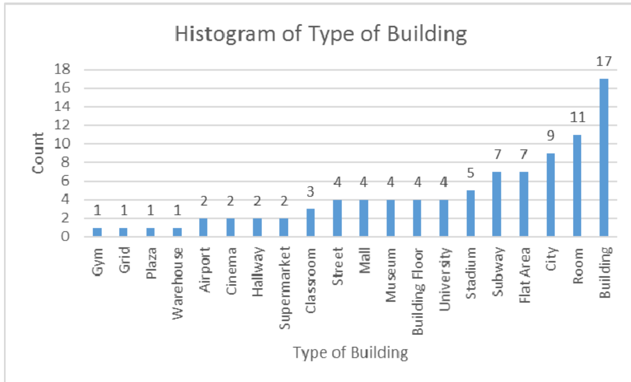

FIGURE 4. Number of Surveyed Articles per Type of Building.

the emergency of wildfires [24] and floods [73], [94]. The majority of the surveyed papers, however, did not target a specific type of emergency evacuation [2], [4], [8], [11], [18], [23], [25], [28]–[41], [50]–[52], [54], [55], [57], [66], [68], [70]–[72], [74], [76]–[78], [80], [82], [85], [87], [95]–[97]. **Fig. 3** shows a breakdown of the articles surveyed according to the emergency type simulated.

Each emergency is different and requires different considerations. For example, in tsunami evacuations, one aspect to consider is **vertical evacuation**. During a tsunami, horizontal evacuations can become complicated, especially in the presence of bridges which can fail in the preceding earthquakes. Moreover, water levels may increase rapidly, making the horizontal evacuation on foot or vehicles challenging [64]. Readers are directed to the research on [98] for a review of the advances and challenges in agent-based models for tsunami evacuation simulations.

Another major variance between different types of emergency evacuations is the length and time scale the pedestrian requires to evacuate [61]. For instance, evacuation plans for building fires and earthquakes usually happen over short time scales, ranging from seconds to a few minutes. In the case of an earthquake, evacuees may take refuge under a piece of furniture within few seconds of feeling the shaking of the building. In the case of a fire in the building, there is usually a delayed evacuation that should be considered when simulating the evacuation [99], [100]. On the other hand, in the case of hurricanes and wildfires, the evacuees have several hours of advanced warning, and usually rely on vehicles to seek shelter. Nearfield tsunamis, on the other hand, arrive within several minutes of an earthquake and can expand over several kilometres of land [61].

C. TYPE AND SCALE OF EVACUATED SPACE

Most models were tested on a specific location and have some limitations on the **type of buildings**they can be applied to. However, some models provided the flexibility to apply the model on other situations with different building structures [1]. In [6], the author described the use of different models for certain building types. Models involved in the study fell into five different categories: (1) models that can simulate any type of building (2) models specialized in in residence buildings, (3) models specialized in public transportation stations, (4) models that are able to simulate low-rise buildings (below 15 stories), and (5) models that only simulate 1-route/exit of the building. Other categories include the evacuation of rooms considering obstacles [25], and models restricted to one level buildings [10]. However, the use of the model for simulating different types of buildings is an aspect worth considering when reviewing simulation literature as each type of building has its own characteristics. For example, subways and underground spaces suffer the absence of natural lightening and ventilation, which may limit the orientation awareness of the pedestrians and increase the possibility of suffocation. Also, exit route paths (i.e. stairs) are always ascending, which may cause fatigue to evacuees [63]. Moreover, the moving dynamics of pedestrians differs in each type of building. Individuals in cinemas and metro stations are usually gathered near points of interests, such as tickets office and vendors [41]. Occupants of a residence building or an office are usually familiar with the building layout and exit paths while visitors of a shopping mall may not be able to navigate confidently in the building [87]. **Fig. 4** shows the distribution of surveyed articles according to the type of building modelled.

The environment in a building or floor is made of walls, interior spaces, doors/connector, and exits. Each component has different characteristics such as the location, geometry, and dimensions [50]. In an evacuation scenario of a city, the environment comprises streets, buildings and obstacles. When simulating emergency evacuations, other aspects such as fire, smoke and water levels are considered as part of the environment. The characteristics of the environment are considered in many papers as they play an important role on the dynamics of agents' movement during evacuation. The physical characteristics of a building are strongly related to the human-decision making process [46]. Each building has its own situational features that impact the evacuation outcomes. For example, the capacity of a building impacts pedestrians' proximity and congestions during the evacuations.

Moreover, the presence of **multiple exits** requires modelling the destination choice behaviour [11] as agents may choose the exit according to visibility or distance [10]. According to [23], agent route choice is determined distance and density. For instance, people often prefer to choose an exit that is closer to their current location as long as the density in the exit zone is not significant. Evacuees also use building **signage** such as doors and exits signs to enhance their wayfinding efficiency [101]. In the simulation model in [87], three types of objects are employed: exits, doors, and exits signs. For instance, once an agent reaches an exit, the agent is removed from the simulation. On the other hand, if an agent exits from a room through a door to another room, the agent is not removed from the simulation. Exits signs serve as an attraction point that offer navigation directions to agents.

Other studies considered the factors that affect **congestions at exits**, such as the impact of obstacles [25], staircases [2], [11], [33], and corridors [18]. Additionally, the ability to simulate **multi-story buildings** aids in finding the maximum structural capacity [2], [10], [11] as well as simulating staircases' congestions as agents move across floors [18], [33]. Moreover, multi-story simulations aid in estimating the evacuation time for each floor [56]. For example, in the work in [55], buildings were simulated as agents representing the physical location of students in campus. Buildings were assigned a height and number of floors that impacted the time needed to descend the building. Other models simulated multi-floor buildings but were limited as agents were not able to move between floors [1]. When studying the evacuation of multi-story buildings, stairs evacuation is usually considered part of the evacuation process. Two aspects are usually considered in regards of the stairs; the stairs design and the occupants' behaviour on stairs [91]. In [102], the authors describe a model that considers the specifications of personal space to describe uni- and bi-directional pedestrian movement on stairs. In spite of this model being presented for non-emergency evacuations, the parameters outlined can be considered for emergency situations if other inputs are measured. Moreover, elevators may be used for evacuation in certain situations, such as non-fire emergencies or when elevators are prepared to operate during fire emergencies [2]. Additionally, the authors in [85] considered agents behaviour to be irrational during panic, allowing agents to use the elevator or even jump from a floor to evacuate.

Modelling large **scale** evacuations including thousands of individuals or more has been also considered. However, albeit the success of existing approaches, work on large scale ABS models has been rare. This is due to the lack of an effective modelling approach to deal with the size and complexity of such simulations, as well as the lack of an appropriate platform to handle such large systems [103].

Multiscale evacuations, which include ABSs based on different modelling paradigms (i.e. differential equations, cellular automata, etc...) and different space-time related scales, have been also studied in the literature [24], [32], [41], [86], [104], [105]. However, there are a few challenges needing addressing in this regard; the modelling of cross-level interactions, heterogenous modelling coupling, and optimizing computational resources [100].

D. SIMULATION SOFTWARE

Some researchers built their simulations using commercially available **simulation software** such as AnyLogic [18], [30], [49], [55], [71], [85], NetLogo [1], [25], [32]–[34], [42], [48], [51], [60], [78], [83], GAMA [83], [89], [90] and Pathfinder [63], [91]. NetLogo and AnyLogic were the software most referenced in the papers surveyed, with NetLogo being used in 13.8% of the simulations and AnyLogic in 7.5%, see **Fig. 5**. AnyLogic [106] offers a pedestrian's library that can be used to model the crowd flow in a physical environment while incorporating a pedestrians' psychology model (AnyLogic, 2017). NetLogo [107] is also a multi-agent programmable modelling environment offering various sample models which allows users to switch between the modelling and simulation perspectives. GAMA [108] is a fully integrated development environment based on Eclipse IDE that also allows the user to switch between the modelling and simulation perspectives [109].

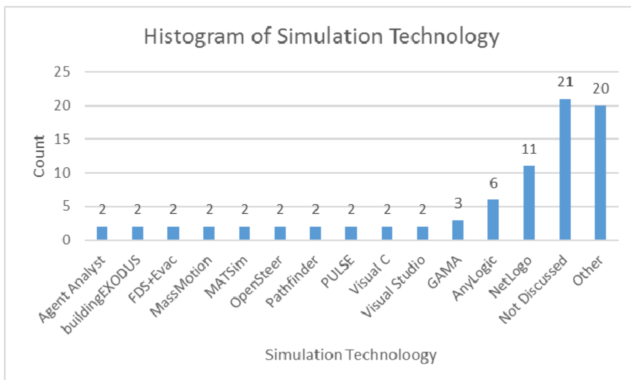

FIGURE 5. Number of Surveyed Articles per Simulation Technology.

Other simulation software include Exitus [11] which is an updated version of BUMMPEE [2], TENDENKO that can be used to model a heterogeneous crowd of evacuees and rescuers agents [56], Agent Analyst [44], [79], AlEva [26], buildingEXODUS [24], [70], CrowdSim [52], EVAC [27], FDS + EVAC [35], [48], MASON [68], MASSEgress [77], Massive [4], [72], MassMotion [40], [47], MATSim [73], [97], Flood Simulator [94], Mercurial [86], NetProLogo [78], OpenSteer [4], [37], [76], PULSE [32], [41], PyroSim [46], Repast [3], [10], [36] and SAFEgress [87].

On the other hand, some simulation models were created using native languages such as C# [57], Java [8] and Visual C [66], [80], or using software packages, such as Visual Studio [31], [51]. For a review of evacuation software and their characteristics, the reader is referred to [6], [110].

Contrarily, 23.8% of the papers surveyed did not provide any details on what simulation software or programming language was used to construct and execute the simulation.

As there are a wide variety of evacuation software to choose form, users should choose the tool according to the project, with the appropriate input features and simulation capabilities. Simulating the same design scenarios using two different software or programming language may result in different egress times. This is due to the different formulas used in each software, such as the movement algorithms [111]. Moreover, some of the software are based on cellular automata approach, which arises several issues such as alignment of grip to environment, exhaustion factor, speed and route selection. Other software use particle-based approaches, which makes them lack realism. On the other hand, most of the crowd simulation software are rule-based, which makes them suitable for low and medium density crowds [8].

E. AGENTS CHARACTERISTICS

Another important dimension is the complexity of modelling individuals. Human characteristics and behaviour factors highly impact the evacuation process making them an essential aspect to create more realistic simulations [77]. Pedestrians in real life have different psychological needs and physiological properties. Therefore, it is of advantage to model evacuating crowds as heterogeneous individuals rather than homogenous [16]. Many studies modelled heterogeneous agents by assigning different characteristics to each group of agents such as age, gender, knowledge, stamina, average speed, and psychology. These characteristics influence the agent performance during an evacuation in regards of decision making and mobility.

However, a complete collection and analysis of data on individual reasoning in real danger events does not exist. Even though experimental drills allow researchers to observe behaviour, data collected in these experiments is not accurate as participants know there is no real danger. Moreover, and despite the analysis of real events and fields studies, not all analysis results are integrated into evacuation planning and modelling. Modelling human behaviour during evacuation requires the integration of many different variables [112]. However, this is not always evident in evacuation simulations. Since agents' behaviour is represented at the micro-level of the simulation [10], the complexity of modelling agents makes it harder to scale them to larger crowds. This issue may be overcome nowadays with the advancing of computer performance. In addition to computational and empirical limitations in simulating human behaviour in emergency events, the issue of selecting the right variables to simulate arises. Human factors include various physical, cognitive, motivational, and social variables. However, the variables that are most relevant for a safe and fast evacuation are not clearly defined [112].

Kuligowski et al. [6] categorize the simulation models according to their modelling method. The categories include behavioural models, movement models, and partial behaviour models. Behavioural models incorporate pedestrians performing actions as well as the movement toward an exit. These models also incorporate the decision-making process of individuals. Movement models move pedestrians from one point of the building to an exit or a safe place without accounting for human behaviour. These models are useful in displaying congestion areas, queuing, or bottlenecks in the building. Finally, partial behaviour models incorporate occupant movement in addition to implicitly represented behaviours such as pre-evacuation time distributions across individuals, unique individual's characteristics, and smoke effects on individuals.

When considering the sociological and psychological factors at the individual's level, the physical characteristic (i.e. stamina, disability), the mental state (i.e. stressed, tired), the knowledge and experience, the personality traits (i.e. risk taking) and motivation (i.e. control, relationship) are all factors that are considered relevant to the evacuation [112]. Moreover, group behaviour and crowd dynamics are important phenomena in evacuation research. Group behaviour relates to the psychological aspects of an individual inside a group. This includes leadership, helping behaviour, family relationships, and other affiliations [76], [112], [113]. On the other hand, crowd dynamics describe pedestrians' movements and interactions in regards of velocity, density, navigation, obstacles and collision avoidance, physical and social interaction, and imitation [114]. For instance, some evacuees would follow the majority of the crowd, while others would run towards the direction of a known exit [39].

1) INDIVIDUALS

Many of the characteristics of individuals influence their performance during an evacuation in regards of decision making and mobility. These characteristics may include gender, age, speed, reaction time, level of familiarity and knowledge, leadership traits, and level of panic. Age and gender are considered important factors in regards of evacuees' movement. Adults are usually faster than children and elderly individuals. For instance, Heliövaara et al. [35] grouped individuals into several categories with distinct speed ranges (adults, females, males, children, elderly). On the other hand, Fang et al. [50] adopted only two categories: adults consisting of both females and males from 15 to 65 years old, and children and seniors including individuals with lower mobility.

Moreover, the ability to represent evacuees' physical characteristics and disabilities is considered very important as they impact their velocity and speed. They also impact the decision-making process. According to the theory of affordance, an agent may choose an action based on its physical characteristics. For example, a young and healthy agent may perceive the physical load of a certain action as easy compared to an elderly agent [85]. People's stamina vary according to their age and gender [26], [67]. Additionally, the endurance capabilities may change after the emergency occurs and people may become injured [10], [25]. Other studies considered people with disabilities in terms of speed and ability to negotiate the environment such as wheelchair users and the visually impaired [2], [11]. Individuals with disabilities, including individuals with mobility [2], and hearing and vision disabilities [11], [63], not only require some sort of assistance during evacuation, but may also block the evacuation of other pedestrians due to their slower speed or larger space requirements [115]. For a more accurate evacuation modelling, the percentage of evacuees with certain needs as well as the general demographics should be considered [112]. Other features of the human body that are strongly related to the calculations of escape routes in buildings include shoulder width, clothing, and luggage [112]. Moreover, the presence of toxic gases resulting from fires can cause symptoms varying from light headaches, where the speed of the evacuee is reduced, to incapacitation, where the evacuee cannot move without assistance [6].

There is a variety of social theories that explain human behaviours during emergencies at an individual level. For example, the affiliative theory dismisses the physical science model, which assumes that evacuees always choose the shortest route [116]. Instead, the affiliative theory states that evacuees usually choose to evacuate the same way they entered the building, due to its familiarity, regardless of the presence of shortest routes [87], [117], [118]. Moreover, the affiliation theory assumes that individuals with close psychological bonds will try to evacuate in groups of two or more [118].

On the other hand, the panic model assumes that individuals are concerned with self-preservation and compete with each other to evacuate from limited exits [118]. Studies have shown that **panic** and impulsive behaviour are the main cause of casualties during emergency evacuation, rather than the actual catastrophe [10], [18], [33], [34]. Consequently, many simulations considered the panic and stress aspects during evacuation. For example, in [10] panic was measured according to three different factors; the visibility of the exit door, the evacuation time, and the density of evacuees. In [68], the panic level is affected by the distance to the exit door, the velocity of the individual compared to the velocity of neighbours heading towards the exit, and the count of neighbours who are moving slowly due to an injury.

Other aspects include waiting or **response time** as people tend to wait for some time before responding to the evacuation alert [11], [26]. According to the behaviour sequence model, individuals pass through three stages once they get a signal of danger; interpret, prepare, and act [117]. Individuals do many things before or instead of complying to an alarm [112]. This hesitation can be caused by different reasons: doubt about the alarm being authentic, need for information, and commitment to other tasks. In this regard, the reader is encouraged to review the literature for pre-evacuation times and distributions that are typical for the emergency being simulated [6].

Many of the surveyed papers assume that all pedestrians have the same amount of knowledge about the environment, such as the location of exits [50]. However, this is not the case in many of the real scenarios as some people have more information than the others, referred to as **information asymmetry**. Information asymmetry directly impacts the evacuation process as individuals without the knowledge of the environment tend to follow the crowd while individuals who know the environment will choose their own route and be less subjective to panic [58].

2) GROUP BEHAVIOUR

Another important aspect that is considered during evacuation is **human relations**. For instance, seeking behaviour is where group members are initially separated and then seek to find each other [4], [77] or search for a missing family member before evacuating [10]. Moreover, evacuees without knowledge of the environment tend to follow other people with better knowledge of the escape route (**leader/follower** behaviour) [34], [67], [77], or **group** together with other people with similar demographics [57]. Social attachment also influences the evacuation process as it refers to the bonds produced by the interaction of individuals with other individuals such as family members, friends, colleagues, and authority figures as well as with objects, places, and tasks [83].

Other psychology aspects include people tendency to stop to **help the injured** [10], [11], [67], and **sharing information** among evacuees regarding the environment [4], [26], [49], [56], [77], [81].

3) CROWD DYNAMICS

At a crowd level, social influence theory and social proof theory have been used to explain how individuals influence each other during the initial phase of evacuation [87]. Examples of simulated behaviours during evacuation include competitive behaviour, queuing behaviour, and herding behaviour [77]. Moreover, **social collective behaviour** is present during evacuation as people can cooperate and evacuate in an ordered manner. For example, in a counter-flow situation, pedestrians moving in opposite directions meet face-to-face in a limited space. Studies had found that people form lines and follow a leader to escape the high density of evacuees. Queuing and collective mobility are also examples of social collective behaviour as people have to cooperate with strangers in order to evacuate safely [34]. Ha and Lykotrafitis [33] also simulated social collective behaviour in evacuations of multi-room multi-floors buildings. **Social force**, is a motivational force that is accountable of agents' acceleration towards a chosen destination, even if their path is blocked. Additionally, people tend to maintain a personal space from other agents or objects to avoid collisions and injury [57]. Therefore, simulations should model a repulsive social force to avoid the physical contact between agents and other objects during the simulation. If the physical contact between an agent and another agent or object, called

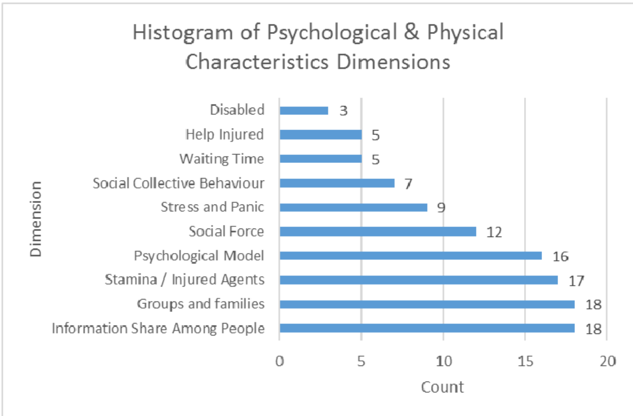

FIGURE 6. Number of Surveyed Articles per Psychological and Physical Characteristics.

compressive force, exceeds a certain limit, an agent may be considered as injured [33], [119].

It is worth noting that simulations of crowd behaviour and pedestrian dynamics in non-emergency situations are closely related to evacuation modelling. However, it is not clear which of their outputs can be transferred to evacuations and emergency situations [112]. **Fig. 6** shows the number of surveyed articles that considered various pedestrian's psychological and physical characteristics.

F. EVACUATION POLICIES SUPPORT

Evacuation procedures include the policies followed during evacuation. This includes the placing of authority figures (AF) [4], having people trained on the evacuation procedures [9], sending rescue officers [71], specifying whether the evacuation is announced or not [55], and delaying the evacuation for certain people [2]. **Fig. 7** shows the number of surveyed articles that considered different evacuation policies and procedures. **Authority figures** have an essential role in evacuating pedestrians as they not only have better knowledge of the environment and shortest routes, but they also have a calming impact on evacuees which may reduce panic and avoid stamping [4], [18]. Moreover, studies have shown that evacuees rely heavily on the directions given by the authorities to evacuate as they consider these directions as a credible source of information [87].

Simulations can also aid in determining the optimal number of authority agents as well as **rescuers** needed for a safe evacuation [56], [71]. Moreover, considering **trained agents** in the evacuation allows the modelling of the Leader/Follower behaviour [9], [34], [67], [77]. In a leader/follower situation, leaders should be familiar and knowledgeable with the floor plan and exit routes and be aware of the evacuation process to play a leader role [31].

Other simulations allow the user to manually set the time needed for individuals to receive and act on **evacuation announcement** [41], [55], [73], [81], [94], [97]. Other authors explored the impact of **delayed evacuation** strategies on evacuation time. This may include initiating the evacuation of individuals based on their floor location or based on a fixed delay time for wheelchair users [2], [11].

G. ANALYSIS AND VALIDATION

There are several measures to assess and account for the quality of an evacuation plan. Evacuation time is considered one of the most utilized measures. Evacuation time is the time between the trigger of an alarm and the evacuation of the last occupant [120]. Other measures such as average evacuation time, average travel distance, average exit time per individual, and average wait time have also been utilized [121]. However, these measures ignore the delay in individuals' response and danger recognition. Thus, required safe egress time (RSET) concept was introduced [122]. RSET is the time for the evacuees to get out of a building safely. RSET starts from the moment fire was detected, an alarm was activated, evacuee decision to take action, and the travel time for the evacuee to reach to a safe area.

The main objective of crowd simulation is creating the most accurate possible representation of the actual behaviour and dynamics of individuals in certain conditions [29]. To guarantee the effectiveness of a simulation model, the model should be validated [30]. Model validation is defined as the process of determining the degree to which the model and its data and calculation methods accurately represent real-word situations [6], [123]. However, there is an ambiguity around the definition of validation of the simulation of evacuation methods, resulting in inconsistent procedures and tests adopted by model developers [123].

In a survey on Agent-based simulation models, Heath et al. [5] categorized models according to whether they were conceptually validated, operationally validated, validated both conceptually and operationally, or not validated at all. The validation of the conceptual model includes validating the underlying theories used, the model development process, and the assumptions underlying the model abstraction process [124], [125]. The validation of the operational model validates results of the simulation against results from a real system or, in the case of evacuations, a real-world

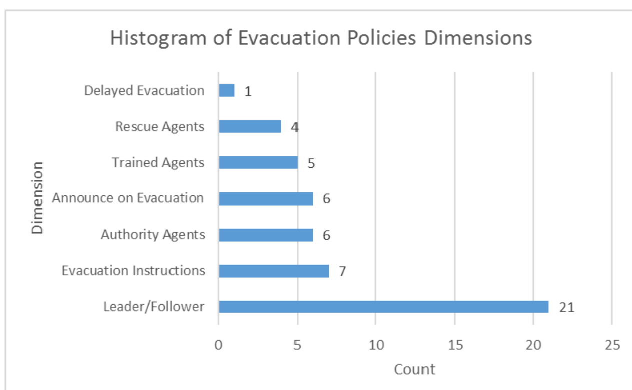

FIGURE 7. Number of Surveyed Articles per Evacuation Policies Support.

scenario. Another aspect considered is the technique used to validate the simulation model. Heath et al. [5] divided the techniques into statistical and non-statistical techniques. Statistical techniques use hypothesis tests to check the validity of the model, or part of it. Non-statistical techniques rely instead on qualitative assessment such as expert opinion. Despite these techniques being plausible in many simulation domains, such as biosystems and economics, their applications in evacuation simulations may not be possible.

In their survey of building evacuation models, Kuligowski et al. [6] listed the ways of validating evacuation models as: validation against code requirements, validation against real drills or other people movement trials, validation against literature on past evacuation experiments, validation against other models, and third party validations. Other ways of validating a model may include validation against empirical or manual engineering calculations [126]–[128]. Moreover, simulations for engineering purposes require strict verification and validation using ISO and other international standards [29]. For example, many international and national organizations defined a set of tests that an evacuation simulation should pass. These tests address aspects such as locomotion behaviour, adaptive exit choice, and threshold for recognizing the fire position [65].

However, model validation in evacuation conditions is lacking in the literature [5], [129]. There are many reasons behind this issue. First, there is a lack of data from evacuation experiments with real humans. Other than being burdensome, the process of monitoring human behaviours in real evacuations is challenging. Moreover, it is very expensive to set up a real-world evacuation experiment [129]. Also, the behaviour of people in an experiment is very likely to be different than their behaviour in impending danger conditions [30]. In addition, performing evacuation experiments may be considered dangerous and unethical. Lastly, the security domain presents an additional level of difficulty due to the confidentiality concerns surrounding data [4].

The validation of the models in the studies reviewed in this paper fall mainly into three categories, ordered from the strongest to the weakest: (1) validation against real world experiments, (2) validation against theoretical and/or expert opinion, (3) qualitative validation. Validation against real world experiments is considered the strongest, but hardest, method of validation. Simulation results are compared to the data from the same simulated building [11], [23], [40], [43], [96], or a similar one [60]. Since real evacuation data may not be available, models can be validated against drills in non-emergency situations [29], [91]. Strongly considered validation methods include results comparison with previously validated models [25], [34], and validating a specific aspect in the simulation against real-world data (i.e. pedestrians densities, bottlenecks) [30]. In some cases, authors use previously validated evacuation models [52]. However, it should be ensured that the model has been validated for similar types of building and that the validation approach used was appropriate [6].

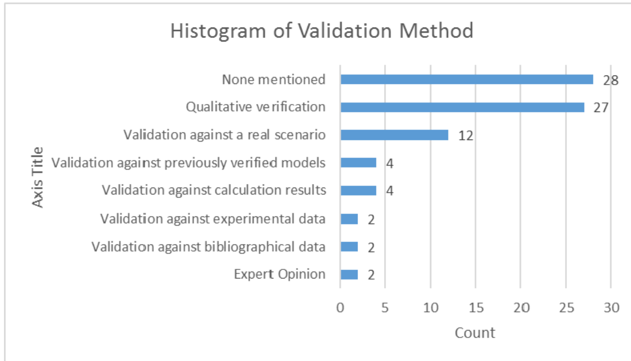

FIGURE 8. Number of Surveyed Articles per validation Method.

The next validation approach includes validating the results against expert opinion [4], [28], [65] and validation against bibliographic and theoretical data [28], [88]. In some cases, the authors may model a simplified version of the simulation and validate it against mathematical calculations [59], [63], [84], [87].

Qualitative validation usually relies on the discussion of "plausible" simulation results and qualitative analysis on the behaviour of the population [6]. Alarmingly, as shown in **Fig. 8**, 33% of the surveyed papers relied on qualitative discussion and 35% of the surveyed papers did not provide any indication of validation of the model provided.

Moreover, almost all of the surveyed papers did not provide a reference to access or replicate the model, which may be due to security reasons or competitive advantage.

Appendix A provides a summary of the papers surveyed, indicating the year of publication, focus of the paper, the type of the emergency being studied, the scale and the type of the space being evacuated, simulation technology used, agents' characteristics, other approaches used in combination with ABS, and the validation method. Appendix B is included to identify the special aspects and features of each evacuation model in the surveyed papers which readers may be interested in simulating. This appendix is included for users interested in simulating certain evacuation scenarios including various aspects. When combining Appendix, A and Appendix B, the user can understand the specific capabilities of each model as well as their context.

IV. CONCLUSION

In this paper, agent-based simulation models for pedestrian evacuation were surveyed to assess the current state of art and identify opportunities for improvement. We identified the main and common aspects and dimensions of emergency evacuation. From the surveyed papers, we identified the current practice of ABS for evacuation in terms of purpose of the simulation, type of emergency and environment considerations, type and scale of evacuated space, simulation software used, agents' characteristics and behaviour, support of evacuation policies, and analysis and validation.

TABLE 1. Summary of papers surveyed.

Paper	Year of Publication	Format	Focus	Emergency	Scale	Simulation Technology	Agents	Additional Approaches*	Validation method
Camillen et al. [74]	2009	Conference	Model pedestrian behaviour	Emergency evacuation	Museum	NetLogo	Heterogenous	N/A	Qualitative verification
Choi & Lee [44]	2009	Journal	Model pedestrian movement	Emergency evacuation	Floor Plan	Agent Analyst	Heterogenous	SF	Qualitative verification
Izquierdo et al. [51]	2009	Journal	Model pedestrian behaviour - assess building structure	Emergency evacuation	Flat Area	Visual Studio	Homogenous	PSO-SF	Qualitative verification
Klügl et al. [65]	2009	Journal	Evaluating emergency system layout	Fire	Subway	N/A	Heterogenous	N/A	Expert Opinion
Korhonen et al. [48]	2009	Journal	Model fire evacuation	Fire	Flat Area	FDS + Evac	Heterogenous	FD-SF	Validation against previously verified models
Lämmel et al. [73]	2009	Journal	Model pedestrian behaviour	Flood	City	MAT-Sim	Homogenous	N/A	Qualitative verification
Lin et al. [96]	2009	Journal	Model pedestrian behaviour	Emergency evacuation	Multi-story building	N/A	Heterogenous	N/A	Validation against real evacuation drill
Ren et al. [3]	2009	Journal	Model pedestrian behaviour	Fire	Room	Repast	Heterogenous	N/A	None mentioned
Shi et al. [26]	2009	Journal	Model fire evacuation	Fire	Gym	AIEva	Heterogenous	CA	Qualitative verification
Zaharia et al. [72]	2009	Conference	Model pedestrian behaviour	Emergency evacuation	Street	Massive	Homogenous	N/A	None mentioned
Qiu & Hu [76]	2010	Journal	Model pedestrian behaviour	Emergency evacuation	Room - Hallway	Open-Steer	Heterogenous	N/A	None mentioned
Rodriguez & Amato [54]	2010	Journal	Evacuation plan	Emergency evacuation	Rooms	N/A	Heterogenous	N/A	None mentioned
Sharma & Lohgaonkar [57]	2010	Conference	Optimize evacuation plan	Emergency evacuation	Room	C#	Homogenous	N/A	None mentioned
Zoumpoulaki et al. [75]	2010	Journal	Model pedestrian behaviour	Fire	Flat Area	N/A	Heterogenous	N/A	Qualitative verification
Chu & Law [87]	2011	Conference	Modelling social behaviour	Emergency evacuation	Building	MAS-SEgress	Heterogenous	N/A	Qualitative verification
Tsai et al. [4]	2011	Conference	Authority figure placement	Emergency evacuation	Airport, mall, museum	Open-Steer & Massive	Heterogenous	N/A	Expert Opinion
Anh et al. [9]	2012	Conference	Evacuation plan	Tsunami	City	N/A	Heterogenous	N/A	Qualitative verification
Goetz & Zipf [97]	2012	Journal	Use geodata for indoor routing	Emergency evacuation	University	MATSim	Heterogenous	N/A	None mentioned
Ha & Lykotrafitis [33]	2012	Journal	Impact of building structure	Emergency evacuation	Building	N/A	Homogenous	SF	Qualitative verification
Heliövaara et al. [35]	2012	Journal	Model pedestrian behaviour	Emergency evacuation	Room - Hallway	FDS+Evac	Heterogenous	SF	Validation against experimental data
Koo et al. [115]	2012	Journal	Assess evacuation strategies	Emergency evacuation	Multi-story building	BUMMPEE	Heterogenous	N/A	Qualitative verification
Manley & Kim [11]	2012	Journal	Assess evacuation strategies	Emergency evacuation	University campus	Exitus	Heterogenous	CA	Validation against real evacuation drill
Stamatopoulou et al. [78]	2012	Conference	Model pedestrian behaviour	Emergency evacuation	Building	Net-ProLogo	Heterogenous	N/A	None mentioned
Van Minh et al. [89]	2012	Journal	Model pedestrian emotions	Fire	Shopping Mall	GAMA	Heterogenous	N/A	None mentioned
Yang et al. [45]	2012	Journal	Optimize evacuation plan	Fire	Plaza	N/A	Heterogenous	FD	None mentioned
Ben et al. [25]	2013	Journal	Building structure impact	Emergency evacuation	Room	N/A	Heterogenous	CA	Validation against previously verified models
Joo et al. [49]	2013	Journal	Model pedestrian behaviour	Fire	Warehouse	Any-Logic	Homogenous	FSA	?
Mordvintsev et al.	2013	Journal	Model flood evacuation	Flood	City	Flood	Hetero-	N/A	None mentioned

TABLE 1. ***(Continued.)*** **Summary of papers surveyed.**

[94]						Simulator	genous		
Tissera et al. [27]	2013	Journal	Model pedestrian behaviour	Fire	Flat Area	EVAC	Heterogenous	CA	None mentioned
Bernardini et al. [43]	2014	Journal	Earthquake risk assessment	Earthquake	City centre	N/A	Heterogenous	SF	Validation against videotape analysis and previous experiments
Collins et al. [36]	2014	Journal	Model pedestrian behaviour	Emergency evacuation	Flat Area	Repast Symphony	Heterogenous	SF	None mentioned
Rivers et al. [40]	2014	Journal	Validate software for use in egress modelling	Emergency evacuation	Building	MassMotion	Heterogenous	SF	Validation against real evacuation drill
Wagner & Agrawal [1]	2014	Journal	Assess building structure	Fire	Stadium	NetLogo	Homogenous	CA	Qualitative verification
Wąs & Lubaś [28]	2014	Journal	Model pedestrian behaviour	Emergency evacuation	Stadium	N/A	Heterogenous	CA	Expert Opinion + Validation against bibliographical data
Zhang et al. [66]	2014	Journal	Assess building structure	Emergency evacuation	Stadium	Visual C	Heterogenous	CA	None mentioned
Okaya et al. [56]	2015	Conference	Optimize evacuation plan	Emergency evacuation	Shopping Mall - Building	TENDENKO	Heterogenous	N/A	None mentioned
Che et al. [58]	2015	Journal	Model pedestrian behaviour/assess evacuation plans	Fire	Supermarket	N/A	Heterogenous	N/A	None mentioned
Karbovskii et al. [41]	2015	Journal	Model a multiscale evacuation	Emergency evacuation	Cinema - City Streets	PULSE	Heterogenous	SF	Qualitative verification
Pluchino et al. [67]	2015	Conference	Test the infrastructure in hazardous scenarios	Evacuation after a blast	Museum & Subway	Netlogo	Heterogenous	N/A	Qualitative verification
Tan et al. [79]	2015	Journal	Model pedestrian behaviour	Fire	Campus Building	Agent Analyst	Heterogenous	N/A	None mentioned
Wang et al. [80]	2015	Journal	Model pedestrian behaviour	Emergency evacuation	Room	Visual C	Heterogenous	N/A	Qualitative verification
Xu et al. [37]	2015	Journal	Model pedestrian behaviour	Emergency evacuation	Flat Area	OpenSteer	Heterogenous	SF	None mentioned
Asgary et al. [55]	2016	Conference	Assess evacuation strategies	Emergency evacuation	University campus	AnyLogic	Homogenous	N/A	Conceptual validation only
Beklaryan & Akopov [71]	2016	Conference	Optimal evacuation strategy for rescuers	Emergency evacuation	Airport	AnyLogic	Heterogenous	N/A	Validation against real video-data
Fang et al. [50]	2016	Journal	Optimize evacuation model	Emergency evacuation	Floor Plan	N/A	Heterogenous	SFM	Qualitative verification
Fang et al. [34]	2016	Journal	Impact of human behaviour	Emergency evacuation	Room	N/A	Heterogenous	SF	Calibration and validation against other models that were previously verified in addition to verification with field data.
Liu et al. [59]	2016	Journal	Impact of building structure and evacuation training	Fire	Classroom	NetLogo	Heterogenous	N/A	Validation against calculation results
Liu et al. [60]	2016	Journal	Impact of building structure and evacuation strategy	Earthquake	Multistory building	NetLogo	Heterogenous	N/A	Validation against real evacuation drills of similar buildings
Lubaś et al. [29]	2016	Journal	Model pedestrian behaviour	Emergency evacuation	Stadium - Lecture Room - Lecture Hall	N/A	Heterogenous	CA	Validation against real evacuation drills (in non emergency situations)
Wang et al. [61]	2016	Journal	Impact of evacuation strategy and decision making	Tsunami	City	NetLogo	Heterogenous	N/A	Qualitative verification
Zhang et al. [30]	2016	Journal	Optimize evacuation plan	Emergency evacuation	Subway	AnyLogic	Homogenous	SF	Validation against observations (in re-

TABLE 1. *(Continued.)* **Summary of papers surveyed.**

									gards of pedestrians density)
Bakar et al. [42]	2017	Con-ference	Propose a conceptual model	Fire	Building	N/A	Hetero-genous	SF	None mentioned
Bangate et al. [83]	2017	Con-ference	Model human behaviour	Earthquake	Building & Roads	GAMA	Hetero-genous	N/A	Qualitative verification
Basak & Gupta [38]	2017	Journal	Model pedestrian behaviour	Emergency evacuation	Street	N/A	Hetero-genous	SF	Qualitative verification
Busogi et al. [85]	2017	Journal	Model and analyze human behaviour	Emergency evacuation	Building	Any-Logic	Hetero-genous	N/A	Qualitative verification
Cassol et al. [52]	2017	Journal	Optimize evacuation plan	Emergency evacuation	Building	Crowd-Sim	Hetero-genous	N/A	Simulation tool previ-ously verified
Cimellaro et al. [10]	2017	Journal	Impact of structural damage on evacuation	Earthquake	Mall	Repast HPC	Hetero-genous	CA	Qualitative verification
Collins & Fryden-lund [84]	2017	Journal	Model human behaviour (theoretical)	Evacuation after a blast	Grid	NetLogo	Hetero-genous	N/A	Validation against calculation results
Dossetti et al. [82]	2017	Journal	Model pedestrian behaviour	Emergency evacuation	Room	N/A	Hetero-genous	N/A	Qualitative verification
Liu et al. [81]	2017	Journal	Model pedestrian behaviour	Fire	Super-market	N/A	Hetero-genous	N/A	Validation against a real scenario
Mohd Ibrahim [39]	2017	Journal	Model human behaviour	Emergency evacuation	Room	N/A	Hetero-genous	SF	Qualitative verification
Song et al. [18]	2017	Journal	Authority figure placement	Emergency evacuation	Subway	Any-Logic	Hetero-genous	SF	Qualitative verification
Chooramun et al. [24]	2018	Journal	Optimize evacuation model	Wildfire	City	building EXO-DUS	Hetero-genous	CA	None mentioned
Delcea et al. [69]	2018	Journal	Impact of room structure (optimization of structure)	Fire	Class-room	NetLogo	Hetero-genous	N/A	None mentioned
Kallianiotis et al. [63]	2018	Journal	Assess evacuation plans	Fire	Subway	Path-finder	Hetero-genous	N/A	Validation against calculation results
Karbovskii et al. [32]	2018	Journal	Optimize evacuation model	Emergency evacuation - flood	Cinema - City	PULSE	Hetero-genous	SF	None mentioned
Kasereka et al. [90]	2018	Journal	Model pedestrian and fire	Fire	Coomer-cial build-ings	GAMA	Hetero-genous	N/A	None mentioned
Liu et al. [31]	2018	Journal	Model pedestrian behavior - optimize evacuation model	Emergency evacuation	Building Floor	Visual Studio	Hetero-genous	SF	Qualitative verification
Makinoshima et al. [62]	2018	Journal	Optimize evacuation model	Tsunami	City	N/A	Hetero-genous	N/A	Validation against experimental and observational results with real pedestrian movement
Richardson et al. [86]	2018	Journal	Model pedestrian behavior	Fire	Building Floor	Mercuri-al	Hetero-genous	N/A	None mentioned
Sun & Turkan [46]	2018	Con-ference	Optimize building layout	Fire	Building	PyroSim	Hetero-genous	FD	Qualitative verification
Trivedi & Rao [68]	2018	Journal	Optimize environment and evacuation plans	Emergency evacuation	Lecture Hall	MASON	Hetero-genous	N/A	Qualitative verification
Yuksel [8]	2018	Journal	Optimize simulation per-formance	Emergency evacuation	Room	Java - Eclipse	Homog-enous	N/A	Qualitative verification
Zheng et al. [91]	2018	Journal	Impact of merging forms on stairs evacuation	Fire	Building	Path-finder	Homog-enous	N/A	Validation against real evacuation drills (in non-emergency situa-tions)
Chen & Wang [132]	2019	Con-ference	Model pedestrian panic	Emergency evacuation	Room	N/A	Homog-enous	N/A	None mentioned
Chu & Law [87]	2019	Journal	Model pedestrian behavior	Emergency evacuation	Stadium	SAFE-gress	Hetero-genous	N/A	Validation against calculation results
Cimellaro [88]	2019	Journal	Model pedestrian behavior	Blast	Museum & Sub-way	NetLogo	Hetero-genous	N/A	Validation using pre-evacuation time test and movement tests

TABLE 1. *(Continued.)* **Summary of papers surveyed.**

Paper	Year of Publication	Format	Focus	Emergency	Scale	Simulation Technology	Agents	Additional Approaches*	Validation method
Hu et al. [70]	2019	Conference	Evaluate efficiency of exits and potential risk	Emergency evacuation	Subway	building EXODUS	Homogenous	N/A	None mentioned
Mirahadi et al. [47]	2019	Journal	Optimize building layout	Fire	Building	MassMotion + FDS	Homogenous	FD	None mentioned
Mostafizi et al. [64]	2019	Journal	Evaluate evacuation plans	Tsunami - earthquake	City	NetLogo	Heterogenous	N/A	None mentioned
Rendón et al. [23]	2019	Journal	Design evacuation plan	Emergency evacuation	University	NetLogo	Heterogenous	N/A	Validation against a real-life drill that has been recorded for the purposes of the study

*** Approaches used in addition to ABS**

Several conclusions can be developed through the analysis of the surveyed papers. First, each of the cited studies included a different set of aspects assuming these aspects are the most significant ones for the simulation. However, not much theoretical foundation behind the choice of factors considered was found. Users should ensure that the behavioural aspects of the simulated model are supported by data and/or theory of human behaviour during evacuation [6]. Moreover, there is a need for a complete collection and analysis of data on individual reasoning in real danger events.

Second, and resulting from the lack of a validated set of aspects most relevant for an evacuation simulation, many papers ignore important factors related to human behaviour, decision making, and heterogeneity. For instance, less than a quarter of the papers considered groups and families relations, only few of the surveyed papers considered the waiting time needed for the evacuees to recognize and act on an alarm, and even less models considered disabled occupants.

Third, papers surveyed followed different methodologies, including the way the results were analysed and validated. With different modelling software, and programmers using different programming languages to create simulations, a unified methodology should be established for evacuation simulations in general, and ABS for evacuation in particular [5]. Moreover, as most of the papers did not provide reference to access or replicate the model due to property or security reasons, there is a need for model describing tools to provide complete descriptions of these models. While ABS for disaster management is still emerging [130], some believe that ABS and simulation will produce revolutionary developments in social sciences [5], [131], highlighting an opportunity for research to expand. Thus, it is important that standards for such research are established.

Fourth, validation is considered one of the most important aspects of model building as the only means to provide evidence that the model can be used for its intended purposes [5]. It is alarming to find that most of the reviewed models (68.8%) did not provide any validation information or relied on qualitative discussion of the results. It should be a requirement from publication outlets as well as reviewers that all models are validated and the validation process documented clearly in the study. Models should be validated both conceptually and operationally. Moreover, validation should rely more on quantitative and statistical techniques rather than qualitative discussion.

This study also has its limitation. The simulation of an evacuation is a complex task and consists of many details that should be considered by the simulationist. In this paper, we attempted to cover the most common and important aspects across surveyed papers. However, the list is not considered complete. Some aspects that were not covered in this paper include the method of agents' movement throughout the building, navigation and path-planning methods, the perspective of the agent about the environment and human-decision models (i.e. Believes, Desires, Intentions – BDI).

APPENDIX

A. SUMMARY OF PAPERS SURVEYED

TABLE 1 provides a summary of the papers surveyed, indicating the year of publication, focus of the paper, the type of the emergency being studied, the scale and the type of the space being evacuated, simulation technology used, agents' characteristics, other approaches used in combination with ABS, and the validation method.

B. EVACUATION DIMENSIONS AND ASPECTS

TABLE 2 is included to identify the special aspects and features of each evacuation model in the surveyed papers which readers may be interested in simulating. This table is included for users interested in simulating certain evacuation scenarios including various aspects. When combining TABLE 1 and TABLE 2, the user can understand the specific capabilities of each model as well as their context.

TABLE 2. Evacuation dimensions and aspects.

Dimension	Evacuation Environment						Procedures								Psychological Characteristics								Physical Characteristics	
Aspect	Multi-Story Buildings	Building Structure & Environment	Smoke and fire	Multiple Exits	Congestion at Exits	Exit Signs	Trained Agents	Rescue Agents	Authority Agents	Leader/Follower	Information Asymmetry	Announce on Evacuation	Evacuation Instructions	Delayed Evacuation	Psychological Model	Stress and Panic	Social Collective Behaviour	Social Force	Information Share Among People	Groups and families	Waiting Time	Help Injured	Stamina / Injured Agents	Disabled
Camillen et al. [74]				■																				
Choi & Lee [44]					■																			
Izquierdo et al. [51]				■	■						■							■						
Klügl et al. [65]			■	■	■	■													■				■	
Korhonen et al. [48]			■	■														■					■	
Lämmel et al. [73]												■	■											
Lin et al. [96]	■			■						■							■	■			■			
Ren et al. [3]			■	■					■	■	■				■					■			■	
Shi et al. [26]		■	■	■							■				■				■		■		■	
Zaharia et al. [72]															■									
Qiu & Hu [76]										■										■				
Rodriguez & Amato [54]				■						■	■								■	■				
Sharma & Lohgaonkar [57]										■					■		■			■				
Zoumpoulaki et al. [75]			■							■	■				■				■	■			■	
Chu & Law [87]						■	■			■	■				■				■	■				
Tsai et al. [4]									■		■				■				■	■				
Anh et al. [9]							■			■	■													
Goetz & Zipf [97]	■			■								■												
Ha & Lykotrafitis [33]	■	■			■											■		■						
Heliövaara et al. [35]				■														■						
Koo et al. [115]	■				■								■	■										■
Manley & Kim [11]	■	■		■	■								■		■						■	■		■
Stamatopoulou et al. [78]				■									■		■									
Van Minh et al. [89]											■				■									
Yang et al. [45]				■							■													
Ben et al. [25]				■	■						■												■	
Joo et al. [49]											■								■					

TABLE 2. *(Continued.)* Evacuation dimensions and aspects.

Aspect	Multi-Story Buildings	Building Structure & Environment	Smoke and fire	Multiple Exits	Congestion at Exits	Exit Signs	Trained Agents	Rescue Agents	Authority Agents	Leader/Follower	Information Asymmetry	Announce on Evacuation	Evacuation Instructions	Delayed Evacuation	Psychological Model	Stress and Panic	Social Collective Behaviour	Social Force	Information Share Among People	Groups and families	Waiting Time	Help Injured	Stamina / Injured Agents	Disabled
Mordvintsev et al. [94]		■										■							■				■	
Tissera et al. [27]		■	■	■						■	■				■								■	
Bernardini et al. [43]		■						■			■								■					
Collins et al. [36]										■								■		■				
Rivers et al. [40]	■																	■						
Wagner & Agrawal [1]	■	■	■																					
Wąs & Lubaś [28]		■		■															■					
Zhang et al. [66]				■																				
Okaya et al. [56]				■		■				■	■													
Che et al. [58]				■		■				■	■													
Karbovskii et al. [41]				■								■												
Pluchino et al. [67]							■			■	■									■		■	■	
Tan et al. [79]		■	■	■						■	■				■	■								
Wang et al. [80]				■	■					■						■							■	
Xu et al. [37]				■													■	■						
Asgary et al. [55]	■											■												
Beklaryan & Akopov [71]											■										■			
Fang et al. [50]				■													■			■			■	
Fang et al. [34]				■	■	■	■			■	■				■	■	■	■		■				
Liu et al. [59]	■	■		■		■					■						■		■	■		■	■	
Liu et al. [60]		■		■			■						■											
Lubaś et al. [29]										■			■						■	■				
Wang et al. [61]											■										■			
Zhang et al. [30]				■																				
Bakar et al. [42]				■	■													■	■		■	■		
Bangate et al. [83]	■	■																		■				
Basak & Gupta [38]				■														■						
Busogi et al. [85]	■														■									

TABLE 2. *(Continued.)* **Evacuation dimensions and aspects.**

Aspect	Multi-Story Buildings	Building Structure & Environment	Smoke and fire	Multiple Exits	Congestion at Exits	Exit Signs	Trained Agents	Rescue Agents	Authority Agents	Leader/Follower	Information Asymmetry	Announce on Evacuation	Evacuation Instructions	Delayed Evacuation	Psychological Model	Stress and Panic	Social Collective Behaviour	Social Force	Information Share Among People	Groups and families	Waiting Time	Help Injured	Stamina / Injured Agents	Disabled
Cassol et al. [52]				■																				
Cimellaro et al. [10]											■										■			
Collins & Frydenlund [84]																				■				
Dossetti et al. [82]			■	■							■	■				■			■					
Liu et al. [81]			■	■							■	■				■			■					
Mohd Ibrahim [39]					■													■	■					
Song et al. [18]	■			■	■				■		■					■								
Chooramun et al. [24]											■													
Delcea et al. [69]				■																				
Kallianiotis et al. [63]				■																				■
Karbovskii et al. [32]											■													
Kasereka et al. [90]			■	■																			■	
Liu et al. [31]				■						■	■									■				
Makinoshima et al. [62]					■																		■	
Richardson et al. [86]			■	■						■	■													
Sun & Turkan [46]		■	■						■	■	■						■							
Trivedi & Rao [68]				■	■					■			■		■	■			■				■	
Yuksel [8]		■																	■					
Zheng et al. [91]	■	■		■																				
Chen & Wang [132]																■								
Chu & Law [87]				■		■			■		■									■				
Cimellaro [88]				■				■		■													■	
Hu et al. [70]				■	■																			
Mirahadi et al. [47]	■		■																					
Mostafizi et al. [64]		■																						
Rendón et al. [23]	■			■		■																		

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